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Pain in Athletes: Current Knowledge and Challenges

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International Journal of Sports Physical Therapy

Pain in athletes has been traditionally equated with tissue damage (i.e., an acute traumatic or overuse injury). However, chronic pain presents a challenge to team sports since it is not fully explained by ongoing biomechanical stress or overuse injury. Although biomechanical factors can indeed be a relevant nociceptive input for some individuals, it cannot be the main factor to explain pain in athletes.

Knowledge about pain has evolved during the last three decades from a cartesian (pain = tissue damage) into a multidimensional perspective in which several factors such as tissue overload, nociceptive gain, cognitive, emotional, behavioral, lifestyle and several other factors interact in complex ways, leaving the individual more or less prone to experience pain. It is well-known that chronic pain cannot be explained solely by patho-anatomical changes. Thus, a narrow focus on biophysical factors (e.g., structural, biomechanical) can contribute to misconceptions about pain, higher threat value of pain, protective behavior and foster disability. In addition, it can lead to overtesting (unnecessary exams), overdetection (detection of clinically unimportant findings), overtreatment (unnecessary treatment for a condition that is not life-threatening or would never cause any symptoms) and high costs.

Although the International Olympic Committee (IOC) published a consensus on pain management in elite athletes enhancing the biopsychosocial approach, the clinical implications of applying current pain knowledge to clinical practice has been barely discussed. According to the IOC consensus, a rational approach to pain management in athletes begins with classifying the type of pain. In this aspect, pain can be classified by its time frame (i.e., acute or chronic), mechanism of onset (i.e., traumatic or non-traumatic) and according to its manifestation (i.e., gradual or sudden). Pain can be classified by its mechanisms as nociceptive, neuropathic or nociplastic. In chronic pain cases, pain can also be classified using the current version of the International Classification of Diseases (ICD-11) as chronic primary pain (e.g., chronic non-specific low back pain) or chronic secondary pain, (e.g., chronic cancer pain, chronic posttraumatic and postsurgical pain, chronic neuropathic pain, chronic headache and orofacial pain, chronic visceral pain, and chronic musculoskeletal pain).

Adequate chronic pain management in athletes depends on identifying pain mechanisms and contributory factors considering a multidimensional perspective. For example, the most commonly reported risk factors for low back pain in sports were higher athlete training volumes, change to increased training load and history of low back pain. Nevertheless, psychosocial factors including emotional distress, symptoms of anxiety, catastrophic thinking, and pain-related fear, were associated with prolonged recovery and lower return to sport rates. Pain catastrophizing was reported as the most important factor associated with increased pain intensity in injured athletes. An athlete's psychological readiness to return to play was associated with the outcomes of rehabilitation. The literature presents evidence that pain-related fear, maladaptive beliefs, catastrophizing, and avoidance behavior are key factors in the development of disability in chronic musculoskeletal and primary pain conditions. The social domain is less commonly discussed in the literature and usually involves relationships, social support, engagement in care, environmental influences, and socioeconomic factors.

Although there have been substantial advances in pain knowledge, there are still some challenges to overcome to properly apply these concepts in sports. First, pain experience should be considered based on complex systems approaches, meaning that pain experience results from the dynamic and non-linear interactions among many (known and unknown) factors. Team sports should also be aware to avoid the pendulum swinging too far from a biophysical to a narrow psychosocial perspective. Thus, it is important not to overlook the “bio” in the multidimensional perspective.
since training parameters and biomechanical factors can be associated with some clinical conditions (e.g., lower limb tendinopathy). It is also important to recognize the limitations of the biopsychosocial model in which several factors (e.g., mental health, guilt, stigma, emotional support, feelings of shame, perceived injustice, interpersonal relationships, culture, class, macro socio-economic, political context, religiosity/spirituality, access to healthcare, sleep and nutrition quality) are rarely investigated and their influence on the athlete’s pain experience remains unknown.\(^\text{10}\) Second, the implementation of the current ICD classification for chronic pain in sports can contribute to better epidemiological data since definitions and reporting styles across studies present a broad variation. Third, focus on the biophysical factors (e.g., exams, tests) can lay aside patient’s perspective on wellness and care experiences. In this aspect, team sports should implement patient-reported outcome measures in their clinical pain assessment to establish patient-oriented evidence to better inform patient care decisions. Several measurement instruments have been developed and tested in non-athletes. Thus, efforts to develop athlete-specific or sport-specific assessment instruments should be done. Lastly, pain curriculum and training in undergraduate health care programs are insufficient in different disciplines and countries. Further discussion on the need and implementation of a specific course in pain and in sports in professional degree education programs should be considered.

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Clinical Viewpoint

Vibration Therapy – A Clinical Commentary

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SCIENTIFIC FOUNDATION

Vibration therapy has been around for many years, and recently has regained popularity. Vibration is detected in the skin, muscles, and joints by Pacinian corpuscles and travels to the Primary Somatosensory Cortex for processing via the dorsal column ascending neural pathway.  

APPLICATION PRINCIPLES

It has been reported that vibration can alter stretch reflex sensitivity and in turn affect the motor unit threshold, firing rate and maximal voluntary strength on muscle action. It is believed that the effect of vibration largely depends on the duration and frequency of the stimulus provided. If applied briefly (2 – 25 seconds) vibration resulted in additional excitation of the motor neuron pool which increased initial firing rates and ultimately enhanced force production.  

However, if applied for prolonged periods (30+ seconds), a decrease in maximal voluntary strength occurs via presynaptic autogenic inhibition. Presynaptic autogenic inhibition is a reduction of muscle spindle activity and golgi tendon organ activation characterized by lower group Ia mean discharge rates, decreased reflex magnitude and increased (slow) reflex latency. This ultimately reduces the net excitation of the motor neuron pool and decreases maximal voluntary strength. 

Regarding specific application of devices, it is suggested that you work with gentle pressure over the indicated treatment area for 20 to 60 seconds. An area requiring increased treatment can be identified by experiencing a different tactile or auditory sensation. The device will either "thud" and "bounce" more aggressively over affected tissue or practitioners may even hear a different pitch in volume from the typical vibratory sound.

INDICATIONS AND CONTRAINDICATIONS

Vibration therapy may be indicated for myofascial pain, autogenic muscle inhibition and delayed onset muscle soreness. While there are no direct contraindications for its use clinicians should proceed with caution for the treatment of certain conditions. Some examples are stress fractures / reactions, neuropathy, fibromyalgia, epilepsy, pregnancy, recent surgery or joint replacement, metal pins or plates, pacemakers, areas with skin rash or open wounds and in individuals with hypertension or those at risk for clotting.

CLINICAL APPLICATION

The ability to regulate muscle activity up or down via vibration is beneficial for clinical use and it is important that practitioners understand the scientific application to appropriately prescribe its use.

While there are many proposed benefits of vibration therapy the literature most strongly supports its clinical application for pain relief, improving tissue extensibility, increasing strength, and decreasing muscle soreness.

The recommendation for application is to provide gentle pressure with continuous motion into the affected tissue. You will know you found an area requiring increased attention when either the response is more pronounced ('bouncy') or louder. This does not mean that more pressure is required, simply sustained gentle pressure.

PAIN MODULATION

In 2015 Lam et al. performed a prospective randomized double-blind study in individuals following arthroscopic rotator cuff repair. They applied a 80-Hz of vibration 5 minutes per day for 6 months following the operation and found significantly lower visual analog (pain) scale scores at the 6 week follow up compared to those who did not receive vibration.
The author utilizes the Hyperice venom shoulder (Figure 1) prior to treatment with patients following a rotator cuff repair. This helps to provide superficial heat for tissue extensibility combined with vibration for proposed benefits mentioned to improve range of motion in early and mid-phases of rehabilitation.

Additionally, this device can be used in the overhead athlete. It is known that internal rotation significantly decreases immediately following and 24 hours after throwing. Thus, the author will use this device to provide cool down following a throwing session to help maintain tissue extensibility and reduce the side effects from activity.

**RANGE OF MOTION**

In 2020 Tilp et al. analyzed dorsiflexion ROM following the use of the hypervolt massage gun (Figure 2). They worked for 2.5 minutes on each gastroc head at 53 Hz while the control group received no intervention and found a 5.4% increase in ROM following treatment. The group that received intervention demonstrated no change in max voluntary contraction. This has clinical implication in the athletic setting to improve flexibility without compromising strength.

In 2021 Nakamura et al further supported this by having two groups perform 3 sets of 60 second bouts of foam rolling from their achilles to popliteal fossa using the Hyperice Vyper 2.0 (Figure 3). One group left the device off and the other set the frequency to 48 Hz and 1.5 mm amp. What they found was that while both groups increased DF PROM the vibration group demonstrated a significant decrease in shear elastic modulus (which correlates with stiffness) and additionally an increase in motor unit recruitment. Those who used the non-vibrating foam roller demonstrated a decrease in maximal voluntary contraction during concentric plantar flexion activity.

Based on the data supporting improved ROM and tissue extensibility without loss of strength the author utilizes both vibrating massage guns and vibrating foam rollers during mid to late-stage rehabilitation to prepare individuals for treatment sessions. There has been a great deal of subjective feedback from patients and athletes indicating the improved comfort of a vibrating foam roller as compared to traditional rollers.

**MOTOR UNIT RECRUITMENT**

Regarding strength Brunetti et al demonstrated that by applying 100Hz & 20µm amps to the distal quadriceps during isometric contraction in patients who underwent ACL reconstruction, peak torque increased at the 90 and 270 day follow up. High frequency and high amplitude parameters will increase stimulus to tissue and thus improve neural drive via increased motor unit recruitment.

This principle can be extremely beneficial during early-stage ACL rehab by combining this approach with the use of external biofeedback. Biofeedback devices can help with additional recruitment by providing visual cueing for quadriceps contraction which we know becomes of increasing cognitive demand following an ACL injury. Clinically the author has found that by combining the use of vibration devices with quadriceps contraction motor unit recruitment increases on biofeedback versus contraction without additional vibratory stimulus (Figure 4).
DELYED ONSET MUSCLE SORENESS

Lastly, vibration devices can alleviate delayed onset muscle soreness. Two similarly designed studies indicate that subjective soreness scores and systemic response are improved if vibration stimulus is applied prior to or post exercise.

In 2007 Bakhtiari et al had 50 participants walk for 30 minutes on a 10° decline. Prior to this one group applied vibration therapy to each quadriceps, hamstring, and calf at 50Hz for 1 minute each. The group that did not receive intervention reported a higher soreness rating following the activity, demonstrated decreased isometric voluntary muscle contraction, and even presented with increased serum creatine kinase enzyme in their blood biomarkers indicating inflammation.15

Broadbent et al followed this up in 2011.16 They had two groups of individuals run on a decline for 40 minutes at 70% VO2 max. One group applied 40Hz, 5 mm amplitude once per day for 3 minutes to their quadriceps, hamstrings, calves, and IT band for 5 days following their run while the other did not. What they found was that those who applied vibration therapy had reduced muscle soreness at 24, 96 and 120 hours following. Additionally, they found changes in blood biomarkers: decreased interleukin 6, decreased histamine, decreased lymphocytes, and increased neutrophils; all of which are markers indicating reduced systemic inflammation.

These studies reveal that whether applied prior to or following exercise intervention vibration therapy can alleviate delayed onset muscle soreness not only from a subjective standpoint but an objective component too. This solidifies the importance of use in the clinical rehab or higher-level athletic setting to ensure that individuals can maintain the ability to adhere to the demands of a vigorous training regime.

RECOMMENDATIONS

When it comes to vibration therapy, the author is an advocate for its use based on the benefits mentioned throughout. To summarize lower frequency, amplitude coupled with longer duration (30+ seconds) helps alleviate pain, improve tissue extensibility, and reduce the potential for delayed onset muscle soreness, which can be beneficial in patients who are post-operative, dealing with chronic pain or just finished performing strenuous eccentric exercises. Higher frequency, amplitude with short duration usage (<30 seconds) can assist with motor unit recruitment and tissue preparedness which can be beneficial prior to or during exercise activity.

CONCLUSION

Vibration therapy has been all the buzz in recent years due to the many different devices on the market. These devices can be a great adjunct tool to boost performance in rehab and competition. There are many settings and parameters which can yield a variety of clinical outcomes. It is important that practitioners understand the scientific foundation behind these tools to guide clinical application in professional setting and also educate their patients on appropriate use at home. Overall vibration therapy is a safe, inexpensive, and accessible form of treatment with many benefits. Further studies are warranted to study the effects of different frequency, amplitude and time parameters as they relate to physiologic response of tendon and ligament conditions.

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Systematic Review/Meta-Analysis

Physical impairments in Adults with Developmental Dysplasia of the Hip (DDH) undergoing Periacetabular osteotomy (PAO): A Systematic Review and Meta-Analysis


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Background

Developmental dysplasia of the hip (DDH) is a condition associated with hip pain and impairments. Periacetabular osteotomy (PAO) is a common surgical treatment for DDH. Outcomes following PAO have historically been based on radiology or patient reported outcomes, and not physical impairments.

Objective

To investigate differences in physical impairments in adults with DDH undergoing PAO compared with asymptomatic participants, and to investigate pre- to post-PAO changes in physical impairments.

Design

Systematic review with meta-analysis

Methods

A literature search was performed in five databases (MEDLINE, CINAHL, EMBASE, Sports Discuss, and PsychINFO), using the PRISMA checklist. Studies were considered eligible if patients were aged 15 years and older, treated with PAO for DDH and if they included a physical impairment outcome measure. Two independent reviewers performed data extraction and assessed methodological quality, using a modified version of the Downs and Black checklist.

Results

Of 5,017 studies, 24 studies were included with 2190 patients. The methodological quality scores ranged from 59% to 88%. With low level of evidence, meta-analysis showed 58% of patients had a positive anterior impingement test (95%CI: 39-76%), prior to PAO and one to three years after PAO. Five years after PAO, the proportion fell to 17% (95%CI: 11-24%). Prior to PAO, patients with DDH walked with a lower peak hip extension angle, compared to asymptomatic participants (SMD 0.65 (95%CI 0.21-1.10). Best evidence synthesis of non-pooled data showed limited evidence of increased walking velocity, stride length and improved hip flexion and extension moment 18-months post-PAO compared to pre-op. Cadence, hip abduction and hip flexion strength did not change.

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Conclusion

Most patients with DDH have a positive hip impingement test, pre-PAO. Compared to asymptomatic participants, patients with DDH demonstrate physical impairments during walking which appear to improve after surgery. Hip abduction and flexion strength did not change pre- to post-PAO.

Level of Evidence

1b

INTRODUCTION

Developmental dysplasia of the hip (DDH) defines a hip joint with reduced acetabular coverage of the femoral head and is prevalent in 32% of primary care patients with hip pain. The radiologic features of dysplasia are found in 3-20% of the general population. Patients with DDH may experience hip pain, impaired physical function, and low quality of life. An association with DDH and early development of hip osteoarthritis (OA) has been established with three times greater odds of progressing from mild to end-stage OA or total hip replacement. The acetabular coverage can be increased with the surgical procedure, periacetabular osteotomy (PAO). The goal of the PAO is to reduce the likelihood of hip OA by increasing the acetabular coverage of the femoral head.

Historically, outcomes of PAO have been derived from surgeons’ definition of success, which are often based on imaging outcomes. However, in recent years, there has been a shift towards including other measures of successful surgery, including physical impairments and patient-reported outcomes. This is supported by studies which suggest structural pathology may not be the sole contributing factor to pain. For example, a high prevalence of labral tears (54%) has been shown to exist in asymptomatic subjects. Mose et al. also reported no association between the level of pain and severity of labral lesions or to the degree of bony coverage in patients with DDH. For patients to give truly informed consent to undergo PAO, there must be robust evidence of the likely outcome of surgery on not only pain, but also in regard to physical function.

Physical impairments may potentially explain deficits in those with worse outcomes following PAO. Patients with DDH who undergo PAO have reported improvements in pain, function, and quality of life. However, up to 32-months after PAO, these outcomes were still significantly worse compared with asymptomatic participants. It is possible that these deficits are related to physical impairments. Physical impairments after PAO have been reported in individual studies. However, no reviews have systematically synthesized physical impairments in patients with DDH undergoing PAO. For future patients to be appropriately informed, and to improve clinicians’ knowledge and ability to help these patients, a systematic review on physical impairments in patients with DDH undergoing PAO is warranted.

This systematic review aimed (i) to compare physical impairments in patients undergoing PAO for DDH to asymptomatic participants, and (ii) to investigate pre- to post-PAO changes in physical impairments in patients with DDH.

METHODS

Study selection, eligibility criteria, data extraction, and statistical analysis were performed according to the Cochrane Collaboration guidelines. The systematic review was reported in accordance with the preferred reporting guidelines for systematic reviews and meta-analysis (PRISMA) guidelines, and was registered on the Prospero international prospective register of systematic reviews (ID: CRD42020180571).

SEARCH STRATEGY

A comprehensive, reproducible search strategy was performed on the following databases MEDLINE CINAHL, EMBASE, Sports Discuss, and PsychINFO from inception until 5th January 2021.

The search strategy was conducted by two reviewers (MO, AS) and used the following concepts:

- Humans with DDH aged 15 years and older
- Periacetabular Osteotomy
- Joint Instability OR instability OR unstable
- lax OR laxity OR subluxation OR dysplasia OR dysplastic
- OR antversion
- retroversion
- AND (Periacetabular OR peri-acetabular OR Osteotomy OR osteo-ty OR Hip OR hips OR Hip OR hips OR Hip OR hips OR Hip Joint OR coxofemoral joint)
- AND Pelvis OR Pelvic

The search strategy was modified for each database. All potential references were imported into Endnote X8 (Thomson Reuters, Carlsbad, California, USA) and duplicates were removed. All included studies were then uploaded into Covidence software (Veritas Health Innovation Ltd, Australia) for screening. Title, abstract and full text screening was conducted by three independent reviewers (MO A-Z, CS A-M, LT N-Z). Any disagreements were resolved by a fourth independent reviewer (JK).

ELIGIBILITY CRITERIA

Studies were eligible for inclusion if they used a hip-specific physical impairment measure and were written in English. All quantitative observational study designs were considered eligible including randomised control trials, non-randomised controlled trials, case series, prospective or ret-
rospective study designs. Animal studies and case studies were excluded.

**PARTICIPANTS/POPULATION**

People aged 15 years and older with DDH undergoing PAO (based on the mean or median age of the study sample) were included. Studies were not eligible if the PAO was undertaken in people with Cerebral Palsy, Down Syndrome or Charcot-Marie Tooth Disease.

**INTERVENTION(S), EXPOSURE(S)**

Studies that used PAO surgery as primary intervention for DDH were included. The terms 'Bernese Osteotomy' and 'Ganz Osteotomy' were considered interchangeable with 'Periacetabular Osteotomy'. Studies were not eligible if the PAO was reported to be a 'rotational' or 'curved' as these procedures differ in surgical technique.

**COMPARATOR(S)/CONTROL**

Studies using sham treatment, no treatment or other treatment (e.g., total hip joint replacement or hip arthroscopy surgery) as the comparator/control treatment were included. We also included studies where no comparison group was present if they used two timepoints (for example: case series). In this instance, the pre-intervention timepoint was considered the 'comparison'.

**OUTCOMES**

Primary outcomes of interest were hip-related physical impairment measures. These included pain provocation tests, hip muscle strength, hip range of motion (ROM) and gait analysis.

**QUALITY EVALUATION**

A modified version of the Downs and Black checklist was used to assess the quality of included studies. This modified version scores 18 potential criteria and has been used in other systematic reviews on hip pain. Studies were considered high quality with a score of more than 60%. Included studies were rated by two independent reviewers (MO, LT). Any disagreements between reviewers were discussed in a consensus meeting and an independent arbitrator (JK) was employed when consensus could not be met. Agreement between rates was determined using Cohen's Kappa (κ).

The Grades of Recommendation, Assessment, Development and Evaluation (GRADE) was applied to assess the quality of evidence for each meta-analysis. The overall GRADE certainty ratings included 'very low', 'low', 'moderate' and 'high'. Observational data was initially graded as 'low' and could be increased or decreased. Certainty could be rated up for (i) large magnitude of effect, (ii) clear dose-response gradient suggesting causal relationship, (iii) all residual confounding would decrease magnitude of effect. Certainty could be rated down for (i) methodological quality (if mean modified epidemiology appraisal instru-

ment scored less than 60%), (ii) imprecision (if upper or lower confidence interval (CI) spanned a standardized mean difference (SMD) or standardized paired difference (SPD) of 0.5 in either direction), (iii) inconsistency (if $I^2$ was 25% or greater), (iv) indirectness (if clinically heterogeneous) and (v) publication bias (for example, small studies that are industry-sponsored).

**DATA EXTRACTION, SYNTHESIS AND ANALYSES**

Data were extracted by two independent reviewers (MO, LT) into customized excel worksheets. The following data was extracted: Author, year, country of origin, number of participants, demographic characteristics of participants (age, sex, body mass index (BMI), type of PAO), physical impairment measure, length of follow-up and a summary of findings were collated. Any discrepancies in data extraction were resolved by an independent reviewer (JK).

Studies were grouped according to design including (i) between-group studies (asymptomatic participants or other intervention) or (ii) paired-data studies assessing change between pre- and post-PAO, and by assessment time-points such as 6-months or 12-months post-PAO. If studies used a similar outcome at similar timepoints then we performed meta-analysis using random effects model. For between-group results this was done using Review Manager (RevMan) (Version 5.4.1 The Cochrane Collaboration, 2020) with a SMD and 95% CI for continuous data. For analysis of paired-data studies, an SPD was calculated using R software (version 4.0.4, Metafor package version 5.0-2). The SPD and 95% CI were calculated from the sample size, mean and standard deviation (SD) of the difference between timepoints. SMDs and SPDs of 0.2, 0.5 and 0.8 were interpreted as small, moderate and large effect sizes, respectively. Subgroup analyses were performed for different timepoints. Statistical heterogeneity across the pooled data was assessed using an $I^2$ statistic, with 25% considered low, 50% moderate and 75% as high levels of heterogeneity. Proportions such as hip impingement test data were pooled using Jamovi (Version 1.8.1.0) providing mean and 95% CI calculations. If SMD or SPD was unable to be calculated due to missing information (such as no variance measure), then we reported this as not estimable.

Where individual studies were not sufficiently homogeneous to be included in a meta-analysis, a best evidence synthesis was used to provide an overall rating for the body of information. Grading of the best evidence synthesis was completed using previously published criteria. They were graded as strong ($\geq$2 studies with high methodological quality and $\geq$75% agreement of findings), moderate ($\geq$2 studies including at least one with high methodological quality and $\geq$75% agreement), limited ($\geq$1 low methodological quality study, with $\geq$75% agreement, or one high methodological quality study), conflicting (inconsistent findings <75% agreement), and no evidence.
RESULTS

The search yielded 5017 titles and abstracts for screening. Eighty-one full-text studies were screened, and 57 studies were excluded. There were 24 studies included in the final analyses. An overview of the study identification process is provided in Figure 1.

METHODOLOGICAL QUALITY

Supplementary Appendix 1 contains the results of quality appraisal using the modified Downs & Black checklist. Initial agreement between quality assessors was moderate (K=0.55). The methodological quality scores ranged from 39% to 88%, with an overall mean (SD) rating of 72% (13.2%). All the included studies clearly described their aims or hypothesis. Only five studies (21%) provided characteristics of patients lost to follow-up and four studies (17%) stated if the main outcome measures used were valid and reliable.

PARTICIPANTS

The 24 studies included 2412 participants, with 2190 of these participants undergoing PAO surgery. A proportion of these participants represent data-points that were published on multiple occasions. Sample sizes of the PAO groups ranged from nine patients to 1051 patients. One study contained only male participants, three studies contained only female participants, and the remaining studies contained both males and females. The mean ages for patients in the included studies ranged from 16 years to 39 years. Ten studies were cohort studies, seven were cross-sectional studies, eight were case series, two were of cross-sectional design, and one was a feasibility study.

OUTCOME MEASURES

Ten studies assessed walking, nine assessed the impingement sign, six measured hip ROM, four assessed strength and one study assessed muscle-tendon pain. Study details are contained in Supplementary Table 1. Two studies provided no SD but did provide inter-quartile range scores. Using published methods, we approximated SD from the inter-quartile range scores.

POOLED OUTCOME DATA

WALKING

Two high-quality studies compared biomechanics during walking in patients undergoing PAO to asymptomatic participants. Meta-analysis was performed at the pre-op timepoint (Figure 2). Peak hip extension angle during walking was greater in asymptomatic participants (SMD 0.65; 95%CI 0.21 to 1.10). In one study, this difference remained six months post-PAO, but not at 12 months post-PAO. Observational designs were used which means these results provide low-level of evidence that asymptomatic participants demonstrate increased peak hip extension angle when walking compared to patients with DDH undergoing PAO.

The same two studies also showed a higher peak hip extension moment in asymptomatic participants compared to patients undergoing PAO (Figure 3). Meta-analysis showed no other differences between asymptomatic participants and patients undergoing PAO, including walking speed (supplementary Appendix 2),
HIP IMPINGEMENT TEST

Six high-quality studies assessed the anterior hip impingement test.\textsuperscript{7,38,44,48,49,51} Prior to PAO, 58% (95% CI: 39% to 76%) of patients with DDH undergoing PAO had a positive impingement test (Figure 4). The result remained one to three years post-PAO (Figure 5).\textsuperscript{7,38} However, the proportion of positive impingement test reduced to 17% (11% to 24%) in patients five or more years after PAO (Figure 6).\textsuperscript{44,51} The results provided low-level of evidence that 58% of patients had a positive impingement test prior to and up to one to three years post-PAO with a reduction to 17% >5 years post-PAO.

BEST EVIDENCE SYNTHESIS

WALKING

When comparing patients pre-operative and 18-months post-PAO, Pedersen et al.\textsuperscript{39} found an increase in walking...
peak joint moment for extension (SPD 0.84; 95%CI 0.08 to 1.6) and flexion (0.91; 0.14 to 1.69), with no difference in peak hip joint extension angle (0.41; -0.27 to 1.09). Similar findings were reported by Jacobsen et al., demonstrating increased peak hip flexion moment 12 months post-PAO compared to pre-PAO. One-year post-PAO, another high-quality study reported increased walking velocity (0.42; 0.02 to 0.81) and stride length (0.46; 0.06 to 0.85), with no difference in cadence (0.23; -0.15 to 0.61). These studies provide limited evidence that walking peak hip flexion and extension moment improved 18-months post-PAO, also at one-year post-PAO, walking velocity and stride length both increased, without change in cadence.
HIP RANGE OF MOTION

HIP FLEXION ROM

Four high-quality studies investigated pre- to post-PAO changes in hip flexion ROM.\textsuperscript{38,41,48,52} Maldonado et al.\textsuperscript{52} found a reduction at minimum five years post-PAO (SPD -0.71; 95\% CI -1.26 to 0.16), as did Ziebarth et al.\textsuperscript{35} three years post-PAO (0.5; -0.83 to 0.16). Data from Novais et al.\textsuperscript{41} was not estimable but, also favoured reduced hip flexion ROM three years post-PAO, whilst Ricciardi et al.\textsuperscript{48} found no difference when comparing pre- to six-month post-PAO changes (-0.39; -0.88 to 0.11). These studies provided limited evidence of reduced hip flexion ROM following PAO.

Two high-quality studies compared hip flexion ROM between groups of variable DDH depending on their LCEA, pre-operatively.\textsuperscript{40,47} Ricciardi et al.\textsuperscript{47} found no difference in hip flexion between patients with mild and severe DDH (SMD -0.09; 95\% CI -0.62 to 0.45). When dividing patients into three groups (mild, moderate, severe), Fabricant et al.\textsuperscript{40} also found no differences in hip flexion ROM. These two studies provide moderate evidence that hip flexion ROM is not different in patients with variable degree of DDH, as defined by the LCEA. One high-quality study provided limited evidence that hip flexion ROM was not different between males and females with DDH (0.7; 0.34 to 1.05).\textsuperscript{22}

HIP INTERNAL ROTATION ROM

Four high-quality studies compared hip internal rotation ROM pre- and post-PAO.\textsuperscript{38,41,48,52} Maldonado et al.\textsuperscript{52} found no difference at minimum five years post-PAO (SPD -1.09; 95\% CI -1.71 to 0.47) as did Ricciardi et al.\textsuperscript{48} at six-months post-PAO when measured in flexion (0.04; -0.45 to 0.55) and extension (0.2; -0.3 to 0.69). However, three years post-PAO, Ziebarth et al.\textsuperscript{38} found less internal rotation ROM when measured in flexion (-0.37; -0.7 to 0.04), this was also reported by Novais et al.\textsuperscript{41} however, data was not estimable. These studies provided conflicting evidence that hip internal rotation ROM was reduced following PAO.

Two high-quality studies compared hip internal rotation ROM in patients with DDH grouped by their LCEA, pre-PAO.\textsuperscript{40,47} Ricciardi et al.\textsuperscript{47} found no differences between patients with mild and severe DDH when internal rotation ROM was measured in either flexion (SMD 0.0; 95\%CI -0.52 to 0.52) or extension (0.08; -0.63 to 0.48). When dividing patients into three groups (mild, moderate, severe), Fabricant et al.\textsuperscript{40} found no increased internal rotation ROM in flexion in patients with severe compared to moderate DDH (-0.07; -0.22 to 0.09). Also, no difference between mild and severe or moderate, nor any of the groups when internal rotation ROM was measured in extension.\textsuperscript{40} These two studies provide conflicting evidence that hip internal rotation ROM is different in patients with variable degrees of DDH, as defined by the LCEA.

HIP EXTERNAL ROTATION ROM

Three high-quality studies compared hip external rotation ROM pre- and post-PAO.\textsuperscript{38,41,48,52} Maldonado et al.\textsuperscript{52} reported a reduction in external rotation ROM at minimum five years post-PAO (SPD -0.58; 95\% CI -1.11 to -0.05). Six months post-PAO, Ricciardi et al.\textsuperscript{48} found no differences when external rotation was measured in flexion (-0.15; -0.65 to 0.4) or extension (0.4; -0.96 to 0.16). Data from Novais et al.\textsuperscript{41} was not estimable, however, three years post-PAO, the results favored an increase in external rotation when measured in flexion, and a decrease when measured in extension. These studies provided conflicting evidence that hip external rotation ROM was changed following PAO.

Two high-quality studies compared hip external rotation ROM between patients pre-PAO surgery grouped depending on their LCEA.\textsuperscript{40,47} Ricciardi et al.\textsuperscript{47} found no difference between people with mild and severe DDH when external rotation ROM was measured in either flexion (SMD -0.13; 95\%CI -0.65 to 0.4) or extension (-0.4; -0.96 to 0.16). When dividing patients into three groups (mild, moderate, severe), Fabricant et al.\textsuperscript{40} found reduced external rotation ROM when measured in extension in patients with severe compared to mild DDH (-0.35; -0.49 to -0.18), and severe compared to moderate DDH (-0.20; -0.36 to -0.04). The study found no difference between mild and moderate DDH when external rotation was measured in extension (-0.13; -0.27 to 0.01), or between any of the groups when external ROM was measured in flexion. These two studies provided conflicting evidence that hip external rotation ROM is different in patients with variable degree of DDH, as defined by the LCEA.

HIP ABDUCTION ROM

Three high-quality studies compared hip abduction ROM pre- and post-PAO.\textsuperscript{38,41,52} Maldonado et al.\textsuperscript{52} found no difference at a minimum five years post-PAO (SPD -1.47; 95\% CI -2.18 to 0.76). Ziebarth et al.\textsuperscript{38} found a decrease in abduction ROM three years post PAO (-0.41; -0.74 to -0.08). Data from Novais et al.\textsuperscript{41} was not estimable but favoured a decrease in abduction three years post PAO. These studies provided conflicting evidence that hip abduction ROM changed following PAO.

Two high-quality studies compared hip abduction ROM between groups of variable DDH depending on their LCEA, pre-PAO.\textsuperscript{40,47} Ricciardi et al.\textsuperscript{47} found no difference between patients with mild and severe DDH (SMD -0.27; 95\% CI -0.81 to 0.26). When dividing patients into three groups (mild, moderate, severe), Fabricant et al.\textsuperscript{40} also found no difference in hip abduction ROM. These two studies provided moderate evidence that hip abduction ROM is not different in those with variable degrees of DDH, as defined by the LCEA.

When dividing patients with DDH into three groups (mild, moderate, severe), Fabricant et al.\textsuperscript{40} found significantly increased hip abduction ROM in those with severe versus mild DDH (SMD 0.26; 95\%CI 0.1 to 0.41). No difference was found between patients with severe compared to moderate DDH (0.12; -0.04 to 0.28) or moderate compared
to mild DDH (0.13; -0.01 to 0.27). This study provided limited evidence that patients with severe DDH had increased hip abduction ROM compared to those with mild DDH, as defined by the LCEA.

**HIP MUSCLE STRENGTH**

Four studies assessed strength as an outcome measure.²⁵,³⁷,⁴⁵,⁵³ Two studies likely used the same cohort of patients,²⁵,³⁷ the data from the older study was not estimable and therefore only results from the more recent study were used.²⁵ De La Rocha et al.⁴³ compared patients undergoing PAO who had had previous pelvic surgery with patients who had not. The high-quality study by Sucato et al.²⁵ provided limited evidence that hip abduction strength was unchanged one year after PAO (0.56; -0.07 to 0.79). Another high-quality study by De La Rocha et al.⁴³ provided limited evidence that compared to patients with previous pelvic surgery, patients without previous pelvic surgery (i.e. PAO as their first pelvic surgical procedure) were stronger in hip flexion pre-PAO (1.03; 0.21 to 1.86) and one-year post-PAO (1.04; 0.22 to 1.87), but not six months post-PAO (0.7; -0.1 to 1.49).

Mortensen et al.⁵³ compared strength in affected and non-affected limbs pre-PAO, isometrically and isokinetically (concentric and eccentric) in hip flexion and extension. No differences were found isometrically (SMD -0.07; 95%CI -0.76 to 0.62), concentrically (-0.14; 0.84 to 0.57) or eccentrically (-0.07; -0.78 to 0.65). The authors also compared hip extension strength in affected and non-affected limbs.⁵³ No differences were found isometrically (-0.25; -0.95 to 0.44), concentrically (0.13; 0.57 to 0.84) or eccentrically (-0.05; -0.74 to 0.67) between limbs. This study provides limited evidence of no differences in hip extension strength between affected and non-affected limb in patients pre-PAO.

**HIP MUSCLE-TENDON PAIN**

In one high-quality study by Jacobsen et al.,⁷ muscle-tendon pain in the hip and groin region was assessed clinically pre- and one-year post-PAO. Iliopsoas- (SDP -52%; 95%CI -46 to -17%) and abductor-related pain (-22%; -56% to -8%) decreased from pre- to post-PAO. No changes were found for adductor- (-5%; -16% to 6%), hamstring- (-5%; -12% to 2%) or rectus-abdominus-related pain (-4%; -9% to 2%).

This study provided limited evidence that iliopsoas- and abductor-related pain decreased one-year post-PAO.

**FUNCTIONAL TASKS**

Scott et al.¹⁷ found better performance in functional tasks in asymptomatic participants compared to symptomatic patients undergoing PAO. This study provided limited evidence that asymptomatic patients were faster in timed stair ascent (SMD -1.44; 95%CI -2.11 to -0.78), five sit-to-stands (-1.35; -1.98 to -0.68) and four-square step test (-0.64; -1.24 to -0.04), compared to patients undergoing PAO for DDH.

**RUNNING**

One high-quality study by Jacobsen et al.⁸ provided limited evidence comparing running in patients undergoing PAO with asymptomatic participants. Asymptomatic participants ran faster (SMD -0.57; 95%CI -1.10 to -0.05) and had higher peak hip joint extension moment (-0.58; -1.12 to -0.05), but no differences existed for peak hip joint extension angle (-0.31; -0.84 to 0.22) and peak hip joint flexion moment (-0.74; -1.0 to 0.07).

**DISCUSSION**

This systematic review aimed to investigate physical impairments in adults undergoing PAO for DDH. Prior to PAO, there was low level of evidence that people with DDH had (i) reduced peak hip extension angle, (ii) reduced peak hip extension moment, and (iii) reduced peak hip flexion moment, during walking, compared to asymptomatic participants. One year following PAO there were no longer differences in walking between the groups. A positive hip impingement test was found in 58% of patients with DDH both pre-operatively and at 1-3 years post-PAO, then from 5-years onwards this reduced to 17%. Best evidence synthesis of non-pooled data revealed limited evidence of reduced hip flexion ROM, but conflicting evidence for internal and external rotation ROM, following PAO. There was limited evidence demonstrating no change in hip abduction or hip flexion strength following PAO. There was also limited evidence to support poorer running and functional task performance in symptomatic patients undergoing PAO compared to asymptomatic participants.

Limited evidence was found that patients with DDH walk faster, with a longer stride length 12-18 months post-PAO compared to pre-PAO, with larger peak hip joint extension and flexion moments. Clinically, reduced peak hip extension angle during walking pre-PAO likely reflects an avoidance of terminal extension, which appears to be restored post-operatively. Compared to asymptomatic participants, patients undergoing PAO did not run as fast and had a reduced peak hip extension moment in running. These findings suggest adaptations occur in people with DDH in both walking and running, seen as reduced speed, hip extension angle, and hip extension and flexion moments. Reduced anterior acetabular coverage commonly associated with DDH.
may contribute to less stability and/or apprehension when the hip moves into end range extension. These adaptations may represent an attempt to minimize apprehension by generating less force through the hip joint and/or reduce stress on painful anterior structures. Painful structures could include the iliopsoas muscle which sits immediately anteriorly to the hip joint and has been found to be painful in almost half of people with DDH pre-PAO and/or the anterosuperior aspect of the hip capsule and labrum which have been found to have dense nociceptive innervation. Future studies need to confirm whether these changes can be modified, and whether improvements in these impairments are related to improvements in pain and the progression to hip OA and total hip joint replacement.

This systematic review examined clinical outcomes including hip muscle strength, hip joint ROM, and functional performance. People with DDH are commonly considered to have increased hip joint ROM. The finding that hip flexion ROM is reduced following PAO is likely the result of improved femoral head coverage by the acetabulum. Hip muscle strength was found not to change following PAO, despite improvements in walking. In contrast, the results of a recent study (published after our data collection) showed improved isometric hip flexion and abduction strength one-year post-PAO compared to pre-PAO in 82 patients with DDH. The variation in findings may exist due to the low power of included studies, as the study populations were below 30 patients, whereas paired analyses were done in 82 patients with DDH in the study by Jacobsen. Also, of relevance, an included study in this systematic review, showed that strength increases in pre-PAO patients with a resistance training program. This study found that progressive resistance training was safe and feasible in patients with DDH, and may improve pain, strength, and functional performance. A resistance training program is likely advantageous both before and after PAO, but further research is required in this space and should also compare the effect of PAO versus a resistance training program on hip strength in patients with DDH.

The hip anterior impingement test is also commonly known as the Flexion, Adduction, Internal Rotation (FADIR) or FADIR test. The FADIR test is widely known as part of the criteria for diagnosing femoroacetabular impingement syndrome (FAIS), and a positive test may commonly lead a clinician toward this diagnosis in a young adult with hip pain. Our findings show that patients undergoing PAO for DDH have a positive ‘impingement’ test more often than not. Inaccurate and delayed diagnosis are common in those with DDH, and clinicians should recognize this as a common impairment finding in those with DDH.

Preliminary evidence from De La Rocha shows poorer hip abduction and hip flexion strength post-PAO in those who have had previous pelvic surgery, compared to those who have not had previous pelvic surgery. Performing a PAO for a patient who has residual DDH following previous pelvic surgery may be more difficult due to scarring from initial surgery and distorted anatomy. Patients with previous pelvic surgery undergoing PAO may not experience the same level of improvement as those without, modifying expectations in these patients may be warranted.

LIMITATIONS

This review has several limitations. There were no randomised controlled trials, and a large proportion of included studies were retrospective in design. This has potential for introducing selection, detection, and performance bias. Many included studies did not provide characteristics of patients lost to follow-up or report on the validity and reliability of the outcomes used. There was significant variability in the post-operative assessment timepoints, and the type of outcomes measures used which limited opportunities to perform meta-analysis. The above factors made it impossible to obtain findings with ‘high’ level evidence and certainty ratings. Prospective longitudinal cohort studies are vital to better understand what causes physical impairments in those with DDH undergoing PAO.

This review did not explore whether impairments seen post-PAO were related to common surgical complications that might impede physical performance, such as delayed bony union or neuropathies. Future research should examine these outcomes, and their potential on physical performance post-PAO. This review also only investigated physical impairments in those who were awaiting, or had undergone, PAO surgery. Exploring outcomes in those with DDH who are not at this point, potentially earlier in the disease progression, should also be a focus of future research.

CONCLUSION

Prior to PAO, patients with DDH demonstrate physical impairments during walking, which improved from one-year after PAO. The majority of patients with DDH had a positive hip impingement test (58%) prior to PAO, and initially after PAO, this drops to 17% from 5-years onwards. Hip abduction and flexion strength did not change pre- to post-PAO. Clinicians should be aware that patients with DDH have physical impairments that should be considered pre- and post-PAO.

CONFLICTS OF INTEREST

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Supplemental Appendices
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99233.docx?auth_token=DLiYNpiAX5MjWushr7e

Supplementary Table 1. Summary of included studies
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Rehabilitation Guidelines for Use Following a Periacetabular Osteotomy (PAO): A North American Based Delphi Consensus

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Background

Treatment of acetabular dysplasia with a periacetabular osteotomy (PAO) has been shown to improve long-term outcomes and is considered the gold standard in the setting of symptomatic hip dysplasia in patients younger than 35 years of age. Post-operative rehabilitation following a PAO plays an important role in helping patients return to their prior level of function and reduce the impact of strength deficits that may persist. Currently, there is a paucity of research supporting post-operative rehabilitation guidelines. The purpose of this study is to present expert-driven rehabilitation guidelines to reduce practice variation following a PAO.

Methods

A panel of 16 physiotherapists from across the United States and Canada who were identified as experts in PAO rehabilitation by high-volume hip preservation surgeons participated in this Delphi study. Panelists were presented with 11 questions pertaining to rehabilitation guidelines following a PAO. Three iterative survey rounds were presented to the panelists based on responses to these questions. This three-step Delphi method was utilized to establish consensus on post-operative rehabilitation guidelines following a PAO.

Results

Total (100%) participation was achieved for all three survey rounds. Consensus (>75%) was reached for 11/11 questions pertaining to the following areas: 1) weight-bearing and range of motion (ROM) precautions, 2) therapeutic exercise prescription including neuromuscular control, cardiovascular exercise, and flexibility, and 3) objective measures for return to straight line running and return to full participation in sports.

Conclusion

This Delphi study established expert-driven rehabilitation guidelines for use following a PAO. The standardization of rehabilitative care following PAO is essential for achieving optimal outcomes despite other factors such as geographical location and socioeconomic status. Further research on patient-reported outcomes is necessary to confirm successful rehabilitation following the guidelines outlined in this study.

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BACKGROUND

Acetabular dysplasia, defined as a bony abnormality of the acetabulum with abnormal coverage of the femoral head, is a well-recognized cause of hip pain in young adults. This structural abnormality leads to a decrease in contact area of the hip, excessive wear on the articular cartilage, and degenerative changes of the acetabular labrum. Acetabular dysplasia can lead to severe pain, disability, and early onset arthritis without appropriate management. Treatment of acetabular dysplasia with a periacetabular ostetomy (PAO) has been shown to improve long-term outcomes and is considered the gold standard for symptomatic hip dysplasia. Although post-operative rehabilitation is important to help patients return to prior level of function, there is a paucity of research supporting post-operative rehabilitation guidelines following a PAO.

Inadequate rehabilitation after PAO may lead to poor outcomes, which may include prolonged impairments in hip strength. It is well accepted that adequate strength of the lumbopelvic stabilizers is necessary to provide stability to the hip joint and maintain appropriate pelvic positioning during weight-bearing tasks. While improvements in isometric hip flexion and abduction are observed at one year following a PAO, strength values were shown to remain 13-34% lower than that of healthy controls. Other studies have reported similar improvements in hip abductor, hip flexor, and hip extensor strength values one year following a PAO when compared to pre-operative values, but no comparison was done to healthy controls. Prolonged impairments in hip strength may lead to decreased performance on functional tasks as hip abductor weakness is associated with impaired hip kinematics during a single-leg squat task when compared to healthy controls.

Understanding important rehabilitation parameters, including early weight-bearing and range of motion (ROM) precautions, exercise progression throughout recovery, and metrics for clearance to return-to-run and return-to-sport, is crucial to maximize patient recovery following a PAO. The purpose of this study is to present expert-driven rehabilitation guidelines to reduce practice variation following a PAO.

METHODS

DELPHI PANEL

The expert panel in PAO rehabilitation consisted of sixteen physiotherapists who were purposefully sampled from geographically different institutions spread throughout the United States and Canada. Participants were selected based on multiple criteria, including (1) treating at least 10 patients following PAO per year, (2) identified by high-volume hip preservation surgeons as an expert in the rehabilitation of PAO patients, and/or (3) experts in rehabilitation of non-arthritic hip disorders. All members consented to participate in this IRB exempted study, and participants were blinded to each other for the entire duration of the study.

DELPHI STRUCTURE AND DATA COLLECTION

A three-step classic Delphi method was used to establish consensus techniques in the diagnostic evaluation of pediatric ACL injuries. Consensus was defined a priori as ≥75%, which is moderate per standard Delphi methods to account for expected variation in a content area with little available evidence. Definitions of consensus level are commonly based on accepted standards such as voting percentages (simple majority, two-thirds majority, absolute majority) and a supermajority was determine most appropriate for this study. This study had the dual objective of achieving consensus and, equally importantly, understanding areas where consensus could not be reached and reasons for disagreement.

Panelists were presented with three iterative rounds of surveys. Questionnaires for rounds one through three were distributed online via an emailed link with responses de-identified for analysis. For each survey round, analysis of the participants’ responses was completed by two study members (AD and KE). Any disagreements were resolved by a third team member (MM).

In the first survey round, panelists were presented with eleven free-response questions regarding their physical rehabilitation practice:

1. What weight-bearing precautions do you use? What objective measures do you use to discharge crutches?
2. What range of motion precautions do you utilize postoperatively? How long do you follow these precautions? When do you expect the patient to achieve full range of motion?
3. How do you begin to rehabilitate the hip flexor complex? When do you begin to rehabilitate the hip flexor complex?
4. Do you limit active long lever hip flexion? If so, how long?
5. What exercises do you utilize to improve lower extremity lumbopelvic control?
6. What exercises do you utilize to strengthen the gluteus medius? What exercises do you avoid when strengthening the gluteus medius?
7. What exercises do you utilize to facilitate lumbopelvic neuromuscular control? When do you begin these exercises?
8. When do you initiate end range stretching?
9. When do you begin low level cardiovascular exercise? (ie. upright stationary biking and elliptical)
10. What objective measures do you utilize to determine if a patient is ready to begin running?
11. What criteria do you utilize to determine if a patient is ready to return to full participation in sports?

Panelists provided detailed descriptions of treatment parameters for each question. Responses were collected and coded for common thematic content. Responses reported by >50% of panelists were considered modal, while responses reported by >25% of panelists formed a second tier of responses.

In round two, panelists were presented the original questions along with the modal response derived from the
first round of responses. Panelists were asked to agree or disagree with the modal response, and those who disagreed were allowed to add or subtract items. The second-tier responses were included as potential additions, but free text addition was also permitted. Resulting responses were again coded for thematic content and modal responses were adjusted as appropriate.

In round three, panelists again received ten of the eleven questions with revised modal and second-tier responses. Similar to round two, panelists were asked to agree or disagree with the modal response, and those who disagreed were allowed to add or detract items. Disagreement prompted a free-response box for the panelist to explicitly detail their disagreement. Analysis of the third-round data provided concepts for which consensus had been gained as well as rationale for disagreement.

RESULTS

The expert panel in this study consisted of sixteen physiotherapists who were identified as an expert in PAO rehabilitation. Overall, 100% participation was achieved with all sixteen therapists completing all three Delphi rounds. The expert panel received eleven questions covering a variety of topics related to rehabilitation following a PAO, and 100% consensus was achieved for all topics of interest by the third Delphi round.

WEIGHT-BEARING PRECAUTIONS

For weight-bearing precautions that should be utilized immediately following a PAO, 15/16 (94%) panelists agreed that weight-bearing should be limited to 25%, foot-flat weight-bearing for 6-8 weeks. It was noted that concomitant procedures, such as hip arthroscopy or microfracture, may prolong these recommendations.

DISCHARGING CRUTCHES

For objective measures to discharge crutches after 6-8 weeks of protected weight-bearing, 16/16 (100%) panelists agreed that observed gait deviations and surgeon clearance should be utilized. Examples of gait deviations listed in the question included Trendelenburg gait, abductor lurch, and antalgic gait.

ROM PRECAUTIONS

For ROM precautions immediately following a PAO, 15/16 (81%) panelists agreed that flexion should be limited to 90 degrees and external rotation limited to 20 degrees in 90 degrees of flexion. The 13 panelists agreed that these precautions should be maintained for 4-6 weeks. It was noted that concomitant procedures, such as hip arthroscopy or microfracture, may prolong or alter these recommendations to include limitations in hip extension and hip internal rotation.

Two dissenting panelists had different points of contention. One panelist felt that flexion should be limited to 70 degrees for three weeks, and then limited to 90 degrees for the following week along with avoidance of rotation of the femur in flexion and avoidance of hip extension until the fourth week. The second panelist stated that there should be no flexion past 90 degrees and no external rotation in any range. For achieving full ROM following an isolated PAO, 16/16 (100%) panelists agreed that the patient should achieve full hip ROM by 12-16 weeks (3-4 months).

For the initiation of end range stretching, 15/16 (94%) panelists agreed that it can begin somewhere between 8-12 weeks post-operatively as tolerated. The one dissenting panelist stated that it should only occur as needed after 16 weeks post-operatively.

PROTECTION OF THE HIP FLEXOR COMPLEX

For rehabilitation of the hip flexor complex following a PAO, 16/16 (100%) panelists agreed to the general protocol:

1. Long lever active hip flexion in supine should be limited for 8-12 weeks following an isolated PAO.
2. Initiation of therapeutic exercise targeting the hip flexor complex should begin between 4-8 weeks as tolerated by pain.
3. Active assistive ROM (AAROM), heel slides, and/or isometrics should be utilized to initiate rehabilitation of hip flexor complex, progressing as tolerated.

LUMBOPELVIC AND POSTERIOR–LATERAL HIP STRENGTHENING

For the initiation of lumbopelvic control following a PAO, 16/16 (100%) panelists agreed that a core progression should include supine and quadruped activities.

For strengthening of the gluteus medius following a PAO, 15/16 (94%) panelists agreed to the general guidelines:

1. In general, gluteus medius strengthening should begin with isometrics progressing to non-weight bearing (NWB) progressive resistance exercises followed by double and single leg weight bearing exercises. Other positions and different lever arms can be utilized to progress strengthening exercises.
2. Exercises that increase anterior hip activation/pain (ie. hip flexor and tensor fascia lata compensation) should be avoided when beginning gluteus med strengthening.

The dissenting panelist stated that strengthening of the gluteus medius should begin with isometric strength exercises, followed by functional movements, then progress to weight-bearing exercises.

LUMBOPELVIC AND LOWER EXTREMITY NEUROMUSCULAR CONTROL

For improving lower extremity neuromuscular control following a PAO, 14/16 (88%) panelists agreed to the general guidelines:

1. Double and single leg exercises in the closed chain challenging frontal plane control and femoral IR control (valgus).
2. These exercises can begin in NWB as the patient tolerates and should progress to WB at six weeks or immediately after the patient is cleared for WB.

Only one of the dissenting panelists provided a retort, stating initiation of lower extremity neuromuscular control should begin in passive weight-bearing positions, such as quadruped or tall kneeling prior to double or single leg.

RETURN TO SPORT CRITERIA

For beginning low level cardiovascular exercise following a PAO, 13/16 (81%) panelists agreed to the general guidelines that patients may begin upright stationary biking 6-8 weeks post-operatively and begin using an elliptical by 10-12 weeks. Only two of the three dissenting panelists elaborated on their disagreement. One of the panelists stated that stationary biking may begin at two weeks with no resistance, followed by walking in the pool at four weeks. The other panelist stated that stationary biking may begin at two weeks maintaining 90-degree flexion precautions, and the elliptical may begin when the patient is walking normally, progressing through strength exercises, and can bike for 30 minutes.

For objective measures to begin a running progression, 14/16 (88%) panelists agreed to the general guidelines:

1. Normalized hip strength (with a focus on glute med and ER strength)
2. Performance on functional tasks (SL squat, Y-Balance, etc)

The two dissenting panelists agreed to the above guidelines but thought that quadriceps/hamstring strength and surgeon clearance with radiographic support were needed to progress to running as well.

For objective criteria required to return to sport, 16/16 (100%) panelists agreed to the guidelines:

1. Involved: uninvolved hip abductor strength ratio of >80%.
3. Performance on sport specific drills chosen based on patient specific demands

DISCUSSION

This Delphi study was performed to establish consensus among physiotherapy experts for post-operative rehabilitation guidelines following a PAO. No studies currently exist supporting specific weight-bearing and ROM precautions, therapeutic exercise prescription, or metrics for clearance to return-run and return-to-sport. Therefore, the Delphi method was utilized to generate expert opinion in a content area where evidence is lacking. Across all three rounds of this study, 100% participation was achieved from the 16 physiotherapists and consensus was achieved across all domains. These post-operative guidelines may reduce unwanted practice variation and help patients achieve more normal hip strength values to maximize functional potential and minimize reinjury risk. A summary of recommendations can be found in Table 1.

WEIGHT-BEARING PRECAUTIONS

**Consensus Point:** Patients should ambulate with 25% foot-flat weight-bearing through the affected lower extremity for 6-8 weeks following a PAO. Crutches can be discharged after radiographic evidence of bony healing and a normalized gait pattern.

In the immediate post-operative phase, modified weight-bearing is utilized to allow for bony healing. Post-operative stress fractures have been reported as a complication in the literature with an incidence between 2-18.4%. Early weight-bearing, pubic non-union, a larger preoperative deformity, advanced age, and a higher post-operative center-edge angle have been identified as possible factors for developing a stress fracture following a PAO. Ito et al. reported a higher incidence of postoperative fractures of the ischial ramus and posterior column with full weight-bearing immediately following surgery compared to two months of modified weight-bearing. In a normal pelvis, load transfer is higher through the superior pubic ramus as compared to the inferior pubic ramus. However, following a PAO, increased load transfer occurs through the inferior pubic ramus, ischium, and posterior column. These changes in load transmission patterns increase stress and strain through these bony structures and potentially result in a post-operative stress fracture. Therefore, modified weight-bearing in the early post-operative phase is indicated. The current results are consistent with these recommendations as 15/16 participants recommend 25% foot-flat weight-bearing until 6-8 weeks at which point weight-bearing can be progressed only if the patient demonstrates radiographic evidence of bony healing and a normalized gait pattern. It was noted that concomitant procedures, such as hip arthroscopy or microfracture, may prolong these recommendations to protect the healing capsuloligamentous structures and joint cartilage.

RANGE OF MOTION PRECAUTIONS

**Consensus Point:** Hip flexion and external rotation ROM should be protected for 4-6 weeks followed by progressive, pain-free restoration of ROM. End range stretching can be initiated between 8-12 weeks as tolerated with full ROM achieved by 12-16 weeks post-operatively.

Restoration of hip range of motion is essential to allow for participation in both daily and recreational activities. Similar to a hip arthroscopy, end ranges of motion should be protected in the early post-operative period. This includes end range flexion, which approximates the femur and the acetabulum, and hip external rotation, which stresses the anterior hip capsule. After a period of protected motion allowing for a reduction in inflammation and bony healing, a gradual approach to improving range of motion is essential to limit joint irritation. Consensus regarding all passive and active ROM precautions was achieved as panelists agreed that hip flexion and external rotation ROM should be limited for 4-6 weeks, with normal passive hip
Table 1. Summary of rehabilitation guidelines for use following a periacetabular osteotomy (PAO)

<table>
<thead>
<tr>
<th>PAO Rehabilitation Guidelines</th>
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| **Phase I: Immediate Post-Operative Phase**  
  **Weeks 1-4** |
| **Goals:**  
  Protect healing tissues and osteotomy sites  
  Reduce post-operative pain and inflammation  
  Normalize gait pattern with appropriate assistive device  |
| **Precautions:**  
  Weightbearing: Foot flat weight bearing 25% body weight  
  Range of Motion:  
  Hip flexion limited to 90°  
  Hip external rotation limited to 20°  |
| **Therapeutic Interventions:**  
  Ankle pumps and submaximal hip isometric exercises  
  Cryotherapy and compression for inflammation and edema control  |
| **Phase II: Early Post-Operative Phase**  
  **Weeks 4-6** |
| **Goals:**  
  Gentle progression of ROM  
  Continue protecting healing osteotomy sites  
  Limit irritation of surrounding soft tissues with increasing activity  |
| **Precautions:**  
  Weightbearing: Foot flat weight bearing 25% body weight  
  Range of Motion:  
  Hip flexion limited to 90°  
  Hip external rotation limited to 20°  
  Active long lever hip flexion contraindicated until week 8-12  |
| **Physical Therapy:**  
  Submaximal isometrics in all directions  
  Gradual loading of iliopsoas tendon is critical to avoid tendonitis  
  Short lever A/AAROM  
  Lumbopelvic neuromuscular control exercises in supine  |
| **Phase III: Initial Strengthening Phase**  
  **Weeks 6-12** |
| **Goals:**  
  Near full, symmetrical ROM  
  Improve hip and core strength and neuromuscular control  
  Gradual WB progression (normalized gait pattern and physician clearance required for discharging assistive device)  |
| **Precautions:**  
  Monitor for symptoms of intra- and extra-articular irritation with exercise and WB progression  
  Avoid premature weaning from assistive device  
  Active long lever hip flexion contraindicated until week 8-12  |
| **Physical Therapy:**  
  Gradual progression of functional ROM  
  Introduce upright stationary bike between 6-8 weeks  
  Introduce elliptical between 10-12 weeks as tolerated  
  Introduce stretching progression between 8-12 weeks  
  Initiate closed chain strengthening progression  
  Progress lumbopelvic stabilization and postural control exercises  |
| **Phase IV: Advanced Strengthening Phase**  
  **Weeks 12-20** |
| **Goals:**  
  Increase muscular and cardiovascular endurance  
  Begin to re-establish neuromuscular control for sport-specific activity  |
| **Precautions:**  
  Avoid provocation of symptoms with progression of exercise  |

*International Journal of Sports Physical Therapy*
motion being achieved by 12-16 weeks. Panelists agreed the upright stationary bike can be initiated between 6-8 weeks and the elliptical trainer between 10-12 weeks to facilitate early-stage passive range of motion as well as cardiovascular endurance. In the setting of concomitant procedures, such as a hip arthroscopy, panelists indicated that ROM precautions may be altered to include extension or internal rotation to further protect healing soft tissue structures.

PROTECTION OF THE HIP FLEXOR COMPLEX

**Consensus Point:** Progressive loading of the hip flexor complex should be done cautiously, with isometrics and short lever active assistive hip flexion exercises beginning between 4-8 weeks as indicated by pain. Long lever active hip flexion should be avoided for 8-12 weeks following a PAO.

The iliopsoas courses directly anterior to the femoral head and acts as a secondary stabilizer to the hip joint. In the setting of hip dysplasia, the iliopsoas may overcompensate for the lack of bony stability and result in tendinous overload, inflammation, and pain. Furthermore, anecdotal evidence has linked weakness of the gluteus medius, which is a common finding in patients with dysplasia and a consequence of a PAO, to iliopsoas tendinitis. Following a PAO, the iliopsoas can impinge on the pubic osteotomy further predisposing these patients to hip flexor irritation. Extreme care should be taken to avoid additional hip flexor irritation in the early post-operative phase and therefore toe touch weight-bearing or non-weight-bearing during gait should be avoided. Instead, patients should ambulate with a foot-flat gait pattern to reduce activity of the iliopsoas. Progressive isometrics and short lever active assistive hip flexion exercises are recommended at 4-8 weeks to progressively load the iliopsoas tendon while allowing long lever hip flexion exercises to be avoided for 8-12 weeks post-operatively. Recommended exercises to progressively load the hip flexor can be found in Figure 1. Additionally, strengthening exercises for the gluteus medius that also activate the anterior hip should be avoided, especially in the setting of iliopsoas pain. Philippeon et al. reported sidelying hip abduction in external rotation and the clamshell exercises demonstrated considerable EMG activation of hip flexor. These findings support a recommendation that these exercises should be avoided or prescribed with caution in the presence of anterior hip pain.

**LUMBOPELVIC AND POSTERIOR-LATERAL HIP STRENGTHENING**

**Consensus Statement:** Lumbopevic strengthening should begin in the early post-operative phase in non-weight-bearing and progress to double and single leg weightbearing exercises as tolerated.

The relationship with lumbopevic and posterior-lateral hip muscle function to lower extremity injury has been demonstrated in the literature. One-year following PAO, patients demonstrate improvements in isometric hip flexion and abduction strength, however, these values were

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<tr>
<th>Phase V: Return to Low Level Impact (Weeks 20-26)</th>
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<tr>
<td><strong>Goals:</strong> Tolerance of running and straight plane agility drills with appropriate lumbopelvic and lower extremity control</td>
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<td><strong>Precautions:</strong> Avoid provocation of symptoms with progression of exercise</td>
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<th>Phase V: Return to Full Participation in Sports (Weeks 26+)</th>
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<tr>
<td><strong>Goals:</strong> Tolerance of jumping, hopping, cutting/pivoting drills with appropriate lumbopelvic and lower extremity control</td>
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<td><strong>Precautions:</strong> Avoid provocation of symptoms with progression of exercise</td>
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<th>Physical Therapy:</th>
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<tr>
<td>Initiate running and agility progressions with emphasis on dynamic control of pelvis and lower extremity</td>
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<tr>
<td>Continue high level strength and control exercises with emphasis on pelvis and lower extremity musculature</td>
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<th>Physical Therapy:</th>
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<tr>
<td>Initiate jumping and hopping progression with emphasis on dynamic control of lower extremity and pelvis</td>
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<tr>
<td>Sport specific cutting and pivoting drills with emphasis on dynamic control of lower extremity and pelvis</td>
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<tr>
<th>PAO Rehabilitation Guidelines</th>
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<tr>
<td>No running, jumping, hopping, or cutting/pivoting</td>
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<tr>
<th>Physical Therapy:</th>
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<tr>
<td>Progress multi-directional hip and LE strengthening</td>
</tr>
<tr>
<td>Progress to end range strengthening with emphasis on dynamic control of lower extremity and pelvis</td>
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<tr>
<td>Core stability progression to meet demands of sport</td>
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shown to remain 13-34% lower than that of healthy controls.\textsuperscript{14} Other studies have reported similar improvements hip abductor, hip flexor, and hip extensor strength values one year following a PAO when compared to pre-operative values, but no comparison was done to healthy controls.\textsuperscript{15,16} Additionally, it has been well established that females exhibit less hip strength, particularly in their hip abductors and external rotators, compared to males.\textsuperscript{33,36} Given that hip dysplasia is more prevalent in females and lumbopelvic strength lags post-operatively, extensive lumbopelvic strengthening is crucial for improving hip joint mechanics and maximizing outcome. Snyder et al.\textsuperscript{37} reported a strengthening program targeted at the hip abductors and external rotators altered lower extremity joint loading. In patients with hip dysplasia, strengthening of the hip abductors was shown to reduce dynamic instability during ambulation.\textsuperscript{38} Without normalization of strength, muscle imbalances in the hip and core can lead to altered force couple relationships and faulty joint arthokinematics.\textsuperscript{39,40}

A graded approach to therapeutic exercise allows for improvements in strength while minimizing musculoskeletal overload and joint irritation. This is an important concept following a PAO as the reorientation of the acetabulum affects the torque-generating capacities of the surrounding musculature which could affect muscle strength and activation.\textsuperscript{41,42} Panelist consensus indicated that strengthening of the core muscles and gluteus medius should begin with non-weight-bearing isometrics and progress to single leg weight-bearing exercise as tolerated. The gluteus medius has been shown to demonstrate high EMG values in a single leg stance position.\textsuperscript{43,44} Therefore, when appropriate, exercises performed in a single-leg stance position should be a focus of post-operative rehabilitation to increase hip abductor strength. Recommended lumbopelvic strengthening exercises can be found in Figures 2 and 3.

**LUMBOPELVIC AND LOWER EXTREMIT Y NEUROMUSCULAR CONTROL**

**Consensus Statement:** Lumbopelvic neuromuscular control exercises should begin in non-weight-bearing in the early post-operative phase with progression to weight-bearing exercises at 6-8 weeks or immediately after the patient is cleared for weight-bearing. In weight-bearing, exercises should consist of double and single leg exercises challenging frontal plane and femoral internal rotation control.

Neuromuscular control training is utilized to improve functional performance, lower extremity biomechanics, and muscle activation patterns. Decreased neuromuscular control of the lumbopelvic region leads to uncontrolled trunk movement and lower extremity valgus, increasing the risk of lower extremity injury.\textsuperscript{45,46} During landing and pivoting movements, females demonstrate increased lower extremity valgus resulting in increased load through the lower extremity.\textsuperscript{47–51} The gluteus medius, gluteus maximus, and deep external rotators are responsible for maintaining stability of the pelvis in the closed chain while the core is responsible for providing a stable base for force transfer between the trunk and the lower extremity.\textsuperscript{39,52–56} The goal of rehabilitation is to improve dynamic stabilization of the hip, especially during single-leg weight-bearing tasks when loads within the hip are the highest.\textsuperscript{12,13,57} Myer et al.\textsuperscript{58} reported a 15% increase in hip abduction strength in healthy individuals with a 10-week targeted neuromuscular control training compared to no increase in strength in the control group. Similarly, Hewett et al.\textsuperscript{59} reported a significant improvement in hip external rotation moments and moment impulses, increased peak trunk flexion, and decreased peak trunk extension following a 10-week targeted neuromuscular control training program.

Panelists agreed that an emphasis should be placed on lumbopelvic and lower extremity neuromuscular control beginning in the immediate post-operative phase. Early education on the importance of the transversus abdominis, which contributes to spinal stability during weight-bearing tasks, will set the foundation for appropriate lumbopelvic control for the later stages of recovery.\textsuperscript{60,61} These exercises should begin in supine during the immediate post-operative phase progressing to quadruped, tall-kneeling, and double and single leg stance as indicated. Recommended lumbopelvic and lower extremity neuromuscular control exercises can be found in Figure 4.

**RETURN TO SPORT CRITERIA**

**Consensus Statement:** The upright stationary bike can be initiated between 6-8 weeks and the elliptical trainer between 10-12 weeks to facilitate early-stage cardiovascular endurance, as well as passive range of motion of the hip. Panelists recommend utilizing a combination of strength, endurance, and functional performance measures during return to play testing, including but not limited to hip abductor to adductor strength ratios, the Y-Balance test, and various hop tests.

Return to sport is a goal of many patients undergoing a PAO, as these patients tend to be young, active individuals. Heyworth et al.\textsuperscript{62} found 80% of patients undergoing PAO procedures returned to play at a median of nine months post-operatively with increased pain being the only independent predictor of delayed return. Of these patients, 73% returned to their previous level of sport. Takahashi et al.\textsuperscript{63}
Figure 2. Recommended exercises for posterior-lateral hip strengthening including a) double leg bridges with isometric hip abduction, b) sidelying hip abduction isometrics in neutral hip rotation, c) hip extension isometrics in quadruped, d) standing hip abduction, and e) weight-bearing hip external rotation.

Figure 3. Recommended exercises for lumbopelvic strengthening including a) hooklying transversus abdominis contraction with upper extremity flexion, b) hooklying transversus abdominis contraction with bent knee fall out, c) primal push up, d) forward plank, and e) side plank.

reported similar findings, with 72.2% of patients able to participate in both low and high impact sports following a PAO. It should be noted that no details were provided regarding rehabilitation protocols utilized in these studies. The importance of return to sport metrics to reduce reinjury rates has been well documented in the ACL literature, however, specific guidelines continue to remain elusive.64–69 Following hip arthroscopy, these guidelines are less defined with recommendations including the absence of pain and appropriate control during sport specific activities such as running, lateral agility, and single leg squats.70 These recommendations can serve as a guide when discussing return to sport following a PAO as none currently exist in the literature. Psychological readiness should also be considered during the return to sport phase as this may affect their ability to return to previous level of play and increase the risk of reinjury.71–74 A recent systematic review found positive psychological responses pertaining to mo-
tivation, confidence, and fear were associated with greater likelihood of returning to previous level of participation.\textsuperscript{73} It can be assumed that patients following a PAO will exhibit signs consistent with low confidence and fear given the longstanding nature of dysplasia symptoms and the extensive surgical procedure. These factors should be considered along with functional performance and strength measures when determining readiness to return to sport.

Panelists recommend utilizing a combination of strength, endurance, and functional performance measures during return to play testing, including but not limited to hip abductor/adductor strength ratios, single leg squats, and the star excursion balance test. Recommendations for objective measures for return to straight line running and return to full participation in sports can be found in Table 2.

### LIMITATIONS

There are several limitations to our current study. There is a paucity of research supporting post-operative PAO rehabilitation guidelines. Ellis et al.\textsuperscript{75} published a rehabilitation protocol for use after concomitant PAO and hip arthroscopy, however, this Delphi study was focused on an isolated PAO. Therefore, initial study questions were generated by expert opinion which could result in bias. To minimize resultant bias in the modal responses, the authors recruited a diverse expert panel. It should be noted, however, that all panelists were from North America which may limit the international generalizability of our findings. Additionally, panelists completed all survey rounds on-line which does not allow for clarification or open discussion regarding survey items. Lastly, this Delphi study included rec-
RECOMMENDATIONS pertaining to an isolated PAO, which does not cover the spectrum of possible concomitant procedures performed to address soft tissue injuries or revision procedures.

CONCLUSION

Although post-operative rehabilitation is important to help patients return to prior level of function, there a paucity of research supporting post-operative rehabilitation guidelines following a PAO. Inadequate rehabilitation after PAO may lead to poor outcomes, which may include prolonged impairments in hip strength. This Delphi study established expert-driven rehabilitation guidelines for use following a PAO. The standardization of rehabilitative care following PAO is essential for achieving optimal outcomes despite other factors such as geographical location and socioeconomic status. Further research on patient-reported outcomes is necessary to confirm successful rehabilitation following the guidelines outlined in this study.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

ACKNOWLEDGEMENTS

We want to acknowledge all physiotherapists who put time and effort into answering all survey questions and provided feedback during this Delphi study. Their work was essential to creating this consensus statement.

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REFERENCES


Original Research

The Reliability of the GNRB® Knee Arthrometer in Measuring ACL Stiffness and Laxity: Implications for Clinical Use and Clinical Trial Design

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Keywords: laxity, stiffness, arthrometry, ACL, reliability, knee

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International Journal of Sports Physical Therapy

Background

Stability of the knee is dependent on multiple factors including integrity of the anterior cruciate ligament (ACL). Greater knee joint laxity appears to negatively affect dynamic joint function and therefore reliable and valid measures of ACL stiffness and laxity are clinically valuable.

Purpose

The aim of this study was to investigate the reliability of the GENOUBOB, (GNRB®) knee arthrometer device in measuring both stiffness and laxity of the ACL, and to provide information on sample size calculation for future clinical trials.

Study Design

Cross-sectional test-retest study

Method

Twelve healthy student participants (age 24-30 years; 6 females and 6 males) completed testing on two different testing dates. Anterior tibial translation and stiffness were measured using the GNRB® device at forces of 134N and 200N. Reliability analyses were performed using intraclass correlation coefficients (ICC). SEM, MDC, and sample size calculations were also determined.

Results

Average anterior tibial displacements of 3.63mm and 5.32mm were found for 134N and 200N of force respectively. ICC values for intra-rater, inter-rater, and test-retest reliability were similar across measures of anterior tibial translation and stiffness, ranging from .72 to .85 (95% CI: .54 to .90). The standard error of measurement (SEM) for anterior tibial stiffness ranged from 3.47 mm/N to 3.76 mm/N. Minimal detectable change (MDC) for test-retest anterior tibial stiffness was 9.6 mm/N. Sample sizes for crossover and parallel design studies were determined.

Conclusion

ACL laxity and stiffness measures were found to be reliably obtainable using the GNRB® knee arthrometer under the strict control of the individual’s alignment to the device and patellar pad forces. Reliable laxity and stiffness values may assist practitioners in clinical reasoning and the development of individualized ACL rehabilitation programs. Additionally, the sample size calculations presented may aid in future research design.

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Level of Evidence

INTRODUCTION

Numerous investigators have reported on the risk factors contributing to knee instability, predominantly focused on injury to the anterior cruciate ligament (ACL). Greater knee joint laxity appears to negatively affect dynamic joint function and, therefore, reliable and valid measures of laxity are clinically valuable. Optimal anterior tibial translatory laxity testing requires an appropriate and known force to be applied at a consistent speed and perpendicular to the tibia. Previous researchers have used the KT1000 and KT2000 knee arthrometer devices to measure tibial translation and produce ACL laxity metrics. Despite their frequent use in ACL laxity research, the KT devices only demonstrated a modest level of inter-rater reliability. These devices are no longer being manufactured leaving clinicians and researchers seeking access to a reliable and valid knee arthrometer for measurement of tibial translation.

An alternative knee arthrometer measuring anterior tibial translation parameters (displacement and stiffness) is the GENOUROB® (GNRB®). The GNRB®’s automated and robotic nature is thought to apply specific translatory loads at consistent speed and direction.

Previous studies have published results presenting conflicting measures of anterior tibial translation reliability using the GNRB®,. Vauhnik et al. reported relative reliability (95% limits of agreement) of the GNRB® device measuring translation at a test force of 154 N of 2 to 3 millimeters (mm). Additionally, Vauhnik et al. reported intra- and inter-rater reliability of the GNRB® device was comparable to the KT1000 and KT2000 however, the overall inter-rater reliability remained low. Jenny et al. using Bland-Altman Limits of Agreement, reported the GNRB® arthrometer demonstrated satisfactory levels of agreement with both stress radiographs ($R^2 = 0.06$) and the gold standard, intraoperative navigation ($R^2 = 0.12$) for tibial translation. More recently, Mourabes et al. investigating the reliability of the GNRB® device on healthy individuals, reported poor test-retest agreement. The current variability of reliability findings reported in the literature drives the need for additional reliability studies using this device.

An additional measurement feature of the robotic GNRB® arthrometer includes the ability to provide a measure of anterior tibial translatory stiffness calculated directly from the anterior laxity curve (anterior tibial displacement vs applied anterior translation force) during the GNRB®’s standardized laxity testing protocol. Anterior tibial translatory laxity, when discussed in terms of instrumented and manual testing, characterizes the magnitudes of anterior tibial displacement occurring as a result of passive posterior to anteriorly directed forces on the proximal tibia. However, in addition to measures of laxity, the important dynamic strain behaviors of the passive tissues resisting anterior tibial translation can be understood by measuring the force to displacement relationship across a range of controlled increasing forces applied to the posterior proximal tibia (stiffness). The GNRB device provides a measurement of this dynamic relationship between the changes in applied force and the changes in anterior tibial displacement. The changing resistance undergoing deformation from the application of a changing force is important in understanding the dynamic behaviors of the knee joint tissue resisting anterior tibial translation. This measurement of stiffness is thought to be a clinically significant biomechanical parameter of ligamentous resistance (beyond measures of displacement), due to its association with functional anterior knee instability. Nouveau et al. demonstrated the clinical utility of serial anterior tibial translatory stiffness values with the GNRB® device in the assessment of ACL graft maturation following anterior cruciate ligament reconstruction (ACLR) and during rehabilitation interventions of individuals post-ACLR reconstruction. If the stiffness differential value is more than 10umN bilaterally, the authors suggest implementing an alternative rehabilitation protocol to allow optimal healing of the ACL graft and return to function. Once the slope differential re-stabilizes, the rehabilitation protocol progression can resume. The potential use of clinically assessing changes in anterior tibial translatory stiffness with the GNRB® device to guide and individualize rehabilitation protocols against undesirable ACL loading requires acceptable limits of reliability with repeated testing. These same stiffness measures following ACL injury and during ACL rehabilitation programs can also assist in the clinical decision making regarding individualized return to function and sport. Finally, reliable measures of anterior tibial translatory stiffness with the GNRB® device may have further utility towards identifying ligamentous insufficiencies within individuals demonstrating normal magnitudes of anterior tibial displacement (laxity). To the authors knowledge, no previous research has been reported on the reliability of serial measures of stiffness using the GNRB® device.

The purpose of this study was to investigate the reliability of the GNRB® knee arthrometer device in measuring both stiffness and laxity of the ACL, and to provide information on sample size calculation for future clinical trials.

METHODS

STUDY DESIGN

This study followed a test-retest reliability cross-sectional study design with two experienced examiners performing all measurements using the GNRB® knee arthrometer device. Each investigator underwent training with a GNRB® representative as well as several weeks of practice sessions prior to testing.

PARTICIPANTS

Twelve university student and staff volunteers (6 females and 6 males aged 24 - 30 years), were recruited via flyer
and email for the study from June through August 2019; the number of participants recruited was based on previous knee arthrometer reliability studies. Exclusion criteria included no current knee pain or history of ACL compromise. The IRB Committee at the University of St. Augustine for Health Sciences approved the study, and all subjects provided informed consent.

METHODS

Data collection was performed across two sessions, two weeks apart. Both examiners performed measurements on each participant twice on the first test session (intra- and inter-rater reliability data collection), and once each on the second test session (intra-rater and test-retest data collection). Participants were instructed to limit formal lower extremity exercise at least 60 minutes prior to each testing session. Demographic data was collected before test session one and included: age, sex, and body weight. The GNRB® device was calibrated according to the manufacturer's guidelines before each testing session.

The order of testing by examiners was randomized. When participants arrived for testing, they were asked to sit resting in a chair for 10 minutes prior to each test session. Participants were then positioned supine on the examination table with arms resting on the table next to their torso. The trunk was supported in an inclined position 30 degrees relative to the examination table (Figure 1). To decrease potential bias or order effect, the leg to be tested first was determined with randomization via a coin toss. With the GNRB® device secure on the table, the lower limb was placed on the device in a neutral position between internal and external rotation. Temporary skin markings were made on the inferior pole of the patella, the center of the tibial tuberosity, and along the medial and lateral tibiofemoral joint lines of the participants’ knee. The knee was positioned to ensure the marking on the inferior pole of the patella was visible through the cut-out on the patellar pad of the GNRB® device (Figure 2). Both medial and lateral joint line-markings were then visually aligned with the intersection between the femoral stabilization component and the tibial anterior displacement component of the device. The displacement transducer of the device was positioned directly over the tibial tuberosity marking and perpendicular to the tibia (Figure 1). A goniometer was used to ensure the displacement transducer was perpendicular to the tibia. The participant’s foot was placed in a neutral position on the footplate of the GNRB® device. The footplate’s position was adjusted until the plantar aspect of the heel and midfoot were in contact with the footplate. The position of the footplate as indicated on the device was then recorded and used for consistency in all subsequent tests. Patellar stabilization force during the first testing session was achieved via the GNRB®’s patella pad software generated output. Tightening of the patellar straps continued until a minimum force of 60 N was achieved. The average patellar pad force across the three pulls was used in data analysis. All subsequent tests utilized patellar stabilizing force +/- 10 N of the recorded initial test values for each examiner. The patellar pad’s alignment was carefully adjusted in an attempt to distribute the posteriorly directed stabilizing force evenly across the patella. See Figure 1 for patient positioning in the GNRB® device.

The GNRB® device was programmed to perform three consecutive anterior tibial translation ramp forces to a maximum of 200N. During each applied ramp force, translation values at 134N and 200Nconstant stiffness values were recorded. All procedures were immediately repeated on the participant's contralateral limb. The skin markings were then completely removed, and the participant was positioned seated, resting in a chair for ten minutes. The second examiner then performed the same procedure as described above. This sequence was repeated until each examiner tested each subject's knees twice for the assessment of intrarater reliability.

The second testing session occurred two weeks later. The footprint position and the patella stabilization force recorded from test session one were used for consistency in test session two. Each examiner tested each participant once using the same procedure as described for session one, with the time of day consistent between sessions. The re-
results of the second testing session were used in the test-retest analysis.

STATISTICAL ANALYSES

The average patellar pad force, anterior translation, and stiffness values across the three anterior tibial translatory ramp forces for each knee calculated by the GNRB® software were used in data analysis. Testing for normality was completed, and reliability analyses were performed on data for all participants using intraclass correlation coefficients (ICC). A two-way random-effects model based on the mean of the three repeated measurements of the first measurement session and absolute agreement assessed the interrater repeatability. A two-way mixed-effects model, based on the mean of the three repeated measures, was used to assess intra-rater repeatability and test-retest repeatability. Standard deviation/mean × 100 was used to calculate the coefficient of variation. Standard error of measurement (SEM), calculated as: \( \sqrt{\text{SEM}^2 / \text{degrees of freedom}} \), was used to assess the degree to which repeated measures of the GNRB® outputs varied for participants (within-participant deviation). Estimation of the minimum detectable change (MDC), representing the minimum differences in the measurements of anterior laxity and stiffness considered true changes were established using MDC = SEM × 1.96 × \( \sqrt{2} \).

Sample size calculations for both crossover and parallel design studies were performed using various magnitudes of change in anterior laxity parameters. Anterior tibial displacement (mm of movement) at both 134N and 200N of applied force and calculated slope (mm displacement vs force N) values with \( \alpha = 0.05 \) and \( \beta = 0.80, 0.90, \) and 0.95 were evaluated. Calculations were completed using \( 2x(Z\alpha + Z\beta)^2 \times \sigma^2)/d^2 \) for a parallel design and \( (Z\alpha + Z\beta)^2 \times \sigma^2)/d^2 \) for a crossover design. For example, a parallel design powered at 0.90 would require 19 participants to detect an absolute change in anterior proximal tibial displacement of 1 mm assessed at a test force of 134N.

RESULTS

Twelve participants (6 males and 6 females aged 24-30 years) completed the study (24 limbs measured). The average body mass index of participants was 25.0 (SD 3.24) kgm². IBM SPSS Statistics for Windows, version 26 (IBM Corp., Armonk, N.Y., USA) software was used in the statistical analysis.

Moderate to good intratester reliability was found by comparing test one and two for each examiner; ICC values 0.72 – 0.83. Table 1 presents measures related to intratester reliability between the means of the first test and repeated test during session one.

Good interteter reliability was found by comparing test one measures for each examiner; ICC values 0.76 – 0.81. Table 2 presents measures related to interrater reliability between the means of the first test for each examiner during session one.

Test-Retest Repeatability also demonstrated good reliability (ICC 0.77 - 0.85) for both laxity and stiffness measures. Table 3 presents the test-retest repeatability measures between the mean of the first test of session one (Trial 1) and session two (Trial 2).

Sample size calculations for both crossover and parallel design studies, using various magnitudes of change in laxity parameters related to anterior tibial translation are presented in Table 4. Tibial displacement (mm of movement) at both 134N and 200N of applied force and the calculated slope (mm displacement vs force N) values with \( \alpha = 0.05 \) and \( \beta = 0.80, 0.90, \) and 0.95 were evaluated (see Tables 4 and 5). Calculations were completed using \( 2x(Z\alpha + Z\beta)^2 \times \sigma^2)/d^2 \) for a parallel design and \( (Z\alpha + Z\beta)^2 \times \sigma^2)/d^2 \) for a crossover design. For example, a parallel design powered at 0.90 would require 19 participants to detect an absolute change in anterior proximal tibial displacement of 1 mm assessed at a test force of 134N.

DISCUSSION

The results of this study suggest that intrarater, interrater, and test-retest relative reliability were similar across measures of anterior tibial translation and stiffness with ICC values ranging from .72 to .83. (Tables 1, 2, 3). The 95% confidence levels of the ICCs were fairly wide (.54 to .91), suggesting relative reliability ranges from moderate to good. Thus, this study supports previous research findings that concluded the GNRB® device is thought to be useful in diagnostic knee assessment, baseline clinical measurement, and treatment planning related to knee laxity status.3,7,9,10

Specific to measures of anterior tibial displacement, the ICC values found in this study, were higher than those of Vauhnik et al.10 and Moubarbes et al.,3 who reported values between raters and test-retest protocols ranging from 0.22 to 0.42 and 0.41 to 0.49, respectively. At a testing force of 134 N results showed a mean anterior tibial displacement value of 3.6 mm, which is less than the reported values by Vauhnik et al10 (5.6 to 6.5 mm) but in closer agreement with Moubarbes et al13 (3.2 mm) using consistent but lower patellar stabilizing forces. The calculated SEMs for intrarater, interrater, and test-retest were found to be narrow in this study, ranging from 0.48 to .62 mm, suggesting a moderate level of measurement variability. At 200 N of force, the mean anterior displacement increased to 5.32 mm, while SEM values remained narrow, ranging between 0.66 to 0.78 mm. Interestingly, the MDC values at 134 N and 200 N were found to be 2.1 mm/N and 2.5 mm/N respectively. The MDC values can be a clinically significant metric when looking to compare the minimally detectible change between testing sessions of one limb. For instance, a patient who has undergone ACL reconstruction (ACLR) where the contralateral limb cannot be used as comparison (due to previous injury or to disuse during convalescence), the MDC could have utility for detecting laxity changes that occur from early post injury to late rehab beyond the slight ligamentous adaptation/laxity typically expected.
Table 1. Intrarater Reliability

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<tr>
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<th>Trial 1 Mean (SD)*</th>
<th>Trial 2 Mean (SD)*</th>
<th>Mean Absolute Variability T1:T3*</th>
<th>Correlation</th>
<th>CV Trial 1 (%)</th>
<th>CV Trial 2 (%)</th>
<th>Mean CV (%)</th>
<th>ICC (95% CI)*</th>
<th>SEM</th>
<th>MDC</th>
</tr>
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<tbody>
<tr>
<td>Displacement (mm) @ 134N</td>
<td>3.6 (1.0)</td>
<td>3.6 (0.9)</td>
<td>0.4 (0.4)</td>
<td>0.82</td>
<td>26.40</td>
<td>25.30</td>
<td>25.85</td>
<td>.83 (.72 to .90)</td>
<td>0.76</td>
<td>2.11</td>
</tr>
<tr>
<td>Displacement (mm) @ 200N (mm)</td>
<td>5.3 (1.1)</td>
<td>5.4 (1.1)</td>
<td>0.5 (0.4)</td>
<td>0.83</td>
<td>20.30</td>
<td>20.90</td>
<td>20.60</td>
<td>.82 (.71 to .89)</td>
<td>0.89</td>
<td>2.47</td>
</tr>
<tr>
<td>Stiffness /Slope (mm/N)</td>
<td>27.5 (4.0)</td>
<td>26.8 (3.8)</td>
<td>2.0 (1.7)</td>
<td>0.79</td>
<td>14.50</td>
<td>14.00</td>
<td>14.25</td>
<td>.77 (.62 to .87)</td>
<td>3.47</td>
<td>9.6</td>
</tr>
</tbody>
</table>

SD: standard deviation; CV: coefficient of variation; SEM: standard error of measurement; mm: millimeter; N: Newton.

Table 2. Interrater Reliability

<table>
<thead>
<tr>
<th></th>
<th>Rater 1 Mean (SD)*</th>
<th>Rater 2 Mean (SD)*</th>
<th>Mean Absolute Variability T1:T3*</th>
<th>Correlation</th>
<th>CV Trial 1 (%)</th>
<th>CV Trial 2 (%)</th>
<th>Mean CV (%)</th>
<th>ICC (95% CI)*</th>
<th>SEM</th>
<th>MDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm) @ 134N</td>
<td>3.7 (1.0)</td>
<td>3.6 (1.0)</td>
<td>0.5 (0.4)</td>
<td>0.84</td>
<td>28.1</td>
<td>26.2</td>
<td>27.2</td>
<td>.81 (.61 to .91)</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Displacement (mm) @ 200N</td>
<td>5.3 (1.1)</td>
<td>5.3 (1.1)</td>
<td>0.5 (0.5)</td>
<td>0.76</td>
<td>21</td>
<td>20</td>
<td>20.5</td>
<td>.76 (.54 to .88)</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Stiffness /Slope (mm/N)</td>
<td>27.4 (3.9)</td>
<td>27.5 (4.1)</td>
<td>2.1 (1.8)</td>
<td>0.78</td>
<td>14.3</td>
<td>15.1</td>
<td>14.7</td>
<td>.79 (.58 to .90)</td>
<td>3.52</td>
<td></td>
</tr>
</tbody>
</table>

SD: standard deviation; CV: coefficient of variation; SEM: standard error of measurement; mm: millimeters; N: Newton

The Reliability of the GNRB® Knee Arthrometer in Measuring ACL Stiffness and Laxity: Implications for Clinical Use and...
### Table 3. Test-Retest Repeatability

<table>
<thead>
<tr>
<th></th>
<th>Trial 1 Mean (SD)*</th>
<th>Trial 2 Mean (SD)*</th>
<th>Mean Absolute Variability T1:T3*</th>
<th>Correlation</th>
<th>CV Trial 1 (%)</th>
<th>CV Trial 2 (%)</th>
<th>Mean CV (%)</th>
<th>ICC (95% CI)*</th>
<th>SEM</th>
<th>MDC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Displacement (mm) @ 134N</strong></td>
<td>3.6 (1.0)</td>
<td>3.6 (0.9)</td>
<td>0.4 (0.4)</td>
<td>0.82</td>
<td>26.40</td>
<td>25.30</td>
<td>25.85</td>
<td>.83 (.72 to .90)</td>
<td>0.76</td>
<td>2.11</td>
</tr>
<tr>
<td><strong>Displacement (mm) @ 200N (mm)</strong></td>
<td>5.3 (1.1)</td>
<td>5.4 (1.1)</td>
<td>0.5 (0.4)</td>
<td>0.83</td>
<td>20.30</td>
<td>20.90</td>
<td>20.60</td>
<td>.82 (.71 to .89)</td>
<td>0.89</td>
<td>2.47</td>
</tr>
<tr>
<td><strong>Stiffness/Slope (mm/N)</strong></td>
<td>27.5 (4.0)</td>
<td>26.8 (3.8)</td>
<td>2.0 (1.7)</td>
<td>0.79</td>
<td>14.50</td>
<td>14.00</td>
<td>14.25</td>
<td>.77 (.62 to .87)</td>
<td>3.47</td>
<td>9.6</td>
</tr>
</tbody>
</table>

SD: standard deviation; CV: coefficient of variation; ICC: Intraclass correlation coefficient; SEM: standard error of measurement; mm: millimeters; N: Newton; MDC: minimal detectable change.
Like the GNRB’s measurement of anterior tibial displacement, there was a moderate level of variability found during repeated testing regarding its calculated mean values of stiffness, (resistance to anterior tibial translation) with wide ICC confidence intervals (0.57 to 0.90). The SEM for the value of the mean slope from the force displacement curve in this study ranged from 3.47 mm/N (test-retest) to 3.76 mm/N (intrarater), suggesting the GNRB® device demonstrates a moderate level of overall measurement error.

Although not specifically analyzed in this study, a trend towards a decrease in the device’s patellar pad stabilization force (1-2N) within each testing bout across the three robotically driven anterior tibial forces was visually observed during testing. It is unknown whether laxity and stiffness measures are sensitive to these small changes. Possible explanations for the change in patellar pad stabilization forces during testing surround functional shifting of the patellar stabilization straps, changes in activation of the patient’s musculature, and or increased compliance of peri-patellar soft tissues with the sequential repetitive loading.

The results of this study found the MDC for mean stiffness values to be 9.6mm/N. As stated, the MDC is potentially very useful in monitoring changes in anterior translation displacement, (laxity), but also particularly important in relation to assessing changes in anterior tibial translatory stiffness for individuals undergoing post-operative ACLR rehabilitation. A trend toward stiffness values decreasing, (or increasing) over the time course of an individualized rehabilitation program greater than the MCD.
would be significant as it suggests that the change is beyond the random variation observed with robotic ligament testing. Nouveau et al. suggested using a stiffness differential value as a marker to adjust therapeutic interventions during rehabilitation. However, the results of this study suggest, that while an important clinical relationship likely exists between decreasing anterior tibial translatory stiffness values assessed in robotic testing and decreasing resistance to anterior translation, the authors of this study suggest that any calculated change (stiffness differential) should take into account the MDC as well as the SEM values.

The basis for measurement error when utilizing the GNRB® device for anterior tibial displacement have been reported elsewhere. Main sources of error are thought to include incongruency between the flat surface of the displacement sensor and the non-flat tibial tuberosity, the alignment of the device relative to the knee joint itself, the position of the participant, and the consistency of patellar pad force. Based on findings of previous studies, several attempts were made in this study to minimize these previously reported errors. To address potential errors related to participant alignment, a 30-degree inclined rigid foam wedge under the torso was used to standardize participant position and maximize comfort to allow relaxation of the limb during testing. It is the opinion of the investigators that consistent participant positioning and implementing careful skin markings over key landmarks were both critical to maximizing measurement repeatability. Deviation of the transducer between trials from a perpendicular orientation would also offer a potential source of measurement error. To standardize the spatial orientation of the displacement transducer, a goniometer was used to align the transducer perpendicular to the tibial tuberosity.

The design of the GNRB® tightening straps on the patellar stabilization pad consists of a buckle/ratchet tightening system. Therefore, maintaining consistent patellar force between trials was challenging as one step on the ratchet increased or decreased the patellar pad force up to 10N in some participants. Vauhnik et al. and Mourabes et al. reported repeatability of the GNRB® was associated with the consistency of the patellar pad force. Alqahtani et al. found a significant difference in normative values of anterior tibial displacement when patellar pad forces varied by 11.2 N. Therefore, following the recommendations of Vauhnik et al. and Alqahtani et al., this study’s protocol included a minimum of 60 N of patellar pad force and no greater difference than 10 N between trials. Post hoc analysis of the applied patellar pad forces in this study demonstrated consistent forces between all trials with a mean force of 61.4 N (SD 3.2N). Only twice were differences in patellar pad forces within subjects greater than 10 N. Further post hoc statistical analysis found no significant differences in patellar forces within participants or within examiners (p>0.05). The deliberate consistency of patellar pad forces may have played a role in higher reliability findings of this study in comparison to previous studies.

The influence of BMI on displacement and stiffness measures was not directly analyzed in this study; however, it was noted that individuals with greater soft tissue thickness appeared to challenge the processes of achieving consistent application and strap tightening of the GNRB® device. Difficulty with adequately securing the thigh strap without pinching the subject’s skin may have resulted in less femoral stabilization and subsequently altered the measures of anterior excursion detected by the GNRB. Mourabes et al. reported similar challenges with obese subjects attributing excessive soft tissue as a potential source of error. Further studies on the influence of strap tension and anthropometric variables may help understand its role in the measurement process across individuals with various levels and densities of the thigh and calf tissues.

LIMITATIONS

Despite referencing earlier research and attempting to limit error identified in previous studies, there were limitations. This study involved a small number of healthy, younger to middle-aged adults with no current or reported history of significant lower extremity injury. Therefore, interpretation of the results of this study may not be generalizable to other populations; additional studies with larger more diverse populations are needed.

Furthermore, although attempts were made to control against unwanted hamstring activation by maximizing patient comfort and the use of careful participant positioning, the investigators acknowledge the potential influence of hamstring activation on translatory measures. The use of surface electromyography (sEMG) to measure hamstring activation levels has been thought to be a valuable supplemental procedure by some researchers investigating anterior tibial displacement measures. The use of sEMG of the hamstring muscle group may be valuable in post-injury and post-surgical conditions where hamstring muscle activation is not easily controlled. This study investigated healthy participants with no knee injury or pain minimizing these patient relaxation and positioning challenges.

Many studies investigating reliability and changes in ACL laxity include testing forces ranging between 89N-250N. This study investigated forces of 134N and 200N to allow comparison of values obtained in previous research using similar forces. Nesser et al. found the maximum load of 200N to be more sensitive to changes in ACL laxity over lower loads. Whereas Beldame et al. attempted loads higher than 200N and were only able to reach 250N in 84% of subjects due to patient report of unacceptable pain as forces increased. Although the forces used in this study are similar to many studies using knee arthrometer devices, they are well below peak anterior shear forces acting on the knee joint during function; anterior shear forces up to 1070N have been reported during activities such as jumping. Therefore, it is possible that the forces used in this study may not adequately represent those elicited with functional activities. Perhaps, additional studies looking at forces more closely related to those that occur across the knee with functional tasks, while still optimizing patient comfort, will be available in future knee arthrometer designs and may add value to the body of evidence.
Variations in anterior laxity assessment measures may be influenced by female sex hormone levels. This study did not include evaluation of hormone levels, which may have influenced measures between test re-test sessions in females. Although the time of day for each testing session was kept consistent, it is reasonable to hypothesize that variations in anterior tibial displacement parameters may have arisen in the two-week period between measures due to intrinsic changes in ligamentous and capsular knee tissues from the influence of female sex hormones. The current body of evidence is conflicted as to what role, if any, sex hormones such as estrogen and progesterone may have on ligamentous properties. Maruyama et al. found measures of anterior translatory stiffness did not appear to be related to hormonal changes during the menstrual cycle. In contrast, a recent systematic review by Hetzberg et al.; found knee laxity did vary significantly across phases of the menstrual cycle. Although the authors of this study recognize the possible influence of hormones on laxity values, post-hoc analyses (paired t-tests) revealed no statistical differences between test 1 and test 3 (test retest) for either males or females at 134N or 200N. Females did demonstrate increased laxity measures compared to males, with mean values of 0.65 mm and 0.75 mm greater for females compared to males at 134N and 200N respectively. However, the similar reliability values found across genders suggests female sex hormone changes between the two-week period did not strongly influence the laxity values obtained. It is the author’s opinion that future reliability studies involving measurements of absolute anterior tibial displacement parameters using the GNRB® device across the menstrual cycle may be of value in determining the potential effects of sex hormones on repeated measures of anterior tibial displacement and stiffness.

CONCLUSION

Anterior tibial translation and stiffness data appears to be reliably obtainable using the robotic GNRB® knee arthrometer device. Sample size calculations and minimally detectable change values may aid in clinical applications and future research studies. To improve reliability when measuring anterior tibial translatory laxity parameters, the authors recommend assessment using the average of three consecutive measurement trials, with strict control of alignment and consistent patellar stabilization pad force. Given the observed levels of measurement variability found in this study, the calculations of the sample size requirements and MDCs may help clinicians and future researchers evaluate changes in anterior tibial translatory laxity and stiffness values. Reliable stiffness and laxity measures following ACL injury and during ACLR programs may assist in the clinical decision making regarding individualized return to function and sport.

CONFLICT OF INTEREST STATEMENT

The authors report no conflicts of interest.

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REFERENCES


The Effectiveness of Trunk and Balance Warm-up Exercises in Prevention, Severity, and Length of Limitation From Overuse and Acute Lower Limb Injuries in Male Volleyball Players

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Keywords: men's volleyball, exercise-based warm-up, injury burden, overuse, acute injury

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Background
Injuries in volleyball players are most common in the ankles and knees. Many volleyball players suffer from overuse injuries because of the strain placed on the lower extremities from repeated jumping. A characteristic of players who are most at risk for lower extremity injuries is the tendency to display trunk instability during landing, such as lateral flexion and rotation. Research has shown the effectiveness of exercise-based warm-up interventions for acute volleyball injuries. However, comprehensive analyses on the use of lower extremity, trunk, and balance programs to prevent overuse injuries are lacking.

Purpose
To examine the effects of trunk and balance warm-up exercises on the prevention, severity, and length of limitation of overuse and acute lower limb injuries in male volleyball players.

Study Design
Prospective, single-cohort study.

Methods
This study involved the 2019 (control group) and 2021 (intervention group) male volleyball teams. The control and intervention groups were on the same team; however, seven players joined in 2021 through a sports referral program through which different players are recruited. Measurements included injury incidence rate, injury severity, and injury burden. The intervention involved the addition of trunk and balance exercises during the 2021 season.

Results
There was no significant difference in injury incidence rates between groups. Injury severity decreased by 3.7 days for overuse injuries (p=0.04). Injury burden decreased by 11.8 (days/1000 player hours) overall and by 7.1 (days/1000 player hours) for overuse injuries.

Conclusion
The results show that an exercise-based warm-up aimed at improving trunk posture during landing did not reduce the incidence rate of injury in men's volleyball. However, the addition of this warm-up did significantly reduce the severity of overuse injury.

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Level of Evidence

INTRODUCTION

Ankle and knee injuries are among the most common injuries in volleyball players. Jumper’s knee, in particular, accounts for approximately 40% of all lower extremity injuries in these athletes. Many volleyball players develop overuse injuries, such as jumper’s knee, due to the strain placed on the lower extremities with repeated jumping. Additionally, volleyball players have been reported to suffer from lower extremity injuries due to environmental factors, such as the long duration of practice (12 hours/week), the number of jumps, and the material of the gymnasium floor (hard surface) upon which they train and play. Furthermore, physical factors, such as decreased quadriceps muscle strength, jump height, and landing ability may contribute to injuries.

Previous research indicates that lower limb injuries are more likely to occur with an unstable landing motion. De Bleecker et al. examined the landing movements of athletes with lower limb injuries, and several associations with trunk movement were reported. An examination of movements occurring in the thoracic spine, hip, knee, and ankle joints during the drop jump landing from a 30-cm platform, found that a group with medial tibial stress syndrome exhibited significant compensation in the thoracic spine, hip, and ankle joints during landing. These reports suggest that athletes with lower extremity injuries may have greater trunk instability (poorer trunk control) during landing.

In recent years, it has been suggested that a comprehensive exercise-based warm-up that includes lower extremity, trunk, and balance training prior to practice may reduce the incidence of acute injuries, such as those to the anterior cruciate ligament. However, the effect of comprehensive exercise-based warm-up on overuse injuries, such as lower extremity injuries in volleyball players, has not been demonstrated.

Overuse injuries are common among athletes with high practice and competition loads. Consequently, the concept of injury burden has been used to evaluate overuse. Greater losses in playing time indicate a lower team performance. Reduction of incidence and burden of overuse injury is important to team outcomes and performance.

Therefore, the purpose of this study was to examine the effects of trunk and balance warm-up exercises on the prevention, severity, and length of limitation of overuse and acute lower limb injuries in male volleyball players.

METHODS

PARTICIPANTS

Men’s volleyball teams from the first division of a University Federation were included in this study with participants from the 2019 team as the control group and the team from 2021 as the intervention group. The control and intervention groups were on the same team; however, seven players joined through a sports referral program in which different players are recruited (4 outsides, 2 middles, 1 libero). The two groups had the same practice (including training) and match hours (Control: practice=744, match=152, Intervention: practice=687, match=200). This study was approved by the Ethics Committee of the affiliated Hospital. The objectives of this study were explained to the participants in oral and written forms, and their written consent to participate in the study was obtained. The obtained data were de-identified.

SURVEY PERIOD

The study was conducted during the 2019 (January–December 2019) and 2021 (January–December 2021) seasons. Throughout both seasons, the number of days of practices and competitions, participating players, and occurrence of lower extremity injuries were recorded by the athletic trainers affiliated with the teams.

INJURY DEFINITION

After an injury, trainers were asked to classify whether it was an acute (associated with a specific, clearly identifiable traumatic event) or overuse (no specific identifiable event responsible for its occurrence) injury. Furthermore, trainers were required to register the affected anatomical area.

CALCULATION OF INJURY INCIDENCE, SEVERITY, AND BURDEN

The incidence of lower extremity injury incidence was calculated by dividing the number of incidents by the number of potential exposure times (i.e., practice and matches) and multiplying this value by 1000. Using this formula, an incident rate was obtained relative to 1000 player hours. Severity was defined as the number of days from injury to return to play. Cumulative time loss was categorized as: slight (0 days), mild (1–7 days), moderate (8–28 days), or severe (>28 days). Return to competition was defined as the day when the athlete fully participated in all practices or was able to participate in competitions.

Injury burden was defined as the measure of time lost from competition due to injury and was calculated as the product of the incident rate and average severity of the injury.

INTERVENTION METHOD

Prior to the 2019 season, warm-up consisted of three lower extremity exercises (hip circles, reverse Nordic curls, and overhead deadlifts), jogging, stretching, and agility drills for 20 min daily. In the 2021 season, the author added new core and balance exercises. The intervention exercises consisted of three core (abdominal bracing, side plank with hip side raise, and side plank with trunk rotation) and Y-Bal-
ance movements (side reach, posterior-medial reach, and front reach) exercises (Figure 1). These exercises have been reported to improve the ability to maintain the midline position without lateral flexion the trunk during landing after instruction. The newly introduced exercises were performed for approximately 30 min daily during warm up/practice. The exercises were consistently checked by an athletic trainer once a week.

STATISTICAL METHODS

Injury incidence between teams was examined using the \( \chi^2 \) square test. The severity of injuries was compared between groups using an unpaired t-test. All data were analyzed using SPSS software (version 22.0, IBM Corporation, Japan) with a priori alpha level of 0.05.

RESULTS

Table 1 presents the information regarding the two groups. The control group \((n=17\), Age=20.82±0.95 years, Height=184.56±7.66 cm, Mass=75.44±9.06 kg\) and the intervention group \((n=17\), Age=21.06±0.95 years, Height=183.81±10.48 cm, Mass=75.61±8.94 kg\). There were no significant differences in age, height, or mass between the control and intervention groups (Table 1).

The number of incidents of injury in the control group was 22 (overuse: 12; acute:10), while the number of incidents in the intervention group was 16 (overuse 12; acute four). No significant difference in overuse or acute injury incidence was observed (Table 2). The severity of injuries among the control group was eight minor, 11 mild, two moderate, and one major. The severity of injuries among the intervention group was 15 minor, one moderate, and two major. The severity of overuse injury was lower in the intervention group than that of the control group (mean difference: 2.82, 95% CI: 0.17–5.47, Cohen’s d: 0.59, \( p=0.04 \)). Injury burden decreased by 11.8 days/1000 player hours overall, 7.1 days/1000 player hours for overuse injuries, and 4.7 days/1000 player hours for acute injury in the intervention group compared to the control group.

DISCUSSION

The results of this study indicate that comprehensive exercise-based warm-up programs did not reduce acute and overuse injury rates. The number of incidents of injury in the control group was 22, while the number of incidents in the intervention group was 16. The team injury rates in this study were 3.4 and 3.1 days/1000 player hours. Compared to the results of a previous study, which showed a range of 3.6–10.52 days/1000 player hours for professional volleyball teams and players in the World League, the injury rate in this study was low. To prevent overuse, it is necessary to manage the workload, including the amount of practice and the number of games played. The total number of practice hours and the number of games played in both groups were 896 and 887, respectively. The total hours of practice and number of games did not change between the control and intervention groups, and therefore, a likely reason that the incidence rate did not change.

Chronic injury severity may be reduced with the addition of an exercise-based warm-up program. In 2019, chronic injury severity was on average 5.73 days, and in 2021, it was zero days. Chronic injury severity has been reported as 2.9 days in professional female volleyball players and 4.2 days in amateur-level players. Professional players may have lower severity due to better management of conditions. In 2021, the authors hypothesized that the players may have finished the season without missing a practice session by providing an appropriate workload during the season, just like professional players.

The results of this study show that the exercise-based warm up program was able to reduce overall injury burden by 11.8 days/1000 players hours and the injury burden of chronic injuries by 7.1 days/1000 players hours. In this case, the comprehensive loading, including lower extremity exercises as well as trunk exercises, and trunk control, may have allowed athletes with overuse pain to maintain the muscle strength required to participate in practice.

Fuller was able to reduce the number of missed days by four and the overall injury burden by 26%, improving the performance of a rugby team. In the current study, the injury burden decreased by 7.1 days for overuse cases and 4.7 days for acute injury cases. Therefore, the overall injury burden was reduced by 58% (11.8 days) compared to controls. The exercise-based warm-up performed in the cur-

| Table 1. Physical characteristics of the participants and practice game durations |
|-----------------------------------------------|-----------------|-----------------|
| Control \((n=17)\) | Intervention \((n=17)\) | \( p \) |
| Age (years) | 20.82±0.95 | 21.06±0.83 | 0.44 |
| Height (cm) | 184.56±7.66 | 183.81±10.48 | 0.81 |
| Mass (kg) | 75.44±9.06 | 75.61±8.94 | 0.95 |
| Exposure to Volleyball (hours) | | |
| Total | 896 | 887 | 0.98 |
| Training | 744 | 687 | 0.97 |
| Match | 152 | 200 | 0.95 |
Figure 1. Three exercises were performed in 2019 for A. The additional exercises in 2021 included those shown in B and C. For all exercises, the figure on the left demonstrates the starting position, and the figure on the right demonstrates the ending position.

A: Conventional exercises: 1=hip circle, 2= reverse Nordic curl, 3= overhead deadlifts; 10reps*3sets
B: Trunk exercise: 1= abdominal bracing, 2= side plank with hip side raise, and 3= side plank with trunk rotation; 30seconds*3sets
C: Y-Balance exercise: 1= side reach, 2= posterior-medial reach, and 3= front reach; 10reps*3sets
Table 2. Comparison of severity and injury burden between the control and intervention group

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Intervention</th>
<th>p-value</th>
<th>95%CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overuse</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury incidence (/1000AEh)</td>
<td>1.9</td>
<td>2.3</td>
<td>0.85</td>
<td>-0.8, 0</td>
</tr>
<tr>
<td>Severity (time loss days)</td>
<td>3.7</td>
<td>0*</td>
<td>0.03</td>
<td>0.2, 5.5</td>
</tr>
<tr>
<td>Injury burden (time loss days/1000AEh)</td>
<td>7.1</td>
<td>0</td>
<td>-</td>
<td>0.1, 14.0</td>
</tr>
<tr>
<td><strong>Acute</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury incidence (/1000AEh)</td>
<td>1.6</td>
<td>0.8</td>
<td>0.77</td>
<td>-0.1, 1.6</td>
</tr>
<tr>
<td>Severity (time loss days)</td>
<td>13.3</td>
<td>21.3</td>
<td>0.81</td>
<td>-15.9, 0</td>
</tr>
<tr>
<td>Injury burden (time loss days/1000AEh)</td>
<td>21.1</td>
<td>16.4</td>
<td>-</td>
<td>0.1, 9.4</td>
</tr>
</tbody>
</table>

* The severity of overuse injury was lower in the intervention group than that of the control group (p< 0.05)

CONCLUSION

The results of the present study indicate that the a program of trunk and balance warm-up exercises did not reduce the incidence rate of overuse injury in male volleyball players, however, it did reduce the severity injuries, of both overuse and acute mechanisms.

CONFLICTS OF INTEREST

The authors have no COI’s to disclose.

ACKNOWLEDGMENTS

The authors thank all those who participated in the research and the athletic trainer who managed the injuries of the team members.

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REFERENCES


Original Research

A Comparison of Factors Associated with Running-Related Injuries between Adult and Adolescent Runners

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Keywords: youth, physical assessments, strength, functional movement screen, muscle endurance

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Background
There are multiple personal and environmental factors that influence the risk of developing running-related injuries (RRIs). However, it is unclear how these key clinical factors differ between adult and adolescent runners.

Purpose
The purpose of this study was to compare anthropometric, training, and self-reported outcomes among adult and adolescent runners with and without lower extremity musculoskeletal RRIs.

Study Design
Cross-sectional study.

Methods
Questionnaire responses and clinical assessment data were extracted from 38 adult runners (F: 25; M: 13; median age: 25 [range 18-36]) and 91 adolescent runners (F: 56; M: 35; median age: 15 [range 14-16]) who underwent a physical injury prevention evaluation at a hospital-affiliated sports injury prevention center between 2015 and 2021. Participants were sub-grouped into those with (adults: 25; adolescents: 38) and those without (adults: 13; adolescents: 53) a history of self-reported RRIs based on questionnaire responses. Multivariate analyses of covariance (MANCOVA) covarying for gender were conducted to compare outcomes across groups.

Results
Adult runners had lower Functional Movement Screen™ (FMS™) scores (mean differences [MD]: -1.4, p=0.01), were more likely to report intentional weight-loss to improve athletic performance (% difference: 33.0%; p<.001), and more frequently included resistance training into their training routines (% difference: 21.0%, p=0.01) compared to adolescents. Those with a history of RRIs were more likely to report intentional weight-loss compared to uninjured runners (% difference: 21.5; p=0.02) and had shorter single leg bridge durations than those without RRIs (RRI: 35.9±30, uninjured: 72.0±44, p=0.01).

Conclusion
The findings indicate that addressing aspects of biomechanics identified by the FMS™ and behaviors of weight loss as an effort to improve performance may represent targets for the prevention of RRIs for adult and adolescent runners, given the association with history of RRIs.

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Level of Evidence

INTRODUCTION

Runners of all ages and abilities are susceptible to musculoskeletal running-related injuries (RRIs) with average incidence rates ranging between 15-62% across epidemiological studies.1–3 Many RRIs result in time-loss from sport,4,5 and often lead to re-injury throughout athletes’ careers.1,6,7 There are considerable physical and mental health consequences as a result of pausing or stopping running participation due to injury.8–10 These concerns highlight the need to move towards the prevention of RRIs.

There are numerous personal and environmental factors that influence runners’ tissue load tolerance and contribute to the development of RRIs.5,11–13 Running imposes considerable cumulative loads on lower extremity static and dynamic structures, with peak forces reaching approximately two- to three-times a runner’s body weight per step.14 As such, RRIs are often attributed to altered lower extremity alignment,1,15,16 limited range of motion at the foot and ankle,17,18 altered functional movement patterns during fundamental tasks,19,20 and decreased lower extremity muscle strength that inherently limit load attenuation.5,21,22 Furthermore, additional intrinsic dietary considerations relating to relative energy deficiency in sport (RED-S) have been consistently linked with repetitive stress RRIs.23 In conjunction with these personal factors, training errors that predispose the body to abrupt increases in running volume and higher training intensities have been frequently attributed to the risk of developing RRIs.1,3,24,25 The majority of these aforementioned risk factor assessments have been investigated in adult runners.

Youth athletes undergo substantial developmental changes and periods of rapid growth that influence these factors and subsequent responses to environmental stressors.26,27 As such, the risk factors noted among adult runners cannot validly be extrapolated to adolescent runners. While there have been increased efforts to evaluate risk factors for RRIs among adolescent runners,6,27 there are no known studies that have explicitly compared factors between adult and adolescent runners. Specifically a recent youth running consensus statement reflected a dearth in available information on biomechanical factors contributing to RRIs, and highlighted the need to fill in this gap in knowledge.6 Such a comparison would provide clinicians with information on age-related adaptations and insights into specific risk factors for RRIs with which they might hone future injury prevention efforts.

The purpose of this study was to compare anthropometric, training, and wellness factors among adult and adolescent runners with and without a history of lower extremity musculoskeletal RRIs. The primary hypothesis was that there would be significant differences for clinical measures and training volume between age groups due to developmental differences. It was additionally anticipated that lower FMS™ scores, lower strength and muscular endurance, and more weight-loss behaviors among runners with a history of RRIs compared to those without a history of RRIs.

METHODS

This was a cross-sectional study of existing data from adult (>18 years of age) and adolescent (<18 years of age) male and female athletes who underwent an Injury Prevention Evaluation at a hospital-affiliated sports injury prevention center between the years 2015 and 2021 (1,051 athletes total in complete dataset). Participants were included in this analysis if they indicated that their primary sport was cross-country, long-distance running, or track (distance running events only; 800m+), and reported that they either had no lower extremity injury history, or that they had a running-related lower extremity injury. Athletes with non-running-related injuries or incomplete data were excluded from analyses. This study was approved by the hospital’s Institutional Review Board (IRB-P00016162), and informed consent was waived due to the retrospective nature of the study.

INJURY PREVENTION EVALUATION

Injury prevention evaluations (IPEs) are designed to measure potential risk factors for injury, determined by the athletes’ sports, and ultimately develop a prescription for reducing the risk of injury by addressing modifiable risk factors or augmenting training to offset non-modifiable risk factors. IPEs are completed when athletes are uninjured. During an IPE, athletes completed a questionnaire that included demographic variables; sport participation; training volume, intensity, and frequency; inclusion of resistance training into their training regimen; weekday sleep quantity; and intentional weight-loss to improve athletic performance. The questionnaire was generated by a local expert panel of physicians treating adolescent athletes; and questions pertaining to weekday sleep quantity using the validated Patient-Reported Outcomes Information System (PROMIS) Pediatric Daytime Sleepiness Scale,28 and weight-loss using the Food Frequency Questionnaire.29 Participants reported a history of sport-related injuries ever incurred during sport participation and treated by a medical doctor from 25 possible diagnoses (Appendix 1), including which sport they were participating in when they developed the injury. Only injuries incurred during running were included in analyses, and these data were used to group adult and adolescent runners into RRI and uninjured groups.

Following the intake questionnaire, injury prevention specialists (athletic trainers or strength and conditioning specialists with master’s level training in kinesiology) conducted a comprehensive clinical assessment for each athlete. Based on currently available literature and clinical expertise, data was extracted pertaining to quadriceps angle (Q-angle),30 leg length,31 hip abduction strength,21,22,32,35 dorsiflexion range of motion,18,34 single leg bridge duration.
(in seconds), and the FMS™ screen composite score.²⁰,³⁵ Handheld goniometers and dynamometers were used to conduct physical assessments using standard clinical methods.³⁶,³⁷

STATISTICAL ANALYSES

Personal characteristics data were not normally distributed (p<0.05), and, as such, median and interquartile range summary statistics, Mann-Whitney U tests (continuous outcomes), and Chi-square tests (categorical outcomes) were used to compare demographics and anthropometrics by age group (adults, adolescents) and injury history (RRI, uninjured). Questionnaire and physical assessment outcome measures met assumptions for normality, and, therefore, parametric tests were used for statistical analyses. Multivariate analyses of covariance (MANCOVAs) covarying for gender were conducted to compare questionnaire and physical assessment measures across age groups and injury history categories. Alpha was set a priori to 0.05, and Tukey’s post-hoc assessments were conducted in the event of significant group-level differences or interactions.

RESULTS

There were 129 runners that met the inclusion criteria for this study (38 adults [25 RRI, 13 Uninjured], 91 adolescents [38 RRI, 53 Uninjured]) comprising 12.5% of IPE athlete database. (Table 1). The majority of runners participated in track running events (43.4%), and were white (89.9%). Past RRIs self-reported included ankle sprains (49.2%), shin splints (25.4%), lower extremity stress fractures (20.6%), and plantar fasciitis (4.8%). Adult runners had higher BMIs compared to adolescent runners, and a larger proportion of adolescent runners ran cross-country compared to adults (Table 1).

Adult runners more frequently reported intentional weight-loss to improve athletic performance (47% of adults vs. 14% of adolescents; p<0.001; Table 2), and had lower FMS™ composite scores compared to adolescent runners (Mean Difference with Standard Error [MD]: -1.5 [0.6], p=0.02). Similarly, runners with a history of RRIs more frequently reported intentional weight-loss to improve athletic performance (34.9% RRI vs. 13.6% Uninjured, p=0.02), and had lower FMS™ composite scores than uninjured runners (MD: -1.4 [0.5], p=0.01; Table 2).

Adult runners more frequently included resistance training into their training regimens compared to adolescent counterparts (72% of adults vs. 47% of adolescents; p=0.01; Table 2), however, was not significantly different for those with and without RRIs. Regardless of age, runners with a history of RRIs had shorter single leg bridge durations than uninjured runners (MD: -14.1s [8.1s], p=0.01; Table 2).

DISCUSSION

This is the first study that has compared adult and adolescent runners with and without RRIs to determine if there were age-related differences across physical, training, and self-reported factors. The group-level comparisons reflected key differences in weight-loss behaviors and FMS™ scores between adults and adolescents, and between injured and uninjured runners. However, there were no identified age by injury interactions for any of the measures, indicating similar risk factors may contribute to the development of RRIs for adult and adolescent runners. Clinicians may use this information to guide future injury prevention efforts.

CLINICAL ASSESSMENTS

Adolescent and uninjured runners had higher movement quality scores than adult and runners with a history of RRIs, respectively. Previous studies have identified that FMS™ performance scores decrease with age even among physically active adults.³⁵ However, physically active adolescents have better FMS™ scores than physically inactive adolescents, attributed to improved muscular coordination through early sport participation.³⁶ Furthermore, studies show that tactical athletes with FMS™ scores less than 14 are at increased risk of sustaining musculoskeletal injuries.¹⁹,²⁰ This same association has not previously been established in RRIs; however, the current findings indicate that there is an association between lower FMS™ scores and RRIs history overall, but not disproportionately affected by runners’ age.

Contrary to the proposed hypotheses, there were no identified significant differences between age nor injury groups for hip abduction strength or dorsiflexion ROM measures. Previous studies present conflicting findings on lower extremity strength measures in relationship to injury development.²¹,²²,³⁹ The most consistent evidence indicates that gluteal muscle weakness is associated with patellofemoral pain (PFP)¹⁵,²¹,⁴⁰; however, no runners had PFP in our sample. Other assessments, however, have identified inadequate pelvic control, which has been attributed to poor muscular endurance, as a risk factor for injury across lower extremity injury types.³²,⁴¹,⁴² In our study, those with a history of RRIs had significantly decreased single leg bridge duration compared to the uninjured group, supporting the association between impaired neuromuscular control and injury risk. Addressing gluteal endurance among runners might improve pelvic control during sustained activity.⁴³

TRAINING FACTORS

Running training volume and strenuous exercise frequency as a proxy for intensity were similar across age groups and between injured and uninjured groups. This finding may be partially attributed to the timing of the IPE assessment, as those with a history RRIs may have adjusted their training regimens due to injury. Additionally, this study attempted to measure a different facet of training volume.
Table 1. Comparison of adult and adolescent runners with and without running-related injuries.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Adult Runners</th>
<th>Adolescent Runners</th>
<th>p-value (age groups)</th>
<th>p-value (injury status)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>F: 9, M:4, IQR: 21 (18, 24)</td>
<td>F: 16, M:9, IQR: 22 (18, 23)</td>
<td>0.33</td>
<td>0.72</td>
</tr>
<tr>
<td>Age (years)</td>
<td>24 (21, 43)</td>
<td>21 (18, 33)</td>
<td>15 (13, 15)</td>
<td>15 (14, 16)</td>
</tr>
<tr>
<td>Race</td>
<td>White: N=11, Black: N=1, Prefer not to answer: N=1</td>
<td>White: N=46, Black: N=2, Asian: N=2, Native Hawaiian or Other Pacific Islander: N=1, Prefer not to answer: N=1</td>
<td>&lt;0.001*</td>
<td>0.13</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.7 (19.9, 24.8)</td>
<td>23.8 (22.5, 26.0)</td>
<td>20.0 (18.3, 22.3)</td>
<td>19.8 (18.6, 21.6)</td>
</tr>
<tr>
<td>Leg Length Discrepancy (cm)</td>
<td>0.19 (0.50)</td>
<td>0.26 (0.50)</td>
<td>0.26 (0.50)</td>
<td>0.28 (0.50)</td>
</tr>
<tr>
<td>Q-Angle (°)</td>
<td>10 (8, 13)</td>
<td>11 (10, 14)</td>
<td>10.5 (10, 14)</td>
<td>10.5 (9, 12)</td>
</tr>
<tr>
<td>Primary Running Sport</td>
<td>Cross-Country: N=6, Track: N=4, Long-Distance Running: N=12</td>
<td>Cross-Country: N=15, Track: N=7, Long-Distance Running: N=7</td>
<td>&lt;0.001*</td>
<td>0.38</td>
</tr>
<tr>
<td>RRI History</td>
<td>Ankle Sprains: N=15, Shin Splints: N=4, Stress Fractures: N=3</td>
<td>Ankle Sprains: N=16, Shin Splints: N=12, Stress Fractures: N=9, Plantar Fasciitis: N=0</td>
<td>0.67</td>
<td>0.001*</td>
</tr>
</tbody>
</table>

Abbreviations: IQR, interquartile range; BMI, body mass index; Q-angle, quadriceps angle.
*Signifies statistically significant difference at p<0.05

Beyond weekly mileage, as distance often overlooks the quality and time under tension associated with an individual run. However, previous studies comparing young and middle-aged adult runners have identified that older age compounded with higher weekly mileage resulted in altered lower extremity joint kinetics. There is also limited evidence to suggest that higher weekly mileage is a risk factor for RRI among male adolescent runners during pre-season training. These past associations suggest there may be a benefit to assessing weekly mileage in relationship to RRI development across age groups; however, the present findings do not support that training time and strenuous exercise frequency differ across age groups or between those with a history of RRI and those without.

Adult runners in this sample were more likely to include resistance training into their exercise plans. Skeletal muscle mass peaks between 20 to 40 years of age and then gradually declines, emphasizing the importance of incorporating early strengthening to capitalize on the body’s neuromuscular potential. While there was not an association between strength training and RRI, there are additional known benefits of incorporating strength training beyond the context of injury development. Strengthening has been shown to improve running economy beyond other forms of cross-training in adult populations. Additionally, resistance training leads to muscle tissue remodeling to improve strength and load capacity contributing to performance. The present findings that adolescents less frequently incorporate strengthening into their training regimens underscore the need to educate adolescent runners on the known physiological benefits of resistance training.

**WELLNESS MEASURES**

Intentional weight-loss to improve athletic performance was more common among adult runners than adolescent runners. This outcome was anticipated given that metabolism declines with age, exemplified in the included participants’ BMI characteristics. Adolescents are inherently involved in more structured activities through physical ed-
Table 2. Comparison of adult and adolescent runners with and without running-related injuries.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Adult Runners</th>
<th>Adolescent Runners</th>
<th>p-value (age groups)</th>
<th>p-value (injury status)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uninjured (N=13)</td>
<td>RRI (N=25)</td>
<td>Uninjured (N=53)</td>
<td>RRI (N=38)</td>
</tr>
<tr>
<td>Total Hours of Running Per Week (hours)</td>
<td>9.6 ± 8.8</td>
<td>11.1 ± 9.5</td>
<td>9.6 ± 8.8</td>
<td>13.3 ± 10.8</td>
</tr>
<tr>
<td>Strenuous Exercise Frequency (times/week)</td>
<td>3.2 ± 2.6</td>
<td>3.2 ± 2.2</td>
<td>2.8 ± 2.2</td>
<td>3.2 ± 2.6</td>
</tr>
<tr>
<td>Inclusion of Weight Training</td>
<td>Yes: 76% No: 24%</td>
<td>Yes: 69% No: 31%</td>
<td>Yes: 55% No: 45%</td>
<td>Yes: 37% No: 63%</td>
</tr>
<tr>
<td>Hours of Weekday Sleep (hours)</td>
<td>7.5 ± 1.1</td>
<td>7.6 ± 1.0</td>
<td>7.8 ± 1.1</td>
<td>7.5 ± 1.1</td>
</tr>
<tr>
<td>Intentional Weight-Loss</td>
<td>Yes: 31% No: 69%</td>
<td>Yes: 56% No: 44%</td>
<td>Yes: 9% No: 91%</td>
<td>Yes: 21% No: 79%</td>
</tr>
<tr>
<td>Dorsiflexion ROM (°)</td>
<td>-0.4 ± 9.9</td>
<td>2.2 ± 10.1</td>
<td>1.61 ± 9.7</td>
<td>-0.38 ± 9.9</td>
</tr>
<tr>
<td>Hip Abduction Strength (Nm/kg)</td>
<td>118 ± 33</td>
<td>112 ± 32</td>
<td>120 ± 30</td>
<td>112 ± 28</td>
</tr>
<tr>
<td>Single Leg Bridge Duration (s)</td>
<td>76.0 ± 50.0</td>
<td>58.0 ± 31.0</td>
<td>68.0 ± 39.6</td>
<td>57.7 ± 30.5</td>
</tr>
<tr>
<td>FMS™ Composite Score</td>
<td>14 ± 3</td>
<td>11 ± 3</td>
<td>14 ± 3</td>
<td>13 ± 3</td>
</tr>
</tbody>
</table>

Abbreviations: RRI, running-related injury; ROM, range of motion; FMS™, Functional Movement Screen™.
*signifies statistically significant difference at p<0.05.

Education programs in schools designed to combat adolescent weight gain which reduces the need to engage in intentional weight loss behaviors. Adolescents additionally require increased caloric intake to support adequate growth and maturation. However, athletes that reported intentional weight-loss behaviors were more likely to report a history of RRs regardless of age. Disordered eating and caloric restriction associated with RED-S for male and female athletes alike have been identified as independent risk factors for bone stress injuries. Bone mineral density is lowest prior to peak growth velocity and steadily declines with age, especially with insufficient nutrition. Sufficient dietary intake is essential for neuromuscular recovery from exercise, and, as such, restricted fueling associated with intentional weight-loss strategies has important implications for risk of developing RRs.

**Future Directions**

The current assessment identified key age-related changes associated with personal and environmental factors, yet this study found that age groups were similar in terms of risk factors for developing RRs. While this hypothesis-generating study is an important preliminary step to expounding differences between adolescent and adult runners, future work should focus on additional running-specific factors as they compare across age groups and risk of RRs. Furthermore, prospective studies in larger samples including other prevalent RRs, such as PFP, are warranted. There is a robust body of literature exploring the effects of aging on running biomechanical characteristics. While previous work has found age-related biomechanical changes among middle-aged and master’s level runners (ages 65+) compared to younger adults, it is necessary to expand these examinations across the age spectrum.

**Limitations**

As this was a cross-sectional study, causation was not able to be established. This adult running sample was relatively small and consisted of younger adult runners, limiting extrapolation to the greater adult running community. This population of runners self-reported only select RRs, thus, our findings may not necessarily translate to other RRI diagnoses. Finally, this sample was predominately white and consisted of runners undergoing an injury prevention evaluation in a small geographic area, and as such the findings should be interpreted in the context of these limitations.
CONCLUSION

Intentional weight-loss for the purposes of improving athletic performance and lower FMS™ scores were each associated with a history of running related injury for both adult and adolescent runners, suggesting these risk factors are important across age groups. As such, these factors may represent targets for the prevention of adult and adolescent RRIs.

FUNDING SOURCES

None.

ACKNOWLEDGEMENTS

We would like to thank Dr. Adam Tenforde for providing feedback and input during manuscript preparation.

CONFLICTS OF INTEREST

Dr. Meehan receives royalties from 1) ABC-Clio publishing for the sale of his books, Kids, Sports, and Concussion: A guide for coaches and parents, and Concussions; 2) Springer International for the book Head and Neck Injuries in Young Athlete and 3) Wolters Kluver for working as an author for UpToDate. His research is funded, in part, by philanthropic support from the National Hockey League Alumni Association through the Corey C. Griffin Pro-Am Tournament and a grant from the National Football League. Dr. DeJong Lempke is an Associated Personnel with Boston Children’s Hospital, and continues to collaborate on studies at this institution. She has pending grant funding from VALD Performance for a separate project.

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REFERENCES


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Appendix 1

Exploring the Effects of a Neck Strengthening Program on Purposeful Soccer Heading Biomechanics and Neurocognition

Katelyn M. Waring, Edward R Smith, Gary P Austin, Thomas G Bowman

Keywords: CNS vital signs, concussion prevention, cervical strength

International Journal of Sports Physical Therapy

Background

Cervical (neck) strengthening has been proposed as an important factor in concussion prevention. The purpose of the study was to determine if a six-week cervical strengthening program affected neurocognition and purposeful soccer heading biomechanics. The hypothesis was that the neck strengthening program would improve strength, maintain neurocognition, and alter purposeful soccer heading biomechanics.

Study Design

Randomized controlled trial.

Methods

Twenty collegiate soccer athletes (8 males, 12 females, age=20.15±1.35 years, height=171.67±9.01 cm, mass=70.56±11.03 kg) volunteered to participate. Time (pre, post) and group (experimental, control) served as the independent variables. Four composite scores from the CNS Vital Signs computer based neurocognitive test (CNSVS; verbal memory, visual memory, executive function, reaction time) and aspects of heading biomechanics from inertial measurement units (xPatch; peak linear acceleration, peak rotational acceleration, duration, Gadd Severity Index [GSI]) served as the dependent variables. Each athlete completed a baseline measure of neck strength (anterior neck flexors, bilateral anterolateral neck flexors, bilateral cervical rotators) and CNSVS after heading 10 soccer balls at two speeds (11.18 and 17.88 m/s) while wearing the xPatch. The experimental group completed specific cervical neck strengthening exercises twice a week for six weeks using a Shingo Imara™ cervical neck resistance apparatus while the control group did not. After six weeks, the participants completed the same heading protocol followed by measurement of the same outcome variables. The alpha value was set to p<0.05 a priori.

Results

The interaction between time and group was significant for visual memory (F1, 17=5.16, p=0.04, η²=0.23). Interestingly, post hoc results revealed visual memory decreased for the control group from pretest (46.90±4.46) compared to posttest (45.00±4.03; mean difference=5.90, 95% CI=0.77-7.03, p=0.02). Interactions for all other dependent variables were not statistically significant (p>0.05).

Conclusions

The cervical neck strengthening protocol allowed maintenance of visual memory scores but did not alter other neurocognitive measures or heading biomechanics. The link
between cervical neck strengthening and concussion predisposition should continue to be explored.

**Level of Evidence**

**Level 1b**

**INTRODUCTION**

In sports across the globe, some of the most investigated injuries are those related to the head. Most people associate concussions and head-related injuries with American football. However, a study using the National Collegiate Athletic Association Injury Surveillance System found that 8.6% of injuries to women's soccer athletes were concussions as well as 5.8% of injuries in men's soccer athletes.\(^1\) In fact, this number is potentially much larger considering more than 50% of concussions go unreported.\(^2\)–\(^6\) Therefore, the number of concussions reported during soccer activity is likely a conservative measure of incidence.

In addition to concern over concussion in sport, repetitive head impacts without immediate clinical manifestation may cause long term consequences including negative brain health.\(^7\)–\(^13\) On average, players head the ball six to 12 times in a competitive soccer match where the ball could travel over 22 m/s in amateur games.\(^14\) Since soccer is the world's most popular sport and includes more than 265 million players worldwide, soccer heading is a common cause for repetitive head impacts.\(^15\) However, the relationship between subconcussive heading and brain injury remains poorly understood.\(^16\)–\(^18\) There have been multiple studies where researchers have found cognitive dysfunction or negative brain alterations after purposeful heading.\(^2\)–\(^6\),\(^10\),\(^13\) However, another study has shown that there is no detrimental relationship between the number of purposeful headers and neurocognitive measures.\(^10\) Therefore, it remains unknown how repetitive head impacts may affect long term brain health.

Since head impact magnitude has been linked to injury predisposition,\(^19\) it is important to understand how to mitigate the energy received when the head is impacted during soccer participation. Purposeful heading includes repetitive low-level impacts and the magnitude transferred to the head can depend on many factors. Of these factors, neck strength is one that has received considerable recent attention in the literature. A correlation has been shown between neck strength and head impact kinematics where individuals with higher neck strength measurements had lower head accelerations upon impact.\(^20\)–\(^22\) Weaker mean overall neck strength was significantly associated with concussion and that for every pound of neck strength that athletes gain, their chances of a concussion decreases by five percent.\(^20\) Therefore, the current study investigated a way to minimize head accelerations by testing one possible intervention. The purpose of the study was to determine if a six-week cervical strengthening program affected strength, neurocognition, and purposeful soccer heading biomechanics. The following research questions underpinned the purpose: (1) Would a six-week neck strengthening program improve neck strength in soccer players?, (2) What effect would a six-week neck strengthening program have on head impact biomechanics during purposeful soccer ball heading?, and (3) What effect would a six-week neck strengthening program have on neurocognitive outcomes after a bout of purposeful soccer ball heading? The hypothesis was that the strengthening program would increase neck strength which would in turn decrease the impact magnitude the head experiences upon purposeful heading and maintain or improve (learning effect) players’ neurocognition after purposeful heading.

**METHODS**

**PARTICIPANTS**

A total of 20 varsity collegiate soccer players participated in this study (12 female, 8 males, age = 20.15±1.35 years, height = 171.67±9.01 cm, mass = 70.56±11.05 kg). Each participant was over the age of 18 and signed a consent form approved by the host institution’s human subjects review board. The participants also played a variety of positions such as forward (N=4), midfielder (N=8), defender (N=5) and goalie (N=3). A breakdown of demographics between the two groups can be found in Table 1.

**PROCEDURES**

Prior to beginning data collection, the Institutional Review Board at the University of Lynchburg approved the study. All men’s and women’s soccer athletes at one institution sponsoring National Collegiate Athletic Association Division III athletics were sent an email that provided information on the study and were asked to respond if they were interested in participating. To begin the study, participants signed the informed consent form to be made aware of all the risks and benefits of the study. Next, the participants’ height, mass, neck girth, and neck segment length were measured. Participants’ height was measured in centimeters (cm) with a stadiometer (Seca Model 222, Hamburg Germany) and mass was measured in kilograms (kg) using a scale (Tanita BWB-800 Tokyo, Japan). While the participants were sitting straight and looking at an object at eye level, the head-neck segment length and neck girth was measured in cm with a metric tape measure. The participants’ head-neck segment lengths were measured in a straight line using a tape measure from the seventh cervical vertebrae to the most superior region of the head observed in the frontal plane.\(^23\) The participants’ neck girth was measured just above the thyroid cartilage.\(^24\)

After anthropometrics were recorded, half of the male and half of the female athletes were randomly selected for the experimental group while the other half served as the control group. A random number generator was used to determine group membership, and the researcher who col-
lected all data was blinded to group membership. Before completing the baseline tests, the athletes participated in a neck warm up to reduce the possibility of injury. The neck warm up consisted of neck rotations (15 seconds (s) clockwise and 15 s counterclockwise) and neck stretching (two repetitions each of 15 s for flexion and extension). Each athlete completed a series of neck stress tests, purposeful heading biomechanics tests, and a battery of cognitive tests to serve as baselines for a comparison later in the study. The experimental group followed a neck strengthening program for six weeks as part of the normal strength and conditioning program, and the control group did not perform neck strengthening exercises. However, both groups participated in the same soccer specific strength and conditioning program as prescribed by the team Certified Strength and Conditioning Specialist. After the six weeks of neck strength training, the participants completed the same series of neck strength tests, purposeful heading biomechanics tests, and battery of cognitive tests to compare to the baseline testing results.

NECK STRENGTH TESTING

One research team member measured neck strength as described by Kendall et al. with an isometric dynamometer (MicroFET®2 Digital Handheld Dynamometer, Hogan Scientific, Salt Lake City, UT). Using an isometric dynamometer has been found to be a reliable and valid measure of cervical muscle strength in a seated position. However, strength was measured in a supine or prone position as described by Kendall et al. Strength measurements of the anterior neck flexors (Figure 1A); in supine the participants attempted to lift the head straight up, bilateral anterolateral neck flexors (Figure 1B); in supine the participants attempted to lift the head with the head turned completely in one direction/the other direction), bilateral cervical rotators (Figure 1C); in supine the participants turned the head to the left/right), and bilateral posterolateral neck extensors (Figure 1D; in prone participants raised their heads with their head completely turned to left/right) were recorded. In order to familiarize the participants with the testing method, they completed two practice trials followed by three recorded trials for each direction of motion. Participants rested for 30 seconds between each trial and each trial lasted for three seconds. The mean for each position was calculated based on the three trials and used for analysis.

| Table 1. Demographic information across experimental and control groups. |
|---------------------------------|-------------------|-----------------|
| **Age**                        | **Experimental** | **Control** |
| **Height**                     | 20.57±1.13       | 19.44±1.42     | p=0.04, Cohen's d=1.03 |
| **Mass**                       | 177.43±7.79      | 169.00±8.56    | p=0.13, Cohen's d=0.79 |
| **Neck Girth**                 | 75.94±11.44      | 66.23±9.93     | p=0.09, Cohen's d=0.92 |
| **Neck Length**                | 37.50±2.78       | 34.06±2.79     | p=0.03, Cohen's d=1.14 |
| **Comparison**                 |                  |                | p=0.14, Cohen's d=0.77 |

**Figure 1.** Positions for neck stress measurements: anterior neck flexors (A), bilateral anterolateral neck flexors (B), bilateral cervical rotators (C), bilateral posterolateral neck extensor (D)

PURPOSEFUL HEADING BIOMECHANICS TESTING

A JUGS soccer machine (JUGS Inc., Tualatin, OR) was used to simulate a kick that soccer players would be most likely to head in a game or practice. The speed of the ball coming out of the machine was adjusted to two different speeds to simulate low and high velocities of balls that players head during games or practices. A size 5 soccer ball pumped to 5,624.55 kgf/m² was dispensed out of the JUGS machine 35 m away from participants at 11.18 and 17.88 m/s as described in a previous study. Each participant received five balls at each speed with a one-minute rest between balls. The participants were assigned a numbered inertial measurement unit (xPatch sensor, X2 Biosystems, Seattle, WA) that they wore while heading the 10 soccer balls. The sensor was applied over the right mastoid process with an adhesive patch. The xPatch sensor was used to measure the magnitude of the impact of the ball on the head in peak linear acceleration (PLA; g) and peak rotational acceleration (PRA; deg/s²), common metrics used to characterize head impact biomechanics as they are thought to be related to injury risk. The xPatch sensor also provided impact duration (time the ball and head made contact), and Gadd Severity Index (GSI). Higher durations would result in greater force transmission which may have clinical implications leading to the inclusion of duration as a dependent variable. The GSI scores provided information regarding the likelihood of an impact causing catastrophic head
injury. Although the xPatch has been shown to overestimate head impact magnitude, it serves to facilitate frequency and magnitude comparisons between groups when all of the participants wear the sensors which was the case in the current study. Head mounted sensors like the xPatch have been found to provide an accurate detection of the peak angular acceleration when compared to other helmet mounted systems. Once the purposeful heading biomechanics test was completed, the sensor was removed, placed back on the charging dock, and the data were downloaded using a laptop computer (Apple Inc, Macbook Air, Cupertino, California).

COGNITIVE TESTING

After participants finished the purposeful heading biomechanics test, they completed the CNS Vital Signs (CNSVS) computer based cognitive test. The test was used to establish the participants’ neurocognitive performance and symptom load. The CNSVS provided data regarding the participant’s verbal memory, visual memory, executive function, reaction time, and symptom severity scores. Higher values indicate better performance for verbal memory, visual memory, and executive function. Lower reaction time scores indicate superior performance and higher symptom severity scores indicate more symptoms. Age adjusted standard scores for verbal memory, visual memory, and executive function were used while reaction time was measured in milliseconds. Symptom severity scores (range=0-144) summed the individual symptom scores on a 0-6 scale (0=none at all, 1-2=mild, 3-4=moderate, 5-6 severe). Scores were reported in the CNSVS detailed test result reports. CNSVS has been found to have reasonable test-retest reliability previously in broad populations.

NECK STRENGTHENING PROTOCOL

After the baseline testing was complete, the participants in the experimental group participated in a six-week neck strengthening program (three times per week) created by a Certified Strength and Conditioning Specialist. The Shingo Imara™ (Shingo Imara, Ann Arbor, Michigan) was used to provide resistance during neck strengthening exercises. The participants completed the number of repetitions and sets represented in Table 2 for each of four exercises, resisted cervical flexion, extension, and lateral flexion on both sides from a seated position (Figure 2).

A Certified Strength and Conditioning Specialist monitored all exercise prescription, progression, and strength training sessions. The exercises were chosen because they were thought to target the neck muscles most utilized for purposeful heading.

STATISTICAL ANALYSIS

The data were collected and organized in an Excel (2013 version, Microsoft Inc., Redmond, WA) spreadsheet for further analysis. In this study there were two independent variables, group (experimental and control, between factor) and time (pre and post, within factor). The dependent vari-ables were neck strengthening measurements for each direction; PLA, PRA, duration, and GSI for heading biomechanics at each of the two speeds; and verbal memory, visual memory, executive function, reaction time, and symptom severity scores from the cognitive testing. Therefore, a 2x2 mixed model ANOVA was used to analyze the data from each dependent variable separately in SPSS (Version 26, IBM, Inc, Armonk, NY). Partial eta squared ($\eta^2_p$) was calculated as an effect size for the interactions and Cohen’s d as an effect size for post hoc tests. Results were interpreted with $\eta^2_p$=0.01 indicating a small effect, $\eta^2_p$=0.06 indicating a medium effect and $\eta^2_p$=0.14 indicating a large effect while Cohen’s d was interpreted as d=0.2 as small, d=0.5 as medium, and d=0.8 as large. The alpha value was set to p<0.05 a priori and Bonferroni post hoc tests were used to determine where significant pairwise differences existed for significant interactions.

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Repetitions</th>
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</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Week 2</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>Week 3</td>
<td>1</td>
<td>15</td>
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<tr>
<td>Week 4</td>
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<td>10</td>
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<tr>
<td>Week 5</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Week 6</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 2. Strength training prescription during the six-week protocol

Figure 2. Example of cervical extension strengthening exercise using the Shingo Imara (Shingo Imara, Ann Arbor, Michigan)
RESULTS

NECK STRENGTH

Means and standard deviations for strength testing dependent variables can be found in Table 3. The interaction between time and group was significant for anterior strength (F\(_{1,17}=41.78, p=0.04, \eta^2_p=0.22\)), right anterolateral strength (F\(_{1,17}=4.80, p=0.04, \eta^2_p=0.22\)), and left anterolateral strength (F\(_{1,17}=6.48, p=0.02, \eta^2_p=0.28\)) strength measurements. Post hoc tests showed strength improved pre- to post-intervention measures in the anterior direction for both the strengthening (p<0.001) and control (p=0.02) groups, but only for the strengthening group for right anterolateral strength (p=0.001) and left anterolateral (p=0.001) directions. The interaction between time and group was not significant for right rotation (F\(_{1,17}=2.12, p=0.16, \eta^2_p=0.11, 1-\beta=0.28\)), left rotation (F\(_{1,17}=3.20, p=0.09, \eta^2_p=0.16, 1-\beta=0.39\)), right posterolateral (F\(_{1,17}=2.98, p=0.10, \eta^2_p=0.15, 1-\beta=0.57\)), or left posterolateral (F\(_{1,17}=2.86, p=0.10, \eta^2_p=0.14, 1-\beta=0.56\)) strength measurements.

PURPOSEFUL HEADING BIOMECHANICS

Means and standard deviations for head biomechanics dependent variables can be found in Table 4. There was no interaction present between group and time for PLA at 11.18 m/s (F\(_{1,11}=0.66, p=0.45, \eta^2_p=0.06, 1-\beta=0.12\)) or PLA at 17.88 m/s (F\(_{1,11}=0.98, p=0.34, \eta^2_p=0.08, 1-\beta=0.15\)). There was also no interaction present between group and time for PRA at 11.18 m/s (F\(_{1,11}=0.003, p=0.96, \eta^2_p=0.01, 1-\beta=0.05\)) or for PRA at 17.88 m/s (F\(_{1,11}=0.002, p=0.97, \eta^2_p=0.001, 1-\beta=0.05\)). There was no interaction present between group and time for head impact duration at 11.18 m/s (F\(_{1,11}=0.41, p=0.53, \eta^2_p=0.04, 1-\beta=0.09\)) or at 17.88 m/s (F\(_{1,11}=0.08, p=0.79, \eta^2_p=0.01, 1-\beta=0.06\)). Finally, there was no interaction present between group and time for GSI at 11.18 m/s (F\(_{1,1}=1.03, p=0.33, \eta^2_p=0.09, 1-\beta=0.15\)) or at 17.88 m/s (F\(_{1,10}=0.55, p=0.48, \eta^2_p=0.05, 1-\beta=0.10\)).

COGNITIVE TEST

Mean values and standard deviations for cognitive dependent variables can be found in Table 5. When determining the effects on neurocognition and symptoms, the interaction between time and group was significant for visual memory (F\(_{1,17}=5.16, p=0.04, \eta^2_p=0.25\)). Interestingly, post hoc results revealed visual memory decreased for the control group from pretest (46.90±4.46) compared to posttest (43.00±4.03; mean difference=3.90, 95% CI=0.77-7.03, p=0.02, Cohen’s d=0.92). The interaction between time and group was not significant for verbal memory (F\(_{1,17}=0.01, p=0.91, \eta^2_p=0.001, 1-\beta=0.05\)), executive function (F\(_{1,17}=0.71, p=0.41, \eta^2_p=0.04, 1-\beta=0.15\)), reaction time (F\(_{1,17}=1.05, p=0.32, \eta^2_p=0.06, 1-\beta=0.16\)), or symptom severity score (F\(_{1,17}=2.40, p=0.14, \eta^2_p=0.12, 1-\beta=0.51\).
Table 4. Mean and standard deviations for heading biomechanics dependent variables

<table>
<thead>
<tr>
<th></th>
<th>Strengthening Group</th>
<th>Control Group</th>
<th>Interaction</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>PLA at 11.18 m/s</td>
<td>22.70±2.11</td>
<td>20.01±1.59</td>
<td>22.10±2.72</td>
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<td></td>
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<tr>
<td>PRA at 11.18 m/s</td>
<td>4456.20±916.54</td>
<td>3547.10±835.10</td>
<td>5027.84±793.66</td>
</tr>
<tr>
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<tr>
<td>GSI at 11.18 m/s</td>
<td>10.35±0.99</td>
<td>8.78±1.28</td>
<td>11.50±3.22</td>
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<tr>
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<tr>
<td>PLA at 17.88 m/s</td>
<td>24.78±5.08</td>
<td>16.88±3.23</td>
<td>26.30±8.59</td>
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<tr>
<td>PRA at 17.88 m/s</td>
<td>30.84±4.45</td>
<td>22.83±3.29</td>
<td>25.24±1.45</td>
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<tr>
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<tr>
<td>GSI at 17.88 m/s</td>
<td>11.34±1.38</td>
<td>8.91±2.05</td>
<td>12.02±2.56</td>
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PLA=peak linear acceleration, PRA=peak rotational acceleration, GSI=Gadd Severity Index

Table 5. Mean values and standard deviations for cognitive dependent variables

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<tr>
<th></th>
<th>Strengthening Group</th>
<th>Control Group</th>
<th>Interaction</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
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<tr>
<td>Visual Memory</td>
<td>46.67±4.77</td>
<td>47.67±4.90</td>
<td>46.89±4.73</td>
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<tr>
<td></td>
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<tr>
<td>Verbal Memory</td>
<td>51.00±4.69</td>
<td>49.00±5.41</td>
<td>51.56±4.64</td>
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<td></td>
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<tr>
<td>Executive Function</td>
<td>53.78±8.06</td>
<td>48.44±10.92</td>
<td>51.67±8.76</td>
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<tr>
<td></td>
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<tr>
<td>Reaction Time</td>
<td>598.67±48.61</td>
<td>638.56±45.20</td>
<td>630.00±73.40</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Symptom Severity Score</td>
<td>9.22±12.03</td>
<td>4.56±6.23</td>
<td>7.44±7.32</td>
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International Journal of Sports Physical Therapy
injury prevention remains not fully understood. Details regarding the findings related to the three purposes are provided in the sections below.

PURPOSEFUL HEADING BIOMECHANICS

Similar to the current findings, Mihalik et al.34 also found that increasing neck strength failed to lead to lower linear and rotational accelerations of the head during impact. We also reported small to medium effect sizes suggesting limited clinical meaningfulness. It remains unknown why the increases in cervical strength observed failed to alter head impact biomechanics. Although neck musculature activity while performing the purposeful heading trials was not measured, the head impacts were anticipated by the participants as they knew the ball was coming toward them in both groups (experimental and control). Perhaps deep neck stability exercises would provide different results.

Others have shown that there is a correlation between neck strength and head impact kinematics where individuals with higher neck strength measurements had lower head accelerations upon impact.20–22 Weaker mean overall neck strength has been significantly associated with concussion and for every pound of neck strength that athletes gain, their chances of a concussion decreases by five percent.20 Lamond et al.35 found that anticipated headers, such as the ones in the current study, had lower linear and rotational head accelerations than unanticipated deflections or hits. Despite whether they were anticipated or not, head impacts to the front of the head, the maneuver used in the current study, have been found to create linear and rotational accelerations that were well below those associated with traumatic brain injury.35 The magnitudes in the current study align similarly with the literature for similar impact types.35

COGNITIVE TEST

Kaminski et al.17 used a test similar to CNSVS called Automated Neuropsychological Assessment Metrics (ANAM) to evaluate youth soccer players’ neurocognition after purposeful soccer heading over a season and found that there was little to no relationship between heading and measures of neurocognitive performance. In another study by Kaminski et al.,18 collegiate and varsity high school women’s soccer athletes had their cognitive function and balance evaluated before and after the course of a season while heading frequency was recorded. The study used the two-part Wechsler Digit Span test to determine cognitive function which included two of the same neurocognitive sections as the testing used in the current study, visual memory and verbal memory.18 Their results showed that there were no statistically significant changes in cognitive function or in balance. The researchers in these two studies did not determine if neck strength played a role in neurocognitive performance, but findings did show that repetitive heading showed no change in neurocognitive performance. However, one study found cognitive and vestibular impairment immediately following a bout of 20 purposeful headers within three minutes.36 The current findings suggest maintenance of visual memory (statistically significant differences and large effect size) for the neck strengthening group but no effect of group on verbal memory, executive function, or reaction time (no statistically significant differences and small effect sizes) immediately after 10 purposeful headers with longer rest periods between headers. On average, participants’ visual memory scores decreased by 3.90 (95% CI=0.77-7.03) points in the control group. However, these decreases are within one standard deviation of normative data and would be unlikely to flag a patient as impaired.30 Symptom severity score also did not change despite a medium to large effect size. The symptom severity score was included although it is not a measure of cognition because it is often used as part of concussion examination, either as part of the SCAT5 or computer-based neurocognitive testing.37

LIMITATIONS AND FUTURE DIRECTIONS

The results could be explained by many different factors, but there are some that could be addressed and modified in future research. The goal was to observe the effect of strengthening exercises for the neck on heading biomechanics and neurocognition from pre- to posttest. However, the protocol to strengthen the participants’ necks only strengthened the subjects’ necks in the anterior left and right anterolateral directions. In the future, researchers may obtain different results if the strengthening exercises are selected to attempt to strengthen all directions of the neck. Neck strength was measured in either a supine or prone position as described previously.25 However, reliability and a validity of strength measures has only been measured in a seated position,26 and cannot be assumed for measurements taken in supine or prone positions. Also Lamond et al.35 found that unanticipated heading resulted in larger linear and rotational accelerations of the head than anticipated heading. It would be interesting to study the effects of neck strengthening during unanticipated head impacts as they are likely more concerning since they deliver higher accelerations to the head. Finally, neck muscle activation timing was not tested during purposeful heading impacts. Future research should determine if the timing of muscle activation is an important consideration with regards to reducing impact magnitude during purposeful heading.

CONCLUSION

The strengthening program the participants completed resulted in statistically significant improvements in anterior and anterolateral neck strength, but not in rotation or posterolateral strength. The neck strengthening protocol did not affect heading biomechanics of the collegiate soccer athletes in this study. Improving strength in the two anterior directions allowed maintenance of visual memory scores but did not alter other neurocognitive measures following repetitive soccer heading. More research should be completed to determine the role neck strength plays in reducing head injury risk.
CONFLICT OF INTEREST
The authors have no conflicts to disclose.

ACKNOWLEDGMENTS
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Original Research

Relationships between Running Biomechanics, Hip Muscle Strength, and Running-Related Injury in Female Collegiate Cross-country Runners

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Keywords: running-related injuries, running kinematics, hip abductor muscle performance, injury risk, cross-country, female collegiate runners

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Background
Female collegiate cross-country (XC) runners have a high incidence of running-related injury (RRI). Limited reports are available that have examined potential intrinsic factors that may increase RRI risk in this population.

Purpose
To examine the relationships between RRI, hip muscle strength, and lower extremity running kinematics in female collegiate XC runners.

Study Design
Prospective observational cohort.

Methods
Participants included twenty female NCAA collegiate XC runners from Southern California universities who competed in the 2019–20 intercollegiate season. A pre-season questionnaire was used to gather demographic information. Hip muscle strength was measured with isokinetic dynamometry in a sidelying open-chain position and normalized by the runner’s body weight (kg). Running kinematic variables were examined using Qualisys 3D Motion Capture and Visual 3D analysis. RRI occurrence was obtained via post-season questionnaires. Independent t-tests were used to determine mean differences between injured and non-injured runners for hip abductor muscle strength and selected running kinematics. Pearson correlation coefficients were calculated to examine relationships between hip muscle performance and kinematic variables.

Results
End-of-the-season RRI information was gathered from 19 of the 20 participants. During the 2019–20 XC season, 57.9% (11 of 19) of the runners sustained an RRI. There were no significant differences between mean hip abductor normalized muscle strength (p=0.76) or mean normalized hip muscle strength asymmetry (p=0.18) of injured and non-injured runners during the XC season. Similarly, no significant differences were found between mean values of selected kinematic variables of runners who did and who did not report an RRI. Moderate relationships were found between hip abductor strength variables and right knee adduction at footstrike (r=0.50), maximum right knee adduction during stance...
CONCLUSIONS

Hip abduction muscle strength, hip abduction strength asymmetry, and selected running kinematic variables were not associated with elevated risk of RRI in female collegiate XC runners.

Level of Evidence

2.

INTRODUCTION

In 2018-2019, 15,624 female athletes participated on NCAA cross-country (XC) teams.1 Although XC is a non-contact sport, female collegiate runners had a high risk of incurring a running-related injury (RRI) with an RRI rate of 5.85/1000 athletic encounters (AEs), which was 25% greater than their male counterparts.2 More importantly, female collegiate XC runners experienced the highest rate of stress fracture of all collegiate sports in the United States.3 RRRs have serious and sometimes long-term consequences for female collegiate XC runners. According to a 2010 study, 13.1% of RRRs in female collegiate XC runners resulted in greater than three weeks of lost training and competing time.2 These RRRs may jeopardize competitive seasons, can result in a reduction or retraction of an athlete’s scholarship award, and may also negatively influence the runner’s mental health and quality of life.4 RRRs may also increase risk of osteoarthritis and decreased sport participation, which can lead to adverse health outcomes associated with decreased physical activity.5 Thus, identifying factors that may heighten the risk of RRI is necessary to help prevent RRRs at this sport level.

Limited evidence is available on risk factors for RRI in female collegiate XC runners. The few studies that have prospectively examined risk factors for RRI in male and female collegiate XC runners have linked RRI to female athlete triad risk factors, hip abduction strength, pre-season injury, large mileage increases, poor sleep quality, and several biomechanical running factors.6-8

Impaired hip abductor performance contributes to contralateral pelvic drop during gait and has been directly related to instability of the lower kinetic chain.8 In the collegiate population, authors have found associations between hip abductor strength and medial tibial stress syndrome8 and iliotibial band syndrome (ITBS).9 As these studies combined the data for male and female runners, there are no known studies that have reported examining the link between hip abductor strength and RRI specific to female collegiate cross-country runners.

Only a few prospective studies have investigated biomechanical risk factors and risk of RRI in collegiate XC runners. Increased contralateral hip drop and increased vertical excursion of center of mass have been associated with increased odds of future RRI8,10 Kliethermes et al.10 also observed an association between decreased step rate (SR) and increased likelihood of bone-stress injury.

The objective of this study was to examine the relationship between RRI, hip muscle strength, and lower extremity running kinematics in female collegiate XC runners, given the limited prospective cohort studies that have examined injury risk in this specific population.8,10 This study hypothesized that 1) decreased hip abductor strength and 2) biomechanical kinematic factors associated with increased loading (such as lower step rate, lower knee flexion at initial contact, and greater foot contact angle) would increase the odds of RRI. As biomechanical characteristics such as increased knee adduction, increased contralateral hip drop, and increased hip adduction have often been used as clinical indicators of impaired hip abductor performance, it was expected that these running kinematic variables would be negatively correlated with peak hip abductor strength.

METHODS

PARTICIPANTS

Twenty female XC runners from several NCAA Intercollegiate Division I and II XC teams in southern California in 2019 participated in the study. Coaches were first contacted via email to explain the study and request permission to contact the athletes. Athletes were then asked to sign up for the study after an in-person presentation at practice. Participation was voluntary. To be eligible, participants had to (a) be between the ages of 18-28; (b) were free of any lower extremity injury and running without limitation in the two weeks prior to completing the study measurements; (c) run at least 25 mi/week; and (d) have no contraindications to exercise as measured by the study questionnaire. The study was approved by the San Diego State University Institutional Review Board. All participants provided consent prior to participating in the study.

STUDY DESIGN AND DATA COLLECTION

A prospective observational study design was used in this study. Prior to the 2019 NCAA Intercollegiate Division I and II XC competitive seasons, the runners completed a study questionnaire, completed hip abductor muscle strength testing, and underwent 3-D motion capture to evaluate their running biomechanics.

Study Questionnaire. At the time of anthropometric (height and weight) evaluation, running kinematics analysis and hip abductor muscle testing, the runners completed a questionnaire on baseline characteristics including gen-

**(r=0.55), left supination at footstrike (r=0.48), right peak pronation during stance (r=0.47), left supination at footstrike (r=0.51), and right peak pronation during stance (r=0.54) (all p<0.05).**
under, age, school year, running experience, student classification (years in college), and any contraindications to exercises.

Running Kinematics. Each runner’s kinematic data were collected using an 8-camera 3D Qualisys Motion Capture System (Motion Analysis Corporation, Santa Rosa, CA, USA) while running on a treadmill (WOODWAY USA, Inc., Waukesha, WI). Retro-reflective markers for tracking 3D movement were placed on the subject using a modified Helen Hayes marker set. Kinematic data were recorded using Qualisys Track Manager (QTM) software. After static calibration, the runner performed a 5-minute warm-up at a self-selected pace to accommodate to the treadmill. The runner then ran for two minutes at her preferred training speed. During the 2-minute trial, 2 sets of 10 seconds of data were captured at random without informing the runner. Visual 3D (C-Motion Incorporated, Germantown, MD) software was used to process the kinematic data using the QTM Project Automation Framework (PAF) Running module. Variables of interest included vertical displacement of center of mass; hip drop; maximum hip abduction, hip internal rotation, knee adduction, and knee flexion angle during stance; hip adduction, hip internal rotation, knee adduction, knee flexion, tibial inclination, and contact angle at footstrike; supination at footstrike; maximum pronation during stance; horizontal distance from center of mass to footstrike; and SR. All variables except vertical displacement of center of mass and SR were measured bilaterally.

Hip Muscle Strength. Following a 10-minute rest period, each runner was evaluated for hip abductor muscle strength using the Biodex System 4 Pro™ Isokinetic dynamometer. After a practice trial of five submaximal repetitions to accommodate to the testing procedures, runners were instructed to perform 10 concentric, maximal effort hip abduction repetitions at 90° per second through a range of motion from neutral hip abduction to 30 degrees abduction in side-lying using their dominant limb. The dominant limb was defined as the limb with which a participant would kick a sports ball. This process was repeated for the non-dominant limb following an additional 5-minute break period.

Running-Related Injuries. Once the runners finished their XC season, they completed an exit survey where they reported any occurrence of RRI during the XC season. The definition of RRI was any muscle or joint pain that involved the low back or lower extremity and caused the runner to miss one or more practices or competitive events. The runners were provided a list of RRIs specific to body region, side, and type (e.g., strain, Patellofemoral Pain Syndrome, tendinitis, etc.) and were asked to specify date and time missed related to the RRI. The survey also provided open-ended questions to allow runners to specify body regions and type of injuries not available on the survey.

DATA ANALYSIS

Mean (SD) differences and frequencies were determined for demographic (chronological age, grade, GPA, years of cross-country experience) and physical characteristics (height, weight, body mass index [BMI]). Height (m) to the nearest 1.27 cm and weight (kg) to the nearest 0.23 kg were measured using a stadiometer and physician scale, respectively, to calculate body mass index (BMI).

For comparison of peak torque during maximal, concentric hip abductor contraction, peak torque was defined as the mean of the top three of the first 10 repetitions. The values were normalized by the runner’s body weight (kg). Asymmetry values were determined by the absolute difference between left and right limb scores for peak torque. Independent t-tests were used to determine the mean differences of hip abductor muscle asymmetry, peak hip abductor muscle asymmetry, and torque values between injured and non-injured runners.

Independent t-tests were also used to compare differences in mean running kinematic values between injured and non-injured runners. Pearson correlation coefficients were calculated to determine relationships between running kinematic variables and unilateral peak hip abductor strength, peak hip abductor strength asymmetry, and bilateral average peak hip abductor strength.

All study analyses were conducted using SPSS Statistics version 28 (IBM, Armonk, NY) with the alpha level set a priori at 0.05.

RESULTS

The runners had an average age of 19.2 ± 1.1y, (range:17 to 22 y), a mean BMI of 21.0 (+ 1.3), and XC running experience of 7.4 (+ 2.2) years (Table 1). End-of-the-season RRI information was gathered from only 19 of the 20 participants as one participant did not complete the final exit survey. During the season, 11(57.9%) of the runners reported 15 RRIs, and 26.3% (n=5) incurred a bone-stress RRI. The most common type of RRI was ’Exercise Related Leg Pain’ (ERLP [pain between the knee and ankle which occurs with exercise]) (Figure 1).

HIP ABDUCTOR MUSCLE STRENGTH

The bilateral combined average peak muscle strength normalized by bodyweight did not differ significantly between

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>19.2 (1.1)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>57.3 (5.2)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.6 (0.6)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.0 (1.3)</td>
</tr>
<tr>
<td>College Status (n, %)</td>
<td></td>
</tr>
<tr>
<td>Freshman</td>
<td>4 (20.0)</td>
</tr>
<tr>
<td>Sophomore</td>
<td>9 (45.0)</td>
</tr>
<tr>
<td>Junior</td>
<td>6 (30.0)</td>
</tr>
<tr>
<td>Senior</td>
<td>1 (5.0)</td>
</tr>
<tr>
<td>Years of XC experience</td>
<td>7.4 (2.2)</td>
</tr>
</tbody>
</table>

BMI, Body mass index; XC, Cross-country.
injured (1.59 Nm/kg±0.24) and non-injured runners (1.55 Nm/kg ±0.36) (p=0.76) (Figure 2). The mean normalized muscle strength asymmetry was also not significantly different between injured (0.14 Nm/kg±0.08) and non-injured runners (0.23 Nm/kg±0.17) [p=0.18] (Figure 3).

RUNNING KINEMATICS

No statistically significant differences (p>0.05) were found between the running kinematic variables of injured and non-injured runners (Table 2). Several running kinematic variables approached statistically significant differences: left knee flexion at foot-strike (p=0.14), right hip internal rotation at footstrike (p=0.10), and right hip internal rotation at stance (p=0.06).

Moderate positive correlations were found between overall peak hip abductor muscle strength and right knee adduction at footstrike and stance (r=0.50, r=0.55) and left supination at footstrike (r=0.48) (all p≤0.05, Table 3). A statistically significant moderate negative correlation was found between overall peak hip abductor muscle strength and right peak pronation during stance (r=-0.47) (p<0.05).

Statistically significant correlations were also observed between right hip abductor muscle strength and left supination at footstrike (r=0.51) and left hip abductor muscle strength and right peak pronation during stance (r=0.54) (all p<0.05).

DISCUSSION

The primary purpose of this study was to examine the relationship between hip muscle strength and running kinematics and occurrence of RRI among female NCAA cross-country runners during an intercollegiate XC season. The findings indicated that hip abductor muscle strength and selected running kinematic variables were not significantly associated with increased occurrence of RRI. The findings of this study also found few significant correlations existed between hip abductor muscle peak strength or asymmetry and the measured running kinematic variables. The statistically significant moderate correlations observed were between hip abductor muscle peak strength and knee adduction and foot position in the frontal plane at footstrike and stance.

HIP ABDUCTOR MUSCLE STRENGTH

Few studies have prospectively investigated the relationship between hip muscle strength and RRI in NCAA female collegiate XC runners. The current study’s findings did not support prior evidence that demonstrated a direct relationship between hip abductor muscle strength and RRI. Using a prospective study design, Becker et al.9 reported that isometric hip abductor strength predicted medial tibial stress syndrome in collegiate female and male runners. In a cross-sectional study of collegiate female runners, Fredericson et al.9 also reported finding an association between isomet-
Table 2. Mean Differences Between Selected Biomechanical Variables During Running at Self-selected Speeds for Injured and Non-Injured Female NCAA XC Runners.

<table>
<thead>
<tr>
<th>Side</th>
<th>Variable</th>
<th>Injured Mean</th>
<th>Injured SD</th>
<th>Non-injured Mean</th>
<th>Non-injured SD</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Vertical Displacement of Center of Mass (cm)</td>
<td>9.1</td>
<td>1.4</td>
<td>9.1</td>
<td>0.9</td>
<td>0.98</td>
</tr>
<tr>
<td>R</td>
<td>Maximum Trunk Flexion (°)</td>
<td>10.3</td>
<td>3.8</td>
<td>10.3</td>
<td>5.4</td>
<td>0.99</td>
</tr>
<tr>
<td>L</td>
<td>Hip Drop (°)</td>
<td>6.5</td>
<td>2.0</td>
<td>6.6</td>
<td>2.7</td>
<td>0.90</td>
</tr>
<tr>
<td>R</td>
<td>Hip Drop (°)</td>
<td>5.0</td>
<td>2.7</td>
<td>5.1</td>
<td>1.4</td>
<td>0.92</td>
</tr>
<tr>
<td>L</td>
<td>Hip Adduction at Footstrike (°)</td>
<td>4.9</td>
<td>4.0</td>
<td>6.4</td>
<td>3.1</td>
<td>0.38</td>
</tr>
<tr>
<td>R</td>
<td>Hip Adduction at Footstrike (°)</td>
<td>7.0</td>
<td>2.7</td>
<td>8.3</td>
<td>2.7</td>
<td>0.33</td>
</tr>
<tr>
<td>L</td>
<td>Hip Adduction at Stance (°)</td>
<td>9.8</td>
<td>4.0</td>
<td>11.2</td>
<td>2.6</td>
<td>0.41</td>
</tr>
<tr>
<td>R</td>
<td>Hip Adduction at Stance (°)</td>
<td>12.8</td>
<td>1.9</td>
<td>13.7</td>
<td>4.5</td>
<td>0.60</td>
</tr>
<tr>
<td>L</td>
<td>Hip Internal Rotation at Footstrike (°)</td>
<td>13.2</td>
<td>8.1</td>
<td>9.3</td>
<td>6.1</td>
<td>0.26</td>
</tr>
<tr>
<td>R</td>
<td>Hip Internal Rotation at Footstrike (°)</td>
<td>15.4</td>
<td>4.8</td>
<td>11.3</td>
<td>5.0</td>
<td>0.10</td>
</tr>
<tr>
<td>L</td>
<td>Hip Internal Rotation at Stance (°)</td>
<td>14.6</td>
<td>7.1</td>
<td>11.4</td>
<td>4.8</td>
<td>0.29</td>
</tr>
<tr>
<td>R</td>
<td>Hip Internal Rotation at Stance (°)</td>
<td>16.8</td>
<td>4.1</td>
<td>12.4</td>
<td>5.4</td>
<td>0.06</td>
</tr>
<tr>
<td>L</td>
<td>Knee Adduction at Footstrike (°)</td>
<td>6.5</td>
<td>2.1</td>
<td>5.4</td>
<td>2.7</td>
<td>0.31</td>
</tr>
<tr>
<td>R</td>
<td>Knee Adduction at Footstrike (°)</td>
<td>6.5</td>
<td>1.7</td>
<td>5.2</td>
<td>2.7</td>
<td>0.21</td>
</tr>
<tr>
<td>L</td>
<td>Knee Adduction at Stance (°)</td>
<td>8.4</td>
<td>2.7</td>
<td>8.0</td>
<td>3.9</td>
<td>0.83</td>
</tr>
<tr>
<td>R</td>
<td>Knee Adduction at Stance (°)</td>
<td>8.5</td>
<td>2.2</td>
<td>6.6</td>
<td>3.7</td>
<td>0.14</td>
</tr>
<tr>
<td>L</td>
<td>Knee Flexion at Footstrike (°)</td>
<td>14.6</td>
<td>3.9</td>
<td>17.8</td>
<td>5.1</td>
<td>0.14</td>
</tr>
<tr>
<td>R</td>
<td>Knee Flexion at Footstrike (°)</td>
<td>16.4</td>
<td>5.2</td>
<td>19.5</td>
<td>5.8</td>
<td>0.23</td>
</tr>
<tr>
<td>L</td>
<td>Knee Flexion at Stance (°)</td>
<td>43.4</td>
<td>3.7</td>
<td>46.4</td>
<td>6.0</td>
<td>0.19</td>
</tr>
<tr>
<td>R</td>
<td>Knee Flexion at Stance (°)</td>
<td>45.3</td>
<td>4.4</td>
<td>47.9</td>
<td>4.1</td>
<td>0.21</td>
</tr>
<tr>
<td>L</td>
<td>Tibial Inclination Angle at Footstrike (°)</td>
<td>-5.4</td>
<td>2.2</td>
<td>-5.1</td>
<td>2.3</td>
<td>0.75</td>
</tr>
<tr>
<td>R</td>
<td>Tibial Inclination Angle at Footstrike (°)</td>
<td>-4.6</td>
<td>2.6</td>
<td>-3.4</td>
<td>4.6</td>
<td>0.47</td>
</tr>
<tr>
<td>L</td>
<td>Horizontal Distance from Center of Mass to Footstrike (cm)</td>
<td>17.8</td>
<td>2.6</td>
<td>17.3</td>
<td>3.2</td>
<td>0.73</td>
</tr>
<tr>
<td>R</td>
<td>Horizontal Distance from Center of Mass to Footstrike (cm)</td>
<td>17.8</td>
<td>2.5</td>
<td>17.6</td>
<td>2.9</td>
<td>0.87</td>
</tr>
<tr>
<td>L</td>
<td>Contact Angle at Footstrike (°)</td>
<td>11.4</td>
<td>7.3</td>
<td>14.1</td>
<td>4.5</td>
<td>0.36</td>
</tr>
<tr>
<td>R</td>
<td>Contact Angle at Footstrike (°)</td>
<td>9.8</td>
<td>7.0</td>
<td>13.9</td>
<td>5.1</td>
<td>0.17</td>
</tr>
<tr>
<td>L</td>
<td>Supination at Footstrike (°)</td>
<td>10.4</td>
<td>3.6</td>
<td>12.2</td>
<td>2.3</td>
<td>0.23</td>
</tr>
<tr>
<td>R</td>
<td>Supination at Footstrike (°)</td>
<td>11.1</td>
<td>3.7</td>
<td>11.7</td>
<td>2.2</td>
<td>0.71</td>
</tr>
<tr>
<td>L</td>
<td>Pronation at Stance (°)</td>
<td>-11.3</td>
<td>2.6</td>
<td>-10.5</td>
<td>2.3</td>
<td>0.53</td>
</tr>
<tr>
<td>R</td>
<td>Pronation at Stance (°)</td>
<td>-9.1</td>
<td>2.8</td>
<td>-8.9</td>
<td>2.6</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Step Rate (steps/min)</td>
<td>173.0</td>
<td>7.5</td>
<td>175.7</td>
<td>10.0</td>
<td>0.51</td>
</tr>
</tbody>
</table>

R, Right; L, Left; SD, Standard Deviation.

Ric strength and of iliotibial band syndrome (ITBS) in cross-country athletes. The inconsistencies between the prior study’s findings and the current study’s results may be partially related to differences in study design and methodology. Becker et al. had a slightly larger sample size of 24 runners and followed runners for a two-year period. Their sample also included both male and female runners and separate analyses were not reported for the two groups. Additionally, they measured isometric hip abductor muscle strength while the current study analyzed concentric isokinetic hip abductor muscle strength. The current study protocol also required significantly more maximum effort repetitions, which may have influenced runners’ performance on the strength test due to concerns of fatigue the day before practices or preseason competitions. Testing strength shortly after a period of treadmill running may have also contributed to differences between the study results. Similar to Becker et al., the sample studied by Fredericson et
Table 3. Correlation Coefficients Between Selected Biomechanical Variables During Running at Self-selected Speeds and Normalized Peak Hip Abduction Strength for Injured and Non-Injured Female NCAA XC Runners.

<table>
<thead>
<tr>
<th>Side</th>
<th>Variable</th>
<th>R Peak Strength</th>
<th>L Peak Strength</th>
<th>R-L Peak Strength Difference</th>
<th>Overall Peak Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical Displacement of Center of Mass (cm)</td>
<td>-0.10</td>
<td>0.19</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Maximum Trunk Flexion (°)</td>
<td>-0.20</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.09</td>
</tr>
<tr>
<td>L</td>
<td>Hip Drop (°)</td>
<td>0.13</td>
<td>-0.03</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>R</td>
<td>Hip Drop (°)</td>
<td>-0.15</td>
<td>0.10</td>
<td>0.24</td>
<td>-0.03</td>
</tr>
<tr>
<td>L</td>
<td>Hip Adduction at Footstrike (°)</td>
<td>0.23</td>
<td>0.33</td>
<td>0.06</td>
<td>0.30</td>
</tr>
<tr>
<td>R</td>
<td>Hip Adduction at Footstrike (°)</td>
<td>0.09</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.01</td>
</tr>
<tr>
<td>L</td>
<td>Hip Adduction at Stance (°)</td>
<td>0.07</td>
<td>0.25</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td>R</td>
<td>Hip Adduction at Stance (°)</td>
<td>-0.08</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.09</td>
</tr>
<tr>
<td>L</td>
<td>Hip Internal Rotation at Footstrike (°)</td>
<td>0.09</td>
<td>-0.12</td>
<td>-0.30</td>
<td>-0.01</td>
</tr>
<tr>
<td>R</td>
<td>Hip Internal Rotation at Footstrike (°)</td>
<td>-0.21</td>
<td>-0.10</td>
<td>-0.25</td>
<td>-0.17</td>
</tr>
<tr>
<td>L</td>
<td>Hip Internal Rotation at Stance (°)</td>
<td>-0.11</td>
<td>-0.19</td>
<td>-0.23</td>
<td>-0.16</td>
</tr>
<tr>
<td>R</td>
<td>Hip Internal Rotation at Stance (°)</td>
<td>-0.33</td>
<td>-0.10</td>
<td>-0.14</td>
<td>-0.23</td>
</tr>
<tr>
<td>L</td>
<td>Knee Adduction at Footstrike (°)</td>
<td>0.11</td>
<td>0.12</td>
<td>-0.26</td>
<td>0.12</td>
</tr>
<tr>
<td>R</td>
<td>Knee Adduction at Footstrike (°)</td>
<td>0.42</td>
<td>0.50*</td>
<td>0.22</td>
<td>0.50*</td>
</tr>
<tr>
<td>L</td>
<td>Knee Adduction at Stance (°)</td>
<td>0.20</td>
<td>0.25</td>
<td>-0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>R</td>
<td>Knee Adduction at Stance (°)</td>
<td>0.44</td>
<td>0.58†</td>
<td>0.17</td>
<td>0.55*</td>
</tr>
<tr>
<td>L</td>
<td>Knee Flexion at Footstrike (°)</td>
<td>-0.25</td>
<td>0.12</td>
<td>0.38</td>
<td>-0.07</td>
</tr>
<tr>
<td>R</td>
<td>Knee Flexion at Footstrike (°)</td>
<td>-0.15</td>
<td>0.13</td>
<td>0.10</td>
<td>-0.01</td>
</tr>
<tr>
<td>L</td>
<td>L Knee Flexion at Stance (°)</td>
<td>-0.27</td>
<td>0.12</td>
<td>0.42</td>
<td>-0.08</td>
</tr>
<tr>
<td>R</td>
<td>Knee Flexion at Stance (°)</td>
<td>0.03</td>
<td>0.32</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>L</td>
<td>Tibial Inclination Angle at Footstrike (°)</td>
<td>-0.40</td>
<td>-0.09</td>
<td>-0.06</td>
<td>-0.26</td>
</tr>
<tr>
<td>R</td>
<td>Tibial Inclination Angle at Footstrike (°)</td>
<td>-0.29</td>
<td>-0.09</td>
<td>-0.10</td>
<td>-0.20</td>
</tr>
<tr>
<td>L</td>
<td>Horizontal Distance from Center of Mass to Footstrike (cm)</td>
<td>-0.07</td>
<td>0.08</td>
<td>0.35</td>
<td>0.00</td>
</tr>
<tr>
<td>R</td>
<td>Horizontal Distance from Center of Mass to Footstrike (cm)</td>
<td>0.10</td>
<td>0.22</td>
<td>0.41</td>
<td>0.18</td>
</tr>
<tr>
<td>L</td>
<td>Contact Angle at Footstrike (°)</td>
<td>-0.33</td>
<td>-0.29</td>
<td>-0.13</td>
<td>-0.33</td>
</tr>
<tr>
<td>R</td>
<td>Contact Angle at Footstrike (°)</td>
<td>0.03</td>
<td>-0.11</td>
<td>-0.16</td>
<td>-0.04</td>
</tr>
<tr>
<td>L</td>
<td>Supination at Footstrike (°)</td>
<td>0.51*</td>
<td>0.39</td>
<td>0.12</td>
<td>0.48*</td>
</tr>
<tr>
<td>R</td>
<td>Supination at Footstrike (°)</td>
<td>0.06</td>
<td>0.08</td>
<td>0.40</td>
<td>0.08</td>
</tr>
<tr>
<td>L</td>
<td>Pronation at Stance (°)</td>
<td>-0.07</td>
<td>-0.40</td>
<td>-0.02</td>
<td>-0.26</td>
</tr>
<tr>
<td>R</td>
<td>Pronation at Stance (°)</td>
<td>-0.33</td>
<td>-0.54*</td>
<td>0.04</td>
<td>-0.47*</td>
</tr>
<tr>
<td></td>
<td>Step Rate (steps/min)</td>
<td>0.22</td>
<td>-0.14</td>
<td>-0.10</td>
<td>0.04</td>
</tr>
</tbody>
</table>

R, Right; L, Left.

* Correlation is significant at the 0.05 level (2-tailed).
† Correlation is significant at the 0.01 level (2-tailed).

al.9 included 24 female and male runners and also did not report separate data for each gender, which may explain differing results between their study and this study’s findings. Differences in findings between the current study and Fredericson et al.9 may also be a result of variations in study design as Fredericson et al.9 used a cross sectional design and only examined runners with and without ITBS. Both studies also quantified hip abductor strength using methods different from the current study. Becker et al.8 normalized hip abductor muscle strength by weight rather than weight and height, and Fredericson et al.9 reported strength as percentage of body weight. Thus, the differing...
methods used by the studies make it difficult to compare hip abductor muscle strength and RRI between the three studies.

RUNNING KINEMATICS

The current study reported several kinematic variables in the female collegiate population, some of which have been previously reported in other prospective studies in similar populations. In a prospective study of collegiate runners, Kliethermes et al.,\textsuperscript{10} reported similar averages for step rate, center of mass vertical excursion, and peak hip adduction during stance in female runners. However, they reported slightly lower averages (differences of about 5 centimeters) for horizontal distance from center of mass to heel at foot-strike. Differences between the studies could be due to this study’s smaller sample size of 19 runners, which may have allowed for more influence of extreme values compared to Kliethermes et al.\textsuperscript{5,10} sample size of 33 female runners. Discrepancies could also be a result of differences in leg length as these values were not normalized by participant height. Becker et al.\textsuperscript{8} also reported average values for variables reported in this study such as hip internal rotation and contralateral pelvic drop. However, they did not report results for only female runners, preventing comparison to the values in the current study.

The findings of this study observed no statistically significant differences between the running kinematic variables evaluated and RRI incurred by the female XC runners during the collegiate season. This finding was not consistent with Becker et al.,\textsuperscript{3} who found that greater contralateral pelvic drop was associated with increased likelihood of medial tibial stress syndrome in intercollegiate XC runners. The findings of Becker et al.\textsuperscript{8} were based on male and female runners, which may partially explain the differing results between the studies. In addition, their protocol for measuring kinematic variables differed from this study. While runners in their study ran at their own selected pace, they also completed a 5-minute warm-up and 10-minute running trial in which data were collected during the final minute. This longer testing protocol may have better approximated running conditions that increase a female collegiate runner’s odds of incurring an RRI. Conversely, in their prospective study of collegiate runners, Kliethermes et al.\textsuperscript{10} reported similar findings to this study in that no significant relationships were found between risk of bone stress RRI in female athletes and foot inclination angle, horizontal distance from center of mass to heel, and peak adduction during stance. However, they did report that a lower step rate and a greater center of mass excursion was significantly associated with an increased risk for sustaining a bone stress RRI. They also employed a different protocol with runners only completing a 2-minute walking warm-up before data collection at their preferred paces. Additionally, differences in sample size could have accounted for the discrepancy in results as they examined a larger sample size of 33 female runners compared to the 19 studied in this study. Athletes were also followed for 12 months rather than for only the cross-country season, which may have allowed for higher incidence as well as certain types of RRI.

This study’s findings also do not support previous research in recreational and high-school female runner populations where step rate, foot strike pattern, hip internal rotation, knee adduction, and knee flexion angle were found to be associated with multiple types of RRIs.\textsuperscript{14–17} While knee flexion at foot-strike, hip internal rotation at foot-strike, and foot-contact angle at foot-strike trended toward statistical significance, this study’s small sample size likely contributed to the lack of significant findings. Decreased knee flexion at foot-strike has been associated with poorer force absorption at the knee leading to RRI such at ITBS as described in recent literature.\textsuperscript{15–17} Increased hip internal rotation at foot-strike has also been described to be a moderate contributing factor to ITBS.\textsuperscript{14–18} A runner with decreased foot contact angle at foot-strike (e.g., mid to forefoot strike pattern) may be more susceptible to RRIs such as Achilles tendinopathy and calf muscle strains due to increased eccentric activity of the calf musculature. In contrast, increased foot contact angle at foot-strike (e.g., heel strike pattern) transmits greater axial forces through the lower extremities and has been associated with injuries such as Patellofemoral Pain Syndrome.\textsuperscript{14–17,19}

CORRELATIONS BETWEEN HIP ABDUCTOR STRENGTH AND RUNNING KINEMATICS

Few cross-sectional studies have observed the correlation between hip abductor muscle strength and running kinematics in female runners, and no reports are available regarding these relationships in female collegiate cross-country runners. Similar to this study’s findings, Baggaley et al.\textsuperscript{20} found no statistically significant relationships between hip abductor muscle strength and hip adduction during stance. Similarly, Brindle et al.\textsuperscript{21} examined a group of 60 female runners placed into tertiles based on peak adduction during stance and found no significant difference between the hip abductor muscle strength of the groups with largest and smallest angles. After separating a group of female runners into quartiles based on hip abductor muscle strength, Heinert et al.\textsuperscript{22} found that the runners in the bottom quartile had significantly more peak knee adduction at stance compared to those in the top quartile. While the results of the current study also found a significant correlation between knee adduction angle and hip abductor muscle strength; a relationship between peak hip abduction strength to right knee adduction during stance and footstrike was also observed. Notably, the studies by Baggage,\textsuperscript{20} Brindle,\textsuperscript{21} and Heinert\textsuperscript{22} examined female recreational runners rather than collegiate cross-country runners. Thus, differences in competitive levels among the runners in their studies compared to this study’s runners might partially affect differences of the relationships. Ford et al.\textsuperscript{23} examined the relationship between hip abductor muscle strength and hip drop in collegiate cross-country runners and found that strength was inversely correlated with pelvic obliquity, differing from the result of the current study results which no statistical significance was observed between the two variables. However, the partici-
pants studied by Ford et al.\textsuperscript{25} included both men and women and a separate analysis for the female group was not reported to show differences between these groups.

\textbf{STRENGTHS/LIMITATIONS}

The primary strength of this study was the use of a prospective design, which minimized measurement and recall bias of hip muscle strength and running kinematic variables prior to RRI occurrence. In addition, this study reported values for several novel kinematic variables in the female collegiate XC population including knee flexion and adduction at footstrike and stance, tibial inclination angle at footstrike, and maximum trunk flexion. Although none of these kinematic variables were found associated with RRI, they provide values for future study comparisons.

Several limitations should be noted. First, the small sample size due to the limited number of collegiate female runners who could participate decreased the power of this study and limited the ability to show statistically significant relationships between the observed intrinsic factors and RRI. Second, it is possible that some runners may have been experiencing symptoms related to a lower extremity RRI at the time of testing. Consequently, this may have partially affected the true relationship between the running biomechanical factors or hip muscle strength and likelihood of RRI. To minimize this occurrence, the authors reaffirmed with the runner that they had not or were not currently experiencing lower extremity RRI symptoms at the time of testing. Third, the data collected for injury occurrence during the season were based on self-report. Although measures were taken to ensure accuracy of reporting (such as anonymity of questionnaires and study personnel available for questions and clarification), some self-reported data may have been under- or misreported due to recall bias, misunderstanding of survey questions, or fear of judgment by coaches or other runners. Future studies should consider extracting records from a university’s Sports Medicine department in addition to using self-report to improve the accuracy of the injury type reported and decrease recall bias. Finally, as discussed previously, a key limitation in this area of research is that there is no standardization in the running biomechanical testing protocol for length of warm-up and assessment times in collegiate runners. The variance in these parameters may have contributed to the potential discrepancy in findings amongst current studies. Future research should establish a consensus on the proper testing protocol for this population.

\textbf{FUTURE DIRECTIONS}

With regards to hip abductor performance, future research should evaluate hip abductor muscle endurance in addition to peak strength. While hip abductor muscle endurance and hip isometric strength are closely related, a recent study suggested that hip abductor muscular endurance held a greater association with iliotibial band syndrome than did isometric strength in recreational runners.\textsuperscript{24} Finally, protocols for running kinematic collection should be developed to approximate intensity and duration conditions of a typical XC training session. Increased running intensity and running duration may reveal more kinematic correlations to RRI by inducing a more fatiguing environment.

\textbf{CONCLUSIONS}

Hip abduction muscle strength and asymmetries, and the studied kinematic variables were not associated with RRI in female collegiate XC runners. Future studies planning to assess hip muscle performance and running kinematic variables should use larger sample sizes to evaluate their relationships more appropriately to RRI. In addition, future studies should investigate the relationship between hip abductor muscle endurance and RRIs as well as develop a protocol with a longer running analysis session to better simulate a true training environment.

\textbf{CONFLICTS OF INTEREST}

The authors affirm that they 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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Original Research

Thoracolumbar And Lumbopelvic Spinal Alignment During The Deadlift Exercise: A Comparison Between Men And Women

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Background
A neutral spinal alignment is considered important during the execution of the deadlift exercise to decrease the risk of injury. Since male and female powerlifters experience pain in different parts of their backs, it is important to examine whether men and women differ in spinal alignment during the deadlift.

Objectives
The purpose of this study was to quantify the spinal alignment in the upper (thoracolumbar, T11-L2) and lower (lumbopelvic, L2-S2) lumbar spine during the deadlift exercise in male and female lifters. Secondary aims were to compare lumbar spine alignment during the deadlift to standing habitual posture, and determine whether male and female lifters differ in these aspects.

Study Design
Observational, Cross-sectional.

Methods
Twenty-four (14 men, 10 women) lifters performed three repetitions of the deadlift exercise using 70% of their respective one-repetition maximum. Spinal alignment and spinal range of motion were measured using three inertial measurement units placed on the thoracic, lumbar and sacral spine. Data from three different positions were analyzed; habitual posture in standing, and start and stop positions of the deadlift, i.e. bottom and finish position respectively.

Results
During the deadlift, spinal adjustments were evident in all three planes of movement. From standing habitual posture to the start position the lumbar lordosis decreased 15° in the upper and 20° in the lower lumbar spine. From start position to stop position the total range of motion in the sagittal plane was 11° in the upper and 22° in the lower lumbar spine. The decreased lumbar lordosis from standing habitual posture to the start position was significantly greater among men.

Conclusions
Men and women adjust their spinal alignment in all three planes of movement when performing a deadlift and men seem to make greater adjustments from their standing habitual posture to start position in the sagittal plane.

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Level of Evidence

INTRODUCTION

The deadlift is a strength training exercise targeting hip, thigh, grip, and lower back strength. It is also one of three competitive lifts in the sport of powerlifting. In addition to being a fundamental exercise among powerlifters, the deadlift, and variations thereof, is also practised by weightlifters, strongman competitors, CrossFit athletes, and bodybuilders to increase strength and stimulate hypertrophy. In addition, the deadlift has been used as a rehabilitation exercise for patients with low back pain. However, it was recently shown that onset of injuries in the low back region among Swedish sub-elite powerlifters was significantly associated with performing the deadlift in training. Further, although male and female powerlifters reported similar injury frequencies, there were significant differences of their anatomic locations, whereas males had a higher frequency of low back pain and females thoracic and neck pain.

Deadlift technique is considered to be associated with both performance and risk of injury. Regarding the spine, it has been suggested that a lifting technique that enables the lifter to maintain a neutral position of the spine ensures optimal loading on both passive and active structures. For most people, a neutral position of the spine is when the lumbar spine has a slight concave curve (lordotic), the thoracic spine a slight convex (kyphotic) curve and the cervical spine a slight concave curve. In the scientific literature, neutral position has been defined as the region in the joint motion where there is little or no resistance to motion, i.e. a mid-range position (neutral position). It has also been described that in this region, spinal muscles operate with a complex strategy to control motions and that forces exerted on body structures vary depending on the ability to maintain a neutral position of the lumbar spine. This could be of clinical importance since for example when the lumbar spine is fully flexed, the longissimus/iliocostalis muscle complex have been proposed to have a reduced ability to produce posterior shear, which results in higher loads on the posterior passive tissues and high shearing forces.

It has been shown that lifting technique, and thereby lifting mechanics when performing the deadlift, may differ between individuals. For example, it has been shown that high-skilled lifters are better able to keep the bar closer to the body than low-skilled lifters. The purpose of this study was to quantify the spinal alignment in the upper (thoracolumbar, T11-L2) and lower (lumbopelvic, L2-S2) lumbar spine during the deadlift exercise in male and female lifters. Secondary aims were to compare lumbar spine alignment during the deadlift to standing habitual posture, and determine whether male and female lifters differ in these aspects. The authors hypothesised that the lumbar spinal alignment during standing habitual posture would differ from the alignment during the deadlift exercise and that there would be a difference in lumbar spinal alignment between men and women during the the deadlift. The latter hypothesis was based on the results from a study by McKean et al., which showed that men had a significantly larger range of lumbar flexion during the descent phase of the back squat exercise compared to women. Possibly due to differences in pelvic dimensions, lumbar vertebrae sizes, and trunk geometry, that together may influence lifting mechanics.

METHODS

EXPERIMENTAL APPROACH TO THE PROBLEM

Using an observational, comparative study design, this study sought to describe and compare lumbar spine alignment in men and women competitive lifters during standing habitual posture, and whether the spinal alignment changed during execution of the deadlift. Spinal alignment was measured in all three planes of movement using inertial measurement units (IMUs), for the upper lumbar spine (i.e. thoracolumbar) and lower lumbar spine (i.e. lumbopelvic). After a warm-up, spinal alignment was measured in standing habitual posture and during the execution of one set of three deadlift repetitions when lifting 70% of self-estimated 1RM. The reasons for choosing IMUs for monitoring of the spinal movements during the execution of deadlifts were that they can easily be used outside of a movement lab and also show adequate validity of measures of spinal movement compared to 3D motion capture systems.

PARTICIPANTS

Fourteen men and 10 women power- and weightlifters were recruited from local power- and weightlifting clubs. Only lifters with the intent of competing in power- or weightlifting and with at least two years of strength training experience were included. These criteria aimed to minimize variability in movement patterns between repetitions and to ensure that all lifters were familiar with performing heavy deadlifts. Lifters reporting a current injury which may have affected their lifting ability were excluded. Additionally, lifters less than 150 cm in height were excluded because of the risk that the IMUs would contact each other during movements. All lifters completed a questionnaire detailing training and medical history to ensure eligibility criteria was complied with. None of the invited lifters had any recent or previous medical issues which prevented them from participating in the study. Written informed consent was obtained from all lifters prior to participation and the study was approved by the Regional Ethical Review Board of Umeå, Sweden (Dnr 2014-285-3M).

PROCEDURES

Warm-up: Lifters completed a self-administered warm-up with the intention to be prepared for heavy deadlifts. The
warm-up typically consisted of sub-maximal deadlifts with increasing loads. Thereafter, three calibrated IMUs were affixed to the lifter’s back. They were placed at the spinous processes of T11 and L2, and on the sacrum (S2); finally, the lifter completed one further set of bodyweight squats and deadlifts while at the same time. The IMUs were set firmly and did not hinder the deadlift execution.

Data collection: First, the lifters were instructed to assume their habitual posture in standing with their arms at their sides while looking straight ahead (habitual posture). The IMUs then recorded their respective position to provide a measure of spinal alignment. The lifters were asked to perform one set of three deadlift repetitions at 70% of their self-estimated 1RM. In the start position of the deadlift, lifters stood with flexed knees and hips, straight arms, and held the barbell with an optional grip, i.e. a double pronated or mixed grip with one hand pronated and the other supinated (start position). In accordance with the rules of the International Powerlifting Federation, the barbell was then lifted by extension of the knees and hips until the lifter was standing erect (stop position) (Figure 1).

When the barbell was held motionless and standing erect with the hips and knees extended and the shoulders back, the lifter was given a down signal and the barbell was lowered to the ground before the lifter released the grip. The lifter was instructed to stand erect momentarily before beginning with the next repetition. In the present study, only conventional style deadlifts were allowed so that the measurements would be uniform. No additional equipment (e.g., lifting straps, knee wraps, lifting belts) was allowed.

**INSTRUMENTS AND MEASUREMENTS**

For the purpose of this study, the measurement of spinal movements were divided in to two movement segments, hereby referred to as upper lumbar spine (i.e. thoracolumbar spine) and lower lumbar spine (i.e. lumbopelvic spine). The IMUs placed on T11 and L2 measured their respective position (angle) relative to each other in all planes of movement for the upper lumbar spine. For the lower lumbar spine, the IMUs placed on L2 and S2 measured their respective position (angle) relative to each other in all planes of movement. A positive angle in the sagittal plane indicated a lordotic spinal alignment and a negative sagittal plane value indicated a kyphotic spinal alignment. A positive value in the frontal and transverse plane indicated a right lateral flexion or rotation, respectively.

The spinal alignment [degrees] was measured during habitual posture in standing and during execution of the deadlift exercise. The following measurements were selected to quantify the spinal alignment in the upper lumbar spine (thoracolumbar, T11-L2) and lower lumbar spine (lumbopelvic, L2-S2), respectively: 1) habitual posture in standing, 2) start position, 3) stop position, 4) Min angle (the minimum angle in degrees captured during the deadlift exercise in each respective movement plane), 5) Max angle (the maximum angle in degrees captured during the deadlift exercise in each respective movement plane), and 6) range of motion (ROM) between the minimum and maximum angles during the deadlift exercise.

The IMUs (MPU-9150, InvenSense, San Jose, USA) each have a size of Length 60 x Width 45 x Height 10 mm and weigh 14 g, and communicate with a laptop via WiFi. The sampling frequency was 100 Hz with a 16-bit resolution and an anti-aliasing low pass filter set at 50 Hz. The full-scale range was ±1000 /s for the gyroscopes, ±8 g for the accelerometers and ±4800 μT for the magnetometers. Using three axis gyro and three axis accelerometer, the IMUs detected the spinal alignment in all three planes of movement and real-time orientation was calculated using a customised system MoLab™ POSE (Anymo AB, Umeå, Sweden). The placements of the IMUs made it possible to measure movement patterns previously stated important to the performance and risk of injury when squatting, i.e. flexion of the thoracolumbar and lumbopelvic spine. The anatomical location sites of the units were palpated by the same experienced person at each time with the lifters standing erect. IMUs were mounted with double-sided tape and elastic self-adhesive bandage wraps. Further, the deadlift execution was recorded with a web camera to facilitate the determination of start and stop of the squat repetitions when processing the data. Weight plates of official measures were attached to each end of a powerlifting barbell and the weight was adjusted to the nearest 2.5 kg.

Orientation data (i.e. segment angles) from the IMUs were processed in Matlab (version 7.10.0 (R2010a), The MathWorks, Inc., USA). The Euler sequence used for the segment angles were X (rotations in the sagittal plane), Y (rotations in the frontal plane), and Z (rotations in the transverse plane). All orientation data was low-pass filtered with a second order Butterworth filter at a cut-off frequency of 10 Hz. A more detailed description of the used algorithms can be found in Öhberg et al.
Table 1. Participants’ characteristics (mean ± SD).

<table>
<thead>
<tr>
<th>Participants</th>
<th>Age (y)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>Experience (y)*</th>
<th>Deadlift 1RM (kg)†</th>
<th>Wilks Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>All (n=24)</td>
<td>25.4 ± 5.4</td>
<td>80.5 ± 11.2</td>
<td>171.4 ± 7.1</td>
<td>7.7 ± 6.2</td>
<td>162.5 ± 55.5</td>
<td>122.2 ± 25.9</td>
</tr>
<tr>
<td>Men (n=14)</td>
<td>26.9 ± 6.3</td>
<td>85.2 ± 10.8</td>
<td>174.9 ± 5.3</td>
<td>9.8 ± 7.5</td>
<td>197.1 ± 41.7</td>
<td>130.8 ± 23.5</td>
</tr>
<tr>
<td>Powerlifters (n=10)</td>
<td>26.6 ± 4.6</td>
<td>86.3 ± 7.5</td>
<td>175.8 ± 4.1</td>
<td>9.0 ± 5.3</td>
<td>200.5 ± 40.0</td>
<td>131.5 ± 25.5</td>
</tr>
<tr>
<td>Weightlifters (n=4)</td>
<td>27.5 ± 10.4</td>
<td>82.3 ± 17.9</td>
<td>172.8 ± 7.7</td>
<td>11.8 ± 12.3</td>
<td>188.8 ± 51.1</td>
<td>129.1 ± 20.9</td>
</tr>
<tr>
<td>Women (n=10)</td>
<td>23.4 ± 2.9</td>
<td>73.9 ± 8.5</td>
<td>166.4 ± 6.5</td>
<td>4.8 ± 1.9</td>
<td>114 ± 29.5</td>
<td>110.1 ± 25.3</td>
</tr>
<tr>
<td>Powerlifters (n=4)</td>
<td>25.0 ± 0.8</td>
<td>78.0 ± 6.5</td>
<td>165.5 ± 3.7</td>
<td>5.1 ± 2.2</td>
<td>130 ± 41.6</td>
<td>121.5 ± 38.5</td>
</tr>
<tr>
<td>Weightlifters (n=6)</td>
<td>22.3 ± 3.3</td>
<td>71.1 ± 9.0</td>
<td>167.0 ± 8.1</td>
<td>4.6 ± 1.9</td>
<td>103.3 ± 13.7</td>
<td>102.4 ± 9.3</td>
</tr>
</tbody>
</table>

*Strength training experience
†Self-estimated deadlift 1 repetition maximum

STATISTICAL ANALYSES

Statistical analysis was performed using Statistical Package for the Social Sciences (SPSS) version 23 (IBM Corp., Armonk, NY, USA). A factorial repeated measures analysis of variance (mixed ANOVA) was conducted to compare the influence of the independent variables (group: 1=men and 2=women) and the effect of the dependent variable (segment angle at five different positions: 1=habitual posture, 2=start position, 3=stop position, 4=minimum angle at any timepoint, and 5=maximum angle at any timepoint) using the mean values for the three repetitions. Sphericity was calculated using Mauchly’s test of Sphericity. If sphericity was not assumed, a correction was made using the Greenhouse-Geisser estimation. If significant position x group effects were found, the results were also presented separately for men and women. If significant within-subjects effects were found, post-hoc pairwise comparisons were calculated. Effect size was calculated with partial eta squared ($\eta^2_p$) using 0.01, 0.06 and 0.14 to denote small, medium and large effects respectively. Significance level was set at 0.05 and Bonferroni corrections were performed for multiple comparisons.

RESULTS

Background characteristics for the participants are summarized in Table 1, including their Wilks score in deadlift, i.e. a body mass adjusted measure of strength.$^{32}$

The spinal alignment of the upper lumbar spine during standing habitual posture, and during the deadlifts for the start position, stop position, minimum and maximum angle, and range of motion are presented in Table 2. For the upper lumbar spine, there were no statistically significant differences between men and women in spinal alignment (group x position interaction in the sagittal plane ($F(2,0, 43.5)=1.9, p=0.156$), frontal plane ($F(1.6, 34.9)=0.9, p=0.386$), or transverse plane ($F(2.7, 59.9)=0.9, p=0.451$). In all participants their alignment in standing habitual posture differed from the alignment at the start position and further spinal adjustments were made during the deadlift (significant main effect for position in the sagittal plane ($F(2.0, 45.3)=45.8, p<0.001, \eta^2_p=0.676$), frontal plane ($F(1.6, 34.9)=15.6, p<0.001, \eta^2_p=0.414$), and transverse plane ($F(2.7, 59.9)=23.9, p<0.001, \eta^2_p=0.521$).

For the lower lumbar spine (Table 3), the decreased lumbar lordosis during the start position compared to during standing habitual posture was significantly greater among men than women (group x position interaction in sagittal plane spinal alignment ($F(1.9, 41.9)=4.0, p=0.028, \eta^2_p=0.154$). There were no statistically significant differences between men and women in spinal alignment in the frontal plane (group x position interaction) ($F(1.8, 39.9)=0.5, p=0.757$) or in the transverse plane ($F(2.1, 45.5)=1.0, p=0.156$). In all participants their alignment in standing habitual posture differed from the alignment at the start position and further spinal adjustments were made during the deadlift (significant main effect for position in the frontal plane) ($F(1.8, 39.9)=9.2, p=0.001, \eta^2_p=0.294$) and transverse plane ($F(2.1, 45.5)=15.2, p<0.001, \eta^2_p=0.676$).

The factorial repeated measures ANOVA simple effects for position in the upper and lower lumbar sagittal plane spinal alignment are presented in Figures 2 and 3.

DISCUSSION AND IMPLICATIONS

This is the first study to describe and compare spinal alignment, in all planes of movement, during the deadlift exercise in both men and women. The results show that the lifters’ lumbar spinal alignment in standing habitual posture differed from the alignment at the start position of the deadlift, and that further spinal adjustments were made during the deadlift. As shown by the measures of range of motion, neither men nor women kept their spine in a fixed position when performing a heavy deadlift. Specifically, spinal adjustments were made mainly in the sagittal plane, a phenomenon that has also been reported for the squat exercise.$^{22}$

The results showed no differences between men and women although this was initially hypothesized. In regard to the potential impact of differences in anthropometric factors it is not possible to draw any firm conclusions since...
Table 2. Spinal alignment angles of the upper lumbar spine (thoracolumbar region) during standing Habitual posture and during the deadlift for the Start position, Stop position, Minimum (Min) angle, Maximum (Max) angle and range of motion (ROM) in degrees [°] as well as results of the two-way factorial repeated measures ANOVA (within-subjects effect).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Habitual posture (°)†</th>
<th>Start position (°)†</th>
<th>Stop position (°)†</th>
<th>Min angle (°)†</th>
<th>Max angle (°)†</th>
<th>ROM (°)</th>
<th>Within-subjects effect Time*group</th>
<th>Within-subjects effect Time</th>
<th>p</th>
<th>Partial Eta Squared</th>
<th>p</th>
<th>Partial Eta Squared</th>
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<tr>
<td><strong>All</strong></td>
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<tr>
<td>Sagittal plane</td>
<td>17.6 ± 12.2</td>
<td>4.6 ± 7.5*</td>
<td>13.0 ± 11.5*#</td>
<td>2.2 ± 6.6*#</td>
<td>14.0 ± 11.8#</td>
<td>11.8 ± 7.3</td>
<td>0.156</td>
<td>0.081</td>
<td>&lt;0.001</td>
<td>0.676</td>
<td>0.414</td>
<td></td>
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<tr>
<td>Frontal plane</td>
<td>0.8 ± 2.5</td>
<td>-1.8 ± 4.8</td>
<td>-0.4 ± 2.4</td>
<td>-3.3 ± 4.3*#</td>
<td>1.0 ± 2.7#</td>
<td>4.3 ± 2.7</td>
<td>0.386</td>
<td>0.040</td>
<td>&lt;0.001</td>
<td>0.414</td>
<td>0.676</td>
<td></td>
</tr>
<tr>
<td>Transverse plane</td>
<td>-0.3 ± 0.8</td>
<td>0.3 ± 2.2</td>
<td>-0.8 ± 2.0</td>
<td>-1.9 ± 2.0*#</td>
<td>1.5 ± 2.0*#</td>
<td>3.4 ± 1.4</td>
<td>0.451</td>
<td>0.038</td>
<td>&lt;0.001</td>
<td>0.521</td>
<td>0.676</td>
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<tr>
<td><strong>Men</strong></td>
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<tr>
<td>Sagittal plane</td>
<td>12.1 ± 6.1</td>
<td>1.5 ± 4.4</td>
<td>8.3 ± 3.7</td>
<td>-0.6 ± 3.7</td>
<td>9.2 ± 4.1</td>
<td>9.7 ± 4.9</td>
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<td>Frontal plane</td>
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<td>-3.0 ± 5.1</td>
<td>-0.7 ± 2.5</td>
<td>-4.2 ± 4.8</td>
<td>0.1 ± 2.6</td>
<td>4.3 ± 3.2</td>
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<td>-2.0 ± 2.0</td>
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<td>3.5 ± 1.8</td>
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<tr>
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<td>19.6 ± 15.3</td>
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<td>20.8 ± 15.6</td>
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<td>-1.8 ± 2.1</td>
<td>1.6 ± 2.4</td>
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†A positive sagittal plane angle indicated a lordotic spinal alignment and negative sagittal plane angle indicated a kyphotic spinal alignment.

*Significant difference to Habitual posture after adjustment for multiple comparisons using the Bonferroni correction.

#Significant difference to Start position after adjustment for multiple comparisons using the Bonferroni correction.
Table 3. Spinal alignment angles of the lower lumbar spine (lumbopelvic region) during standing Habitual posture, and during the deadlift for the Start position, Stop position, Minimum (Min) angle, Maximum (Max) angle and range of motion (ROM) in degrees [°] as well as results of the two-way factorial repeated measures ANOVA (within-subjects effect).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Habitual posture (°)†</th>
<th>Start position (°)†</th>
<th>Stop position (°)†</th>
<th>Min angle (°)†</th>
<th>Max angle (°)†</th>
<th>ROM (°)</th>
<th>Within-subjects effect Time*group</th>
<th>Within-subjects effect Time*group</th>
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<td>0.154</td>
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<tr>
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<td>-3.7 ± 7.4*</td>
<td>16.2 ± 9.3#</td>
<td>-4.7 ± 7.5*</td>
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<td>21.7 ± 6.4</td>
<td>0.028</td>
<td>0.154</td>
</tr>
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<td>-0.4 ± 2.4</td>
<td>0.6 ± 3.4#</td>
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<td>-1.4 ± 2.2*</td>
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<tr>
<td>Men</td>
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<tr>
<td>Transverse plane</td>
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<td>0.0 ± 1.8</td>
<td>-1.4 ± 2.2</td>
<td>1.3 ± 1.7</td>
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<tr>
<td>Sagittal plane</td>
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<td>Frontal plane</td>
<td>-0.9 ± 3.6</td>
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<td>2.5 ± 1.4</td>
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<tr>
<td>Transverse plane</td>
<td>0.5 ± 0.7</td>
<td>-0.6 ± 3.0</td>
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<td>3.0 ± 1.4</td>
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† A positive sagittal plane angle indicated a lordotic spinal alignment and negative sagittal plane angle indicated a kyphotic spinal alignment.
* Significant difference to Habitual posture after adjustment for multiple comparisons using the Bonferroni correction.
# Significant difference to Start position after adjustment for multiple comparisons using the Bonferroni correction.
Figure 2. Upper (thoracolumbar region) and lower lumbar spine (lumbopelvic region) sagittal plane Habitual posture and Start position in degrees (*) presented in mean values and 95% CI.

LL = Lower lumbar spine (L2-S2), UL = Upper lumbar spine (Th11-L2). The Y axis represents the spinal alignment angles in degrees.

these were not measured specifically. However, the results could indicate that potential anthropometric differences between men and women do not affect range of motion of the spine during deadlifts, as opposed to the findings by McKean et al.\textsuperscript{22} in regards to back squats. Also, regarding the previously observed difference in pain locations,\textsuperscript{8} thoracic and neck regions for women and low back region for men, the results do not present any evidence that movement pattern of the spine could explain those findings.

An inability to maintain the spinal curvature in its neutral position has been proposed to increase the strain on passive structures of the back.\textsuperscript{17,21,33,34} This belief is based on the fact that the spine is better at managing compressive rather than shearing forces, meaning that an upright posture with all vertebrae aligned in a neutral posture is preferable.\textsuperscript{16} Performing the deadlift with the lumbar spine in its fully flexed position, in conjunction with a heavy load, is believed to be injurious to both active and passive structures.\textsuperscript{35} Previous epidemiological research has found that training of the deadlift exercise might be associated with low back pain in powerlifters,\textsuperscript{8} although there is only a limited amount of research reporting the occurrence of specific injuries.\textsuperscript{35} Still, experts in the field of powerlifting have agreed that flexing (rounding), twisting, side bending or hyperextending the low back during deadlifting is a risk factor for low back pain.\textsuperscript{9} Whether lifters adopting any of these adjustments in spinal alignment are in fact more injury-prone remains to be studied. Specifically, there is no in vivo evidence of a causative correlation between spinal alignment and low back pain/injuries.\textsuperscript{35} When it comes to deadlifting with heavy loads, some have argued that it is extremely difficult or almost impossible to maintain a neutral spinal curvature.\textsuperscript{11} This might be explained by an increase in strength in the deadlift while lifting with a flexed back due to an increase of the effectiveness of the back extensors\textsuperscript{36} and shortening of the external moment arm. Also, it is very likely that the back could flex due to several other factors, e.g. the back or hip extensors inability to produce enough torque to withstand the external torque imposed on them, the coordination between back and hip extensors or insufficient range of motion in the hip, knee or ankle joints leading to compensatory movements in the low back. It has also been suggested that the adjustment of the spinal curve during lifting tasks is the human body’s way of managing the additional load by trying to keep the combined body and barbell center of mass vertically in line with the center of gravity.\textsuperscript{22,37} In addition, previous authors have shown that the deadlift exercise entails lumbopelvic movement in all planes\textsuperscript{38} and that visual observation of these movements are very difficult to accurately observe.\textsuperscript{39} These results are be supported by the results of the present study, especially with the small movements detected in the frontal and transverse planes in mind. Therefore, there may be a need to study movement patterns in the deadlift with a range of loads and with more attention to the magnitude of movement in relation to individuals maximum range of motion and less attention to exclusively noting presence of lumbopelvic movement.

For the standing habitual posture, the mean lordosis was 18° in the upper and 17° in the lower lumbar spine. In an earlier study using an inclinometer, the lumbar lordosis of an unloaded lumbar spine of a standing person was shown to be about 25° and the normal ROM for flexion from this point is about 50°.\textsuperscript{40} Beforehand it was hypothesized

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that lumbar spinal alignment during standing habitual posture would differ from lumbar alignment during the deadlift exercise. This was confirmed. In the start position, the lumbar lordosis decreased to five degrees in the upper and into slight flexion (-4°) in the lower lumbar spine. However, during the lift the lifters returned to a more lordotic alignment although it was still significantly less lordotic in the stop position compared to the standing habitual posture in the upper lumbar spine. Regarding the lower lumbar spine, all lifters flexed this area especially during the first part of the lift. After the first part of the lift, the lifters returned to an alignment that was similar to the standing Habitual posture. However, in relation to previously described\(^4\) average maximal ranges of motion, no participant achieved such ranges. The movement pattern of a flexed lumbar spine during execution of heavy deadlifts has also been shown in an earlier study examining the lumbar spine using fluoroscopy.\(^1\) In that study, one of the lifters reported lower back discomfort when the L4/L5 joint exceeded the passive full flexion and the posterior ligaments were fully stretched. However, the authors stated that the extensor moment supported by the ligaments was unlikely to threaten the ligamentous tissue in a healthy intervertebral joint, even though it produced momentary discomfort.\(^1\) The finding that men flexed their back more than women in the start position has not been presented earlier. However, differences in movement patterns between men and women have been reported in the squat exercise\(^2\) and for lifting tasks.\(^4\) While the reason for the differences in spinal movement pattern between sexes during the execution of heavy deadlifts is unknown, the influence of sex on movement pattern has been attributed to anatomical differences.\(^2\) However, a study by Keogh et al.\(^4\) revealed that for powerlifters in New Zealand both men and women seem to have similar anthropometric characteristics in regard to skeletal features like bone lengths and breadths. Another inherent difference could be the structure of the hip joint, whereby men tend to have lesser hip ROM than females and therefore may need to flex their lumbar spine more in order to reach the bar.

Figure 3. Upper (thoracolumbar region) and lower lumbar spine (lumbopelvic region) sagittal plane Start position, Min angle, and Max angle in degrees (*) presented in mean values and 95% CI. 

LL = Lower lumbar spine (L2-S2), UL = Upper lumbar spine (Th11-L2). The Y axis represents the spinal alignment angles in degrees.

Regarding the frontal and transverse spinal alignment, significant differences were found in both the upper and lower lumbar spine during the deadlift when compared to the standing habitual posture. Even though these differences were significant, it could be questioned whether they are clinically relevant since the absolute change was less than 5 degrees. The reason for the adjustments in spinal alignment could be how the lifters gripped the barbell. While some of the lifters gripped the barbell with a double pronated grip, others used a mixed grip with one hand pronated and the other supinated. The alternated grip is thought to induce a hip rotation\(^4\) and hence could explain the transverse plane movements. Movements in the frontal plane during deadlifts have not been reported earlier but it is possible that asymmetries with alternating grip or in grip width could result in movements in frontal plane of this small magnitude.

Methodological considerations of the present study should be noted. Firstly, to increase the internal validity of the study, the lifters were asked to perform conventional deadlifts regardless of whether they competed with the conventional or sumo style deadlifts. As proposed in a recent article,\(^1\) some individuals might be more suited to one of these styles than the other depending on anthropometrics, mobility and strength capacity in individual muscle groups. It is, however, possible that movement patterns would have been different if the choice of deadlift style had been optional. Since the sumo deadlift stance generally en-
ables a more upright torso, and since it has been argued that lumbar lordosis is easier to maintain using the sumo stance, it is reasonable to assume that a different movement pattern in the upper and lower lumbar spine could be reported using sumo style deadlifts. Secondly, all lifts were performed without a lifting belt due to practical reasons concerning the fitting of the IMUs. This could, however, have had an impact on the results, where a lifting belt might have resulted in smaller range of motion in the spine since a belt improves lumbar spine stability.

Thirdly, it is important to consider that the lifters in this study were lifters who, during training and competition, most often attempt to lift the maximum amount of weight possible. Therefore, the lifters might have used a technique enabling them to lift heavy weights in their respective sports but not necessarily to reduce the risk of injury. However, little is known about how the deadlift technique impacts injury risk and whether there is a difference between the optimal technique for performance and injury reduction.

Fourthly, all lifters were instructed to complete three repetitions with a load equivalent to 70% of their self-estimated 1RM. The load and repetition range are commonly used in powerlifting and weightlifting training and were chosen to represent a "minimum" training load. However, previous studies have used loads ranging from no additional load to 1RM. It is important to remember that spinal adjustments might differ depending on load and strength level. The level of strength and training experience among the men and women differed, i.e. the men were more experienced, lifted more weight relative to body mass and had a higher Wilks coefficient than the women. Top ranked lifters on national level have a Wilks coefficient between ~175-215, suggesting that both the men and women performed at an intermediate level.

Lastly, the findings rely on inertial motion sensors and the validity of this measurement approach has to be discussed. It has to be noted that the IMUs were mounted on the skin surface and that the angles might differ from actual skeletal alignment due the possibility that the IMUs could glide on the skin. There is no earlier study to measure the validity of the angles in comparison with a "gold standard" such as radiographs, videofluoroscopy, etc, but the IMUs have been validated to electromagnetic based system for measuring 3D spinal ranges of movement and coupled motion measurement. Finally, it could be argued that the measurement accuracy could be greater in the sagittal plane where the lumbar spine also have more range of motion and vice versa for the frontal and transverse planes.

CONCLUSION

This is the first study to describe spinal alignment; in all planes of movement, during the deadlift among men and women lifters, and to compare this between sexes. The results indicate that both sexes decreased lumbar lordosis from standing habitual posture to the start position of the deadlift and that spinal adjustment were made during execution of the deadlift. The decreased lumbar lordosis from standing habitual posture to the start position of the deadlift was significantly greater among men. As indicated by the measures of lumbar spine ROM, both men and women adjust their spinal alignment in all three planes of movement when performing a deadlift at approximately 70% of 1RM. Despite guidelines that a lumbar lordosis and/or neutral position should be preserved when lifting heavy weights, it seems that men and women lifters partially flex the lower back when performing deadlift at a sub-maximal load. Whether spinal alignment adjustments of this magnitude have an impact on injury risk should be investigated.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

ACKNOWLEDGMENTS

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Original Research

Lower Limb Ground Reaction Force and Center of Pressure Asymmetry During Bodyweight Squats

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Keywords: leg asymmetry, double leg squat, center of pressure, ground reaction force

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Background
Performance asymmetries between the lower limbs have been reported across a variety of variables and for numerous motor tasks including double leg squats. Additionally, the degree of symmetry is often used as a recovery metric during rehabilitation programs.

Hypothesis/Purpose
The purpose of this investigation was to examine leg asymmetry during a bodyweight double leg squat task and assess the effects of squat speed in a physically active population.

Study Design
Cross-over Study Design.

Methods
Eighteen healthy individuals completed two sets of 20 squats at two tempos (preferred tempo and 60 bpm) while ground reaction force and center of pressure data were recorded using dual force plates. Peak vertical ground reaction force, force impulse, and center of pressure (COP) standard deviation in the anterior-posterior (AP) and mediolateral (ML) direction were calculated and analyzed to identify any differences between legs, tempo, and as a function of repetitions. Significance was set at \( p \leq .05 \).

Results
The subjects exhibited greater ground reaction forces during the self-paced tempo compared to the metronome-paced tempo \( (F_{1,79} = 14.48, p < .001) \) with the preferred leg generating larger values than the non-preferred leg during the self-paced condition. There was also a significant tempo x leg interaction for force impulse \( (F_{1,79} = 5.927, p = 0.015) \). A greater amount of COP variability was found in the preferred leg compared to the non-preferred leg in both the AP \( (F_{1,79} = 30.147, p < 0.001) \) and ML \( (F_{1,79} = 41.204, p < 0.001) \) directions.

Conclusions
These findings highlight the importance of considering multiple levels of analysis when assessing lower limb symmetry as separate variables may provide differential evidence for asymmetry. Practically, these results emphasize the need for coaches and practitioners to consider different degrees of lower limb asymmetries that may impact the development and design of strength and rehabilitation programs.
Level of Evidence

INTRODUCTION

The double leg squat, in either the loaded or bodyweight form, serves as a common functional exercise used in weight training and rehabilitation settings. Successful execution of the movement requires the coordination and control of numerous muscles, as well as the maintenance of postural stability. Given the dynamic nature and functional demands of the double leg squat, it is often assumed that symmetric control exists between the right and left legs, as evidenced in part by the common approach to only collect unilateral measurements.\(^1,^2\) Furthermore, it is often postulated that symmetrical kinematics derive from symmetrical force production and symmetrical joint moments during a squat movement.\(^3\) However, redundancies present in the neuromuscular system afford the possibility of bilateral asymmetries across different levels of analysis. Thus, caution should be exercised when interpreting the existence of bilateral symmetry, particularly when used to determine exercise prescription on the common assumption that the demand will be equally split between the two extremities.

Bilateral asymmetries have been examined across a variety of motor tasks including countermovement jumps, single leg countermovement jumps and hops, back squat, gait, and upright standing. Similar to evidence found in gait,\(^4\) conflicting findings exist on whether bilateral differences are present during the squat movement, and this is evident across multiple levels of analysis (e.g., kinetic – joint torque, ground reaction forces or kinematic measurements). However, few studies have addressed the dynamic balance component (e.g., postural sway) of the squatting movement. Flanagan and Salem\(^5\) used a modified center of pressure (COP) variable that was derived as the distance from the ground reaction force (GRF) application point to the ankle joint and showed significantly greater distances for the left lower limb as compared to the right limb across various loading conditions. Using more typical COP measurements, Kohn and colleagues\(^6\) reported postural stability measurements as a function of upward gaze direction during squatting and found that a downward, compared to an upward gaze, reduced COP displacements. However, the preceding evidence focuses on a whole-body COP metric and have yet to address the question of whether the maintenance of balance during this dynamic movement is achieved equally from the right and left limbs.

Although limb asymmetry is commonly interpreted as indicative of pathology, evidence from gait analyses suggests that even healthy individuals display asymmetrical behavior.\(^4\) In fact, most individuals exhibit a degree of lower limb performance preferences manifested as a strong functional advantage for one limb in asymmetrical tasks.\(^7\) Specifically, staggered and tandem standing resulted in increased asymmetrical weight distribution between the legs as compared to a side-by-side posture.\(^8\) During locomotion, an asymmetrical second peak of the vertical GRF curve was found and influenced by walking speed while other kinetic properties remained symmetrical.\(^9\) Collectively, it is important to understand the contributing factors to limb symmetry and to explore how the body adapts to changes in environmental or tasks constraints that may lead to functional advantages for one of the lower limbs.

Bilateral asymmetries can be calculated using a variety of equations that typically revolve around distinctions like dominant versus nondominant, right versus left, stronger versus weaker, or preferred versus nonpreferred limbs. Additionally, different metrics (e.g., symmetry indices, statistical analysis) have been used to examine the degree of symmetry between the right and left legs. In healthy gait, some investigations analyzed ground reaction forces while others examined spatial-temporal properties of walking and running.\(^4\) Additionally, postural control asymmetries have typically been addressed using center of pressure (COP) with evidence of asymmetry found in both static and dynamic balance tasks.\(^8,^10,^11\) Examination of bilateral asymmetries over multiple levels of analysis may provide insight into possible underlying mechanisms that facilitate successful task execution and has the potential to guide practitioners in designing effective training and rehabilitation exercises.

The current investigation explored whether leg asymmetry exists during a bodyweight double leg squat task and assessed the effects of squat speed in a physically active population. First, we examined whether typically used kinetic variables (e.g., vertical ground reaction force – GRF\(_V\)) demonstrated bilateral asymmetries during the double leg squat.\(^12\) A secondary aim addressed the lack of evidence related to postural stability asymmetries by quantifying center-of-pressure (COP) sway of each leg. Increased COP displacements are interpreted as an indication of less postural control and poorer balance performance. Based on the findings of Flanagan and Salem,\(^5\) it was predicted that the left leg would exhibit greater COP displacements. Finally, the pace of movement has been shown to influence movement characteristics,\(^9\) and we sought to examine whether this pattern of results remained consistent for self-paced and metronome-paced movements during 20 repetitions of the double leg squat task.

METHODS

Eighteen physically active young adults (10 F, 23.17 ± 1.72 years, 175.5 ± 10.18 cm, 74.18 ± 16.31 kg) were recruited from a university campus and provided informed consent prior to participation. Participants were considered active if they reported participating in physical activity a minimum of three days per week. Lower limb preference was determined by asking participants which leg they would use to kick a ball for maximum distance (right-preferred =12, left-preferred = 6). Participants reported no lower extremity injury that required surgery in the past year. The following protocol was approved by the Texas Christian University institutional review board prior to implementation and in-
formed consent was obtained from all participants prior to data collection.

Participants completed two sets of 20 repetitions of double leg squats with one set performed at a preferred tempo (self-selected by each participant) while the other set was at a non-preferred tempo (metronome - 60 bpm; one second descent, one second ascent). Feet were positioned shoulder width apart and arms were extended overhead during the bodyweight squats. The order of squat tempo was randomized for each subject. During all squats, participants executed the movement to a depth that was comfortable for them and a researcher observed performance to ensure that participants maintained a similar depth for the set of 20 repetitions. During the repetitive squat movement, bilateral GRF\textsubscript{v} were collected with dual force plates (AMTI, Watertown, MA, USA) using a sampling rate of 100 Hz.

Kinetic data were filtered using a Butterworth filter and a 10 Hz cut-off frequency. A researcher manually identified each squat cycle in Visual 3D (C-Motion, Germantown, MD, USA) with initiation of right knee flexion indicating squat start and termination of right knee extension indicating squat end. The squat phases were then defined as the time from initiation of right knee flexion to maximum knee flexion (descent phase) and maximum knee flexion to termination of right knee extension (ascent phase). The GRF\textsubscript{v} peak and impulse were determined for the right and left legs for the ascent phase of each squat repetition since the peak GRF typically occurs during this phase.\textsuperscript{12} The variability of center of pressure trajectories in the anterior-posterior (AP) and medial-lateral (ML) directions for the preferred and non-preferred legs were computed by standard deviation for the entire duration of each trial.

The dependent variables (movement time, peak GRF\textsubscript{v}, F\textsubscript{impulse}, COP standard deviation – AP, COP standard deviation – ML) were analyzed in separate 2 (leg: preferred vs. non-preferred) x 2 (tempo) x 20 (repetition) repeated measures analysis of variance. Based on the sample size (n = 18), an alpha level set at p < 0.05, and an effect size set to 0.15, the current study achieved a level of statistical power equal to 0.84. Data are reported as mean ± standard deviation. All tests were performed using SPSS statistical software (IBM, Chicago, IL).

RESULTS

Mean movement time was evaluated between the self-paced and metronome conditions through a one-way ANOVA and revealed a significant difference for movement time \(F_{1,37} = 20.95, p < 0.001\) with longer squat times for the self-paced (1.92 ± 0.27 s; 62.5 ± 1.85 bpm) compared to the metronome (1.82 ± 0.13 s; 65.95 ± 3.84 bpm) condition.

The analysis of peak GRF\textsubscript{v} revealed a significant tempo x leg interaction \(F_{1,79} = 7.593, p = 0.006\). Although individuals executed the squat movement with a greater peak GRF\textsubscript{v} during the self-paced (Preferred: 550.27 ± 172.15 N; Non-Preferred: 518.40 ± 154.19 N) than in the metronome (Preferred: 498.96 ± 115.93 N; Non-Preferred: 508.53 ± 130.08 N) condition for both legs \(F_{1,79} = 14.48, p < 0.001\), there were significantly larger peak GRF\textsubscript{v} values for the preferred limb compared to the non-preferred leg during the self-paced condition. No leg difference, repetition effect, or other interactions were found for peak GRF\textsubscript{v} (Figure 1, top panel).

There was also a significant tempo x leg interaction for F\textsubscript{impulse} \(F_{1,79} = 5.927, p = 0.015\), with preferred and non-preferred limbs performing differently depending upon the tempo condition. Post-hoc analysis revealed similar impulses for the preferred and non-preferred limbs during metronome condition (Preferred: 312.55 ± 70.81 Ns; Non-Preferred: 306.98 ± 78.68 Ns, p = 0.34), but significantly greater impulses for the non-preferred limb during the self-paced condition (Preferred: 300.4 ± 67.84 Ns; Non-Preferred: 314.91 ± 77.5 Ns, p < 0.001) – see Figure 1, bottom panel. No significant main effects or other interactions were found for F\textsubscript{impulse} \((p > 0.05)\).

A significant main effect of limb was found on COP standard deviation in both the AP \(F_{1,81} = 50.15, p < 0.001\) and ML \(F_{1,81} = 41.20, p < 0.001\) directions with no other significant main effects or interactions (see Figure 2). In the AP direction, the preferred limb (3.21 ± 0.57 cm) showed greater variability than the non-preferred limb (1.92 ± 0.06 cm) with the same pattern of results observed in the ML direction (preferred: 1.50 ± 0.38 cm; non-preferred: 0.62 ± 0.3 cm).

DISCUSSION

The current study evaluated the degree of (a)symmetry in a double leg squat as a function of squat tempo and repetition. The results revealed bilateral asymmetry for peak GRF\textsubscript{v} and F\textsubscript{impulse} dependent on squat tempo. Higher peak GRF\textsubscript{v} values were observed during self-paced squats compared to metronome-paced squats in both limbs. The preferred limb exhibited a greater difference in peak GRF\textsubscript{v} across tempo conditions, while the non-preferred showed similar values across temps. Complementing the asymmetrical kinetic GRF variables, the results also showed that the preferred limb exhibited greater COP variability in both AP and ML directions compared to the nonpreferred limb. These findings highlight the importance of evaluating the degree of limb symmetry across multiple levels of analysis and indicate a functional specialization exists within the lower extremities when considering force production and postural control properties.

At the GRF level of analysis, the between limb peak GRF\textsubscript{v} asymmetry finding during the squat task supports some previous evidence,\textsuperscript{13} while contrasting other results.\textsuperscript{14} During weighted back squats performed by college athletes Newton et al.\textsuperscript{13} reported significant bilateral differences in peak GRF\textsubscript{v} during the concentric phase of the movement with the dominant leg producing a greater peak force. However, when categorized by right and left leg, no significant difference in peak GRF was found between limbs, seemingly indicating limb symmetry.\textsuperscript{13} In a drop landing task, Schot, Bates, & Dufek\textsuperscript{14} qualitatively observed bilateral asymmetries in GRF peaks at the individual level but reported no significant limb differences when compared at the group level. In alignment with Newton and colleagues,\textsuperscript{13} the cur-
rent study only considered the concentric phase of the squat. Consistent with their findings in a weighted back squat, the current results revealed that peak force asymmetries exist during bodyweight squat. However, Newton et al. categorized the dominant limb based on isokinetic strength testing and linked such strength differences to other functional asymmetries found in explosive movements. Here, preferred limb was identified using a footedness questionnaire which may exhibit differing characteristics than the asymmetric performance advantage (e.g., limb dominance, strength imbalances) observed previously. Future investigation is needed to better understand the connections between limb dominance and preference during the squat movement given that previous evidence has highlighted that injury and fatigue appear to induce greater degrees of lower limb asymmetries.

The functional demands of the squat movement would appear to require symmetrical kinetic properties pertaining to force production, suggesting a lack of functional specialization between the lower limbs in healthy individuals. Bilateral asymmetries have been explored in a variety of motor tasks with the collective evidence failing to provide clear insight on the generality of interlimb performance characteristics. For example, an investigation of limb dominance, foot orientation, and functional asymmetry during normal gait resulted in significant differences between the dominant and non-dominant limb for medial and lateral peak GRF and impulses. In upright standing, some findings indicate that the dominant limb exhibits a performance advantage (e.g., less postural sway) over the non-dominant limb, whereas other findings typically show symmetrical postural sway between the limbs. Furthermore, motor tasks that demand asymmetrical roles (i.e., kicking, stepping on a box) between the limbs do appear to support the notion of asymmetrical control. The results of the current study suggest that the force production characteristics and postural control properties of the lower limbs in healthy individuals both reflect asymmetry but to varying degrees dependent on the tempo of the squat movement. For example, the contrasting findings between the two kinetic variables (GRF peak and impulse) suggest that further delineation may be needed between the control properties of the preferred and non-preferred limbs. A clear performance advantage for the preferred limb was observed in terms of producing peak force values during the self-paced condition of the squat movement. This advantage appears to be complemented by efficient force production in that lower impulses were produced compared to the non-preferred limb. Overall, these findings are consistent with the notion of functional specialization of the lower extremities in most motor tasks.

The variation of movement tempo has been used frequently during walking and running tasks to understand potential shifts of lower limb symmetries. However, manipulation of tempo has received minimal consideration during bodyweight squats despite the relevance to rehabilitation approaches. Here, both the preferred and non-preferred limbs exhibited greater peak GRF during self-paced bodyweight squats compared to squats executed in the metronome condition that was likely associated with an increased movement velocity. This pattern of results held true for the non-preferred limb when considering

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**Figure 1. Significant Tempo x Leg Interactions for Peak GRF<sub>p</sub> and F<sub>impulse</sub>**

Top Panel: Peak GRF<sub>p</sub> was significantly greater for the preferred limb compared to the non-preferred limb in the self-paced condition compared to the metronome condition during bodyweight squats (p < 0.001). No other main effects or interactions were significant for peak GRF<sub>p</sub>. Bottom Panel: F<sub>impulse</sub> was significantly larger for the non-preferred limb during the self-paced condition. GRF<sub>p</sub> vertical ground reaction force; N: Newtons.
GRF_{impulse} but the preferred limb exhibited lower GRF_{impulse} during self-paced squats compared to the metronome condition. Understanding how tempo affects force production and variability, specifically during bodyweight squats, may have an impact on therapeutic exercise prescription as rehabilitation exercises are often performed at a self-selected pace. Here, smaller degrees of asymmetry were observed in the metronome condition compared to the self-paced condition. Promoting symmetrical characteristics is often a primary goal of rehabilitation for most lower limb injuries, and the use of a metronome may facilitate an individual’s ability to control the level of force production between the injured and non-injured limb.

The dynamic nature of bodyweight squats challenges the stabilization control of each leg, and the current findings revealed different postural solutions between the preferred and non-preferred leg not typically found in simple balance tasks.^{20-22} The reduced COP variability observed for the non-preferred as compared to preferred leg suggests an enhanced stabilization component for the non-preferred leg during the propulsion phase of this dynamic movement. Therefore, it appears that the non-preferred leg more effectively countered the mechanical perturbations of body movements, and this was consistent for both AP and ML directions. However, future investigations should consider not only pedal preferences^{8} but also training histories^{16} when interpreting bilateral asymmetries.

Another aim of the current investigation was to examine the potential interaction between two types of asymmetry (ground reaction forces and COP under each foot), which has received minimal study in the literature. Significant differences were observed between the lower limbs for the GRF properties, and the non-preferred limb showed significantly lower COP displacements than the preferred limb. Previous evidence has shown the dependent nature of weight distribution on COP displacements during upright standing. For example, Rougier^{22} showed that the more loaded limb exhibited larger displacements during unstable conditions, suggesting a compensatory strategy between the lower limbs in order to minimize whole body sway. Similarly, King, Wang and Newell^{8} revealed asymmetries that were dependent on weight distribution across different postural configurations (staggered and tandem stances). In the current study, the less stable preferred limb showed increased displacements in both the AP and ML directions. Thus, the reduced COP motion under the non-preferred limb may aid in limiting whole-body COP displacements in a manner that achieves postural stability in both directions during squat execution. Future examinations of the relative contribution of each limb (i.e., weight distribution) to whole-body COP movements would provide insight into the ability of the postural control system to accommodate such variable asymmetries.

While the current study did not directly examine the role of fatigue, it is important to consider the relative impact of fatigue on bilateral asymmetries. A lack of a significant repetition effect suggests that fatigue did not influence the measured bilateral asymmetries (peak GRF_v, COP variability, or impulse = F_{impulse} during the bodyweight squat task within a healthy, active population. Interestingly, during five sets of eight repetitions of a weighted squat exercise, bilateral GRF_v became more symmetric after participants were fatigued within one set, but this symmetrical behavior did not carry over between sets.^{12} Similar results of in-
creased symmetry of load distribution and knee and hip joint loading patterns were observed within a patient population (anterior cruciate ligament reconstruction) during 10 consecutive bodyweight squats completed after a fatiguing protocol. The physical activity level of the participants may have mitigated the role of fatigue across the 20 squat cycles. Additionally, in contrast to typical fatigue protocols, the volume of workload used in the current study may have only resulted in a minor degree of fatigue, and future investigations should examine the process of fatigue onset with increased movement repetitions.

A few limitations of the current study need to be considered. First, the experimental instructions did not impose constraints on participants’ selection of the self-paced tempo to be faster or slower than the metronome-paced tempo, and future investigations should consider individualizing the metronome tempo by manipulating a self-paced tempo by a percentage value. Second, it may be important for future investigations to consider sport-specific training that may influence bilateral asymmetries. Lastly, pedal asymmetry developed through the bilateral or unilateral nature of a sport potentially further contributes to differences in pedal asymmetry.

CONCLUSION

The double leg squat, in either a bodyweight or weighted condition, represents a foundational movement pattern used in most sport training programs and is highly fundamental to rehabilitation environments. While asymmetries in ground reaction forces tend to be minimized through certain training approaches, the observed functional differences of the recorded kinetic properties in the current study indicate that traditional notions of symmetry may not hold true, even within a population of healthy individuals. While these results add to the existing literature, further work is needed to fully understand the impact of tempo, sport training, and fatigue on the functional outcomes associated with the double leg squat, as it is a frequently-used exercise in rehabilitation and athletic settings. Coaches and practitioners need to consider this preferential use of the right and left legs when developing strength training exercises and sport-specific drills in order to maximize overall task performance for these athletes.

CONFLICTS OF INTEREST

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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REFERENCES


Original Research

Establishing Normative Dynamic Postural Control Values in Elite Female Handball Players

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Background

Lower extremity injuries among young female handball players are very common. The modified Star Excursion Balance Test (mSEBT) is a valid clinical tool to assess dynamic postural control and identify athletes with higher risk of injury. However, its interpretation is difficult since performance on this test is highly sport dependent. No normative values on the mSEBT exist in handball.

Purpose

The aim of this investigation was to establish normative ranges of mSEBT performance in young, healthy female handball players to help practitioners when interpreting risk estimates.

Study design

Cross-Sectional Study

Methods

Athletes from 14 elite teams were recruited during a national tournament and performed 3 trials in the anterior (ANT), posteromedial (PM), posterolateral (PL) directions of the mSEBT. Means, standard deviations and 95% confidence intervals (95%CI) of normalized reached distances were calculated for each direction and the composite score (COMP). Level of asymmetry between dominant and non-dominant limbs were calculated for each direction using Bland Altman analyses. Group differences were weighed against the established mSEBT minimum detectable differences (MDD) to compare scores between limbs and across different player positions.

Results

One-hundred and eighty-eight females (16.8±0.9 years) were tested. Mean reach distances were 65.2±5% (64.7-65.7), 110.0±6.2% (109.3-110.6), 107.1±6.2% (106.5-107.8) and 94.1±4.9% (93.6-94.6) for the ANT, PM, PL directions and COMP score respectively. Bias and limits of agreement for limb asymmetry were -0.23% (-5.85%, 5.38%) for ANT, -0.83% (-8.80%, 7.14%) for PM, 0.33% (-8.51%, 9.17%) for PL and -0.27% (-4.88%, 4.33%) for COMP score. No meaningful differences were observed between limbs or across player positions since the values did not exceed the MDD and all 95%CIs overlapped.
Conclusion

This study provides normative performance values for dynamic postural control as measured by the mSEBT among young, healthy, elite female handball players. Considering the high incidence of injury in this population, these values can be used for injury risk reduction and return to sport decisions. Further prospective studies are needed to establish specific cut-off scores in this population.

Level of evidence

2c

INTRODUCTION

Handball is one of the most popular Olympic team sports in Europe with an increased number of players over the past decades. It is now considered as one of the sports with the highest injury rates as it requires high-intensity skills including intermittent sprinting, landing, and one-on-one dual tasks with fast changes of direction. These are all considered to be high-risk demands associated with lower limb injuries since they require challenging technique and coordination elements like catching, throwing, passing, and dribbling. In handball aggressive contacts are also often used not only to stop the opponent but also to intimidate opposing strikers from approaching the goal. Unlike most other team sports, an unlimited number of fouls are allowed to neutralize opponents and disrupt the attacking team’s strategy. Injury incidence has been estimated at 89–129 injuries per 1,000 match hours for males and 84–145/1,000 match hours for females during elite competition. Knee and ankle joint injuries represent 50% of all injuries in handball including lateral ankle sprains (LAS) and anterior cruciate ligament (ACL) ruptures. Young female players (16-18 years old) are considered to be at higher risk for lower limb injuries compared to their male counterparts.

For the sports health care staff and coaches of a competitive team, injury risk reduction remains a central issue, especially among young female athletes. The rehabilitation process and the decision to return to sport also require objective criteria to mitigate the risk of recurrence and allow athletes to return to the field at the same level of play. In order to effectively reduce the risk of injury, it is first important to identify risk factors that predispose athletes to injuries. Normative data or preseason baseline characteristics from healthy similar populations are therefore needed to first understand what is considered to be normal. A careful approach to the selection of relevant test protocols is needed for the health and performance staff around the handball player.

The Star Excursion Balance Test (SEBT) is a reliable and accessible test to assess lower body dynamic postural control. It is a common clinical assessment tool to detect functional deficits associated with chronic ankle instability (CAI) and ACL deficient athletes. It has also demonstrated predictive value for identifying those at greater risk of lower limb injuries in team sports. A modified version (mSEBT) using only three (anterior, posterome..
mates of healthy performance and the normally-occurring asymmetry across handball player positions.

MATERIALS AND METHODS

DESIGN

This cross-sectional study was conducted using a large and homogenous sample of young elite female players recruited during a major women’s national tournament which is the highest-level tournament for this age group.

PARTICIPANTS

Two hundred and sixteen female handball players from fourteen elite female handball teams participated in this study (Figure 1). This study was approved by the Regional Ethics Committee of the University. Informed consent was obtained from all participants and the rights of athletes were protected. As all of them were under 18 years of age, parental or guardian received and signed the institutionally approved informed consent. Athletes were informed of the benefits and risks of the investigation.

As previous injury influences mSEBT performance,15 a clinical examination was performed by a certified sport physiotherapist and injury history was recorded before completing the testing session. Only healthy athletes were selected (e.g. pain free, cleared for full participation, not receiving medical treatment) to create a reliable database of mSEBT performances for handball female players. Players with recent injuries on lower limbs (i.e. less than three months) were not included in the study.

Prior to the test, age, level of play (club division and experience at that level), position on the field and limb dominance were recorded. Athletes were asked to determine their level of fatigue using a Borg scale ranging from 0 to 10.29,30 Then, after the completion of the test, athletes had to report any perception of pain during the test. Athletes who presented a level of fatigue greater than 6 (i.e. strong fatigue) or/and perception of pain were excluded from the analysis. Athletes were also split into four position groups (wing, back, goalkeeper and pivot) according to their usual match and training positions. The dominant limb was defined as the preferred push-off leg during handball tasks such as jumping and shooting.31

There was a homogenous level of competition and practice (8h of training plus one match per week) across athletes as they were considered as the best national handball players under 18 years of age (Elite National 1).

PROCEDURES

The mSEBT procedure followed recently published guidelines16 and methods described in large cohort studies in order to assess dynamic postural control among athletes.13,15,32 Dynamic postural control refers to the task that the subject while standing on a single limb, has to reach as far as possible with the opposite limb along several lines on the floor and return to the initial position without losing balance.15 It therefore reveals the athlete’s postural ability during a dynamic movement of the opposite lower limb. Athletes performed a standardized mSEBT training session prior to the testing session which consists of four practice trials on both legs in each direction.33 No technical skill is needed for implementing the mSEBT, as anyone can administer the test with appropriate training regardless of their qualification. Indeed, Van lieshout et al. showed that if the evaluator is trained properly, test reliability remains good to excellent.34 The instructions for performing

Figure 1. Flow chart of participants selection.

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medial (PM) and posterolateral (PL) directions were calculated from the following equation.\cite{15,34}

\[
\text{Normalized "Given" score} (\%) = \frac{\text{mean of the three trials in "Given" direction (cm)}}{\text{Limb length (cm)}} \times 100
\]

Mean of those directions were used to calculate the composite score (COMP) for each athlete from the following equation:

\[
\text{Composite score} (\%) = \frac{\text{ANT} (\%) + \text{PL} (\%) + \text{PM} (\%)}{3}
\]

**STATISTICAL ANALYSES**

**Assessment of Limb Performance Asymmetry:** To assess the level of side-to-side asymmetry, pairwise t-tests were used to compare the dominant and non-dominant limb for each direction as well as the composite score. Limits of agreement were calculated using Bland Altman methods\cite{36,37} for each direction and COMP score in the overall sample. The asymmetry values were then contextualized based on the established minimum detectable differences (MDD) for each direction in the published literature.\cite{16} Indeed, even if the differences may appear significant, it is necessary to verify that they can be identified with the test by exceeding the MDD.

**Overall mSEBT Performance:** After checking that no side-to-side asymmetry existed, both limbs were pooled to create overall estimates of mSEBT performance for each participant. Means, standard deviation (SD) and 95% Confidence Intervals (95% CI) were used to provide a point estimate and measure of variability of what is considered to be "normal" for female handball players.

**The Influence of Position on mSEBT Performance:** Finally, means and 95% CI were calculated for player position. Forest plots were then generated to visually appreciate any trends associated with player position and mSEBT performance. As well, asymmetry scores were further stratified to player position and the asymmetry upper and lower limits were compared to the established MDD.

All statistical analysis were performed on JASP (Amsterdam 0.16.2.0). Before carrying out the statistical tests, normality was checked using the Shapiro–Wilks test. For all analyses, statistical level of significance was fixed at \( p < 0.05 \) and effect size (i.e. Cohen's \( d \)) were calculated if necessary for all the comparison.

**RESULTS**

After exclusion criteria were applied, 188 (16.8 ±0.9 years) of the 216 original athletes were included in this study (Figure 1). Baseline characteristics for the participants are reported in Table 1.

Normalized performance for the overall sample and estimates for the population (95%CI) can be found for each direction and the COMP score in Table 2. The ANT direction had the lowest normalized reach distances across participants. Performance in both posterior directions was similar and confidence intervals did not overlap with ANT values.

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**Figure 2. Position of the subject for the evaluation of the right limb in the anterior direction.**

The mSEBT were given by the same trained investigator who demonstrated and the test and feedback was provided during the practice trials in accordance to the established guidelines. Athletes performed the mSEBT on each lower limb, starting with the right limb and alternating side for each direction in order to avoid fatigue. They stood barefoot in double limb stance (i.e. feet together) in the middle of the testing grid. In order to ensure an equal position across the measured trials, athletes placed with the most distal aspect of their great toe at the origin line (Figure 2). This foot position remained constant between all testing directions, in accordance with previously published standards.\cite{13,15,26}

Athletes were asked to reach the maximal distance along each direction with the most distal portion of the reaching foot touching the directional line and regaining double limb stance. For each trial, athletes were required to maximally reach in the respective test direction, slightly touch the tape measure with the toe of the reaching limb without shifting weight to it. During the test, athletes were asked to keep their hands on the hips and were not allowed to move or lift the stance foot.\cite{35} Three trials were then recorded for each leg in the three directions.\cite{15} In order to avoid fatigue, the measured limb was alternated between each direction.

Performance was assessed by the same investigator with a measuring tape directly placed on the floor.

For between-athlete comparisons, reach distances were normalized to lower limb length.\cite{15} The leg length was measured in supine position, from the anterior superior iliac spine to the medial malleolus by the same investigator.

The average of the three trials was used for analysis of each outcome measure.\cite{15} Normalized reach distances (i.e. percentage of limb length) for the anterior (ANT), postero-
When analyzing side-to-side asymmetry, no significant differences were found regarding limb dominance for any direction (p>0.05). Performance of the overall sample for dominant and non-dominant limb as well as means of differences and limits of agreements for each direction are presented in Figure 3. Across all mSEBT directions, there was less than 1% asymmetry between limbs, which indicated that there was not a limb bias in mSEBT performance. The difference between the dominant and non-dominant limb (with 95%CI) averaged -0.23% [-5.95; 5.38] for the ANT, -0.85% [-8.80; -7.14] for PM, 0.37% [-8.51; 9.17] for PL and -0.27% [-8.80; 4.33] for the COMP score (Figure 3B, C, D, E). When comparing to the established MDD values for each direction,\textsuperscript{16} the majority of the asymmetries would not be considered meaningful (Figure 3).

Figure 4 illustrates means and 95% CI performance per direction for the overall population and each of the four player positions.

Mean and 95% CI asymmetry of performance for the overall population and across player positions are represented in Figure 5, for each direction.

**DISCUSSION**

The primary purpose of this study was to provide normative values for performance on the mSEBT in young elite female handball athletes. This is the first large sample cross-sectional study investigating mSEBT performance among this at-risk population. Considering the narrow range of 95%CI, clinicians can assume that healthy players from their team should have comparable mSEBT performance (65% for ANT, 110% for PM, 107% for PL direction and 94% for the COMP score) when performing the same testing procedure. Based on the overall trends uncovered, both the PM and PL directions exceed 100% of limb length. When comparing to National Collegiate Athletic Association (NCAA) Division I female players,\textsuperscript{15} this population exhibited higher COMP scores than athletes from all sports that have been previously evaluated (basketball, golf, hockey, soccer, softball and volleyball). Interestingly, the 95% CI reported from this study did not overlap with those calculated from this sample. Those differences seem to be highly influenced by much greater scores in the PL direction compared to others sports.\textsuperscript{15} Comparable performances were observed, especially in basketball, for ANT (64.3% and 63.4%), and in

### Table 1. Baseline characteristics of all participants.

<table>
<thead>
<tr>
<th>Overall (n=188)</th>
<th>Wing (n=58)</th>
<th>Back (n=65)</th>
<th>Goalkeeper (n=33)</th>
<th>Pivot (n=32)</th>
</tr>
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<tbody>
<tr>
<td>Age (Years)</td>
<td>16.8 ± 0.9</td>
<td>16.8 ± 0.9</td>
<td>16.8 ± 0.9</td>
<td>17 ± 0.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>171.5 ± 4.8</td>
<td>165.8 ± 3.4</td>
<td>171.2 ± 1.9</td>
<td>175.2 ± 2.9</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>61.7 ± 6.4</td>
<td>56.6 ± 3.3</td>
<td>58.4 ± 2.7</td>
<td>67.3 ± 7.4</td>
</tr>
</tbody>
</table>

### Table 2. Means, standard deviation (SD) and 95% Confidence Intervals of normalized score (% limb length) for anterior (ANT), posteromedial (PM), posterolateral (PL) direction and composite (COMP) score.

<table>
<thead>
<tr>
<th></th>
<th>Overall population</th>
<th>Wing</th>
<th>Back</th>
<th>Goalkeeper</th>
<th>Pivot</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANT</td>
<td>65.2 ± 5</td>
<td>65.3 ± 5.5</td>
<td>64.9 ± 4.7</td>
<td>64.6 ± 4.5</td>
<td>66.3 ± 5.1</td>
</tr>
<tr>
<td>PM</td>
<td>110.0 ± 6.2</td>
<td>111.4 ± 6.4</td>
<td>109.1 ± 5.9</td>
<td>109.6 ± 5.9</td>
<td>109.6 ± 6.7</td>
</tr>
<tr>
<td>PL</td>
<td>107.1 ± 6.2</td>
<td>108.4 ± 6.5</td>
<td>106.6 ± 5.8</td>
<td>106.1 ± 6.2</td>
<td>106.7 ± 6.4</td>
</tr>
<tr>
<td>COMP</td>
<td>94.1 ± 4.9</td>
<td>95.1 ± 5.3</td>
<td>93.5 ± 4.2</td>
<td>93.4 ± 4.6</td>
<td>94.2 ± 5.2</td>
</tr>
</tbody>
</table>

When analyzing side-to-side asymmetry, no significant differences were found regarding limb dominance for any direction (p>0.05). Performance of the overall sample for dominant and non-dominant limb as well as means of differences and limits of agreements for each direction are presented in Figure 3. Across all mSEBT directions, there was less than 1% asymmetry between limbs, which indicated that there was not a limb bias in mSEBT performance. The difference between the dominant and non-dominant limb (with 95%CI) averaged -0.23% [-5.95; 5.38] for the ANT, -0.85% [-8.80; -7.14] for PM, 0.37% [-8.51; 9.17] for PL and -0.27% [-8.80; 4.33] for the COMP score (Figure 3B, C, D, E). When comparing to the established MDD values for each direction,\textsuperscript{16} the majority of the asymmetries would not be considered meaningful (Figure 3).

Figure 4 illustrates means and 95% CI performance per direction for the overall population and each of the four player positions.

Mean and 95% CI asymmetry of performance for the overall population and across player positions are represented in Figure 5, for each direction.
hockey for PM (110.3 and 113.1%) on the dominant and non-dominant limbs respectively. Results from handball female players are also very similar in PM and PL direction but considerably lower ANT scores than those previously reported (71 to 81%) among high school basketball and older soccer female players.\textsuperscript{25,26} When comparing results from this study with elite and semi-professional female volleyball players,\textsuperscript{32} ANT scores were also lower (73.5% and 68.6% respectively) while all others performance values were much higher (90.4 and 83.7% for PM, 89.3 and 83.6% for PM, 84.5 and 78% for the COMP score) despite similar testing procedures. These results confirm that mSEBT performance appears to be influenced by the type of sport. Those discrepancies may be related mainly to anthropometric differences, physical demands, and movement patterns specific to handball. This sport is indeed characterized by intense body contact and demanding coordination skills, like catching, throwing and dribbling while being pushed by an opponent. Maximum intermittent sprints followed by explosive sidestep cutting maneuvers are also very frequent.

The second objective of this study was to evaluate side-to-side asymmetry according to lower limb dominance on mSEBT. Limb dominance does not appear to be a factor related to mSEBT performance in this group of athletes. This result aligns with evidence from other sports\textsuperscript{16,23} where side-to-side asymmetries on the test were not revealed. Handball female players from this study performed very similarly on their dominant and non-dominant limbs. Indeed, the upper and lower limits of the 95% CI for the level of asymmetry were very similar to the reported MDD (i.e. 5.7 vs 5.87%, 8.79 vs 7.84%, 8.8 vs 7.55% and 4.6 vs 6.7% for ANT, PM, PL direction and COMP score respectively).\textsuperscript{16} More precisely, none of the 188 athletes exceed the MDD for limb asymmetry in the COMP score, while only 6.9% (13 athletes) overlap it in the ANT and PM direction and 10.6% (20 athletes) in PL direction (\textbf{Figure 3}). These results validate the external validity of the limits found in this sample. Thus, although handball is a sport that is considered highly asymmetrical in nature,\textsuperscript{25} there does not appear to be a pattern of differences in performance between the two lower limbs. A major side-to-side asymmetry should therefore be carefully addressed as it may reveal a potential risk factor (see below) for future lower limb injuries.\textsuperscript{20,26} It should be noted that in most studies, the dominant limb is defined as the one used to kick a ball while in handball it systematically refers to the preferred push-off leg.\textsuperscript{5}

The third objective of this study was to determine more specific mSEBT performance and amount of asymmetry according to the player position. This is the first study investigating dynamic postural control across playing position in handball. Team handball is composed of seven players on the court exhibiting various physical profiles.\textsuperscript{27} For example, wingers are the fastest (15 and 30 m sprint), strongest (counter-movement jump), and most enduring players on handball teams compared to other player positions.\textsuperscript{27} In addition, female wingers show different physical and anthropometric characteristics than other positions as they are typically lighter and shorter.\textsuperscript{38} The differences in performance observed in this study could also be explained by positional demands - wing players require more intensive locomotive activity patterns and motor skills such as

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Means and Standard Deviation of normalized performances in anterior (ANT), posteromedial (PM), posterolateral (PL) direction and composite score (COMP) for dominant and non-dominant limb (A). Between limb comparisons using Bland and Altman representation with limits of agreements (dotted) and minimal detectable difference (solid) for ANT (B), PM (C), PL (D) and COMP (E).}
\end{figure}
sprinting, jumping and complex landing with unbalanced distribution than other playing positions. Conversely, goalkeeper activity skills could be considered more static than other players. However, differences across player positions did not exceed the MDD with all 95% CI overlapping. Those results indicate trivial differences between player positions so that practitioners can be confident when comparing athletes from several positions on the field. When focusing on pattern of asymmetry, the narrow range of 95% CI obtained after splitting athletes (Figure 5) confirms the homogeneity of the results.

There is consistent evidence that the mSEBT is a relevant test in the context of injury risk. Indeed, this test is widely used by sport clinicians to target individuals with higher risk of injury. Similarly, numerous studies supported the use of this test in the return to sport decision following lower limb injuries such as ACL reconstruction and lateral ankle sprains. While injuries were not prospectively monitored in the athletes included in this study, several results appear to be relevant for clinicians. As previously mentioned, the obtained COMP score in the overall population (94.1%) and each player positions were higher than most reported studies from various sports. Very interestingly, this value was previously described as an important cut-off score, as female basketball players exhibiting a COMP normalized reach distance lower than 94.0% were 6.5 times more likely to sustain a lower extremity injury. It appears therefore important for medical and technical staff to consider this value as a minimum target for female handball players in the context of injury prevention and the process of return to sport. Similarly, side-to-side asymmetry is a key factor for injury risk, normative values were therefore calculated in this populations. Results show that 95%CI of normalized asymmetry never exceed 3% regardless the direction and player position. Stiffler et al. showed higher risk of lower limb injuries when normalized asymmetry was > 4.5% in the ANT direction, with athletes in the injured group demonstrating 1.9% limb length greater anterior asymmetry on average than those in the healthy group. When applying the cut-off score of 4.5% normalized asymmetry in the ANT direction it represents 22 athletes (11.7%) in our population.

Figure 4. Forrest plot of means (%) and 95% Confident Intervals of normalized performances in anterior (ANT), posteromedial (PM), posterolateral (PL) and composite score (COMP) for each player positions.

Vertical lines in the center represent the mean of overall population and dotted lines indicates the Minimum detectable difference.
Similarly, basketball players exhibiting absolute asymmetric performance greater than 4 cm in the ANT direction were 2.5 times more likely to sustain lower limb injuries. In handball, wing players were more likely to sustain injuries than other positions. Handball coaches and clinicians should be alerted when their players fall outside the reported 95% CI of mSEBT scores and limb asymmetry (Figure 4 et 5). However, prospective studies are needed to confirm and clarify current results and estimates for the population and determine specific asymmetry cut-off scores for team handball players.

Limitations of this study include the players’ background regarding sports activities before handball. It can be argued that practice history before handball could allocate skills that influence performance on mSEBT. Furthermore, the tournament lasted three days and some teams were evaluated at the beginning and others at the end of the competition. Moreover, performance is also influenced by age and sex. Since participants were all recruited from young elite women’s handball teams, the results may not be generalizable to other age groups, participation levels or sport disciplines. Further studies are therefore needed for male handball athletes and across different age groups and ability levels.

CONCLUSION

In this study, a large normative database of mSEBT performance among young, elite, healthy handball players was established. Female handball players are considered a high-risk population for lower limb injuries. Clinicians can use these results as a comparison for preseason baseline testing, to evaluate the rehabilitation process when baseline characteristics are missing or as return to sport criteria. Limb dominance did not influence performance so side-to-side asymmetry that exceeds established MDDs should
alert clinicians and coaches as a potential risk of future injuries. These findings should be used with caution when comparing athletes from different sport populations. Further prospective studies are needed to establish accurate cut-off scores for injury risk.

ETHICS APPROVAL

This study was approved by the Regional Ethics Committee from Savoie-Mont Blanc University.

CONFLICTS OF INTEREST

The authors have no conflicts of interest

ACKNOWLEDGMENTS

The authors would like to thank Aurélie Collomb-Clerc for her precious help during the experimentation, the technical and medical staff of each team for their time and confidence, and all the volunteers who worked for the organization of the competition. The authors also thank all the athletes who volunteered to participate in this study as well as the French Handball Federation.

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REFERENCES


Can Clinician-Stabilization with Hand-Held Dynamometry Yield a Reliable Measure of Knee Flexion Torque?

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Keywords: hand-held dynamometry, hamstring strength, isometric testing, reliability

Background
Assessment of knee flexion torque is a relevant clinical measure following various injuries and surgeries to determine progress in rehabilitation and inform decision making. A variety of methods using hand-held dynamometry have been shown to be reliable in obtaining this measure, and typically require a means of external fixation or stabilization. Clinically efficient methods of reliable clinician-stabilization are sparse in the literature.

Hypothesis/Purpose
Determine inter and intra-rater reliability of two clinically efficient methods of assessing isometric knee flexion torque using hand-held dynamometry with clinician-stabilization. The hypothesis was that each method would yield good to excellent reliability.

Study Design
Cross-Sectional Study

Methods
Twenty healthy individuals were assessed by two clinicians on two separate days. During each session, knee flexion torque was assessed with hand-held dynamometry with two methods: 1) in the seated position with the hip and knee flexed to 90 degrees while the clinician stabilized the dynamometer between the participant’s leg and table and 2) in prone with the hip at 0 degrees and knee at 90 degrees while the clinician assumed a stride stance with elbows locked in extension to stabilize the dynamometer on the participant’s leg. Inter and intra-rater reliability were determined for each method.

Results
ICC values were 0.88-0.94 and 0.77-0.90 for inter and intra-rater reliability respectively with the seated method. The prone method yielded ICC values of 0.84-0.96 and 0.89-0.94 for inter and intra-rater reliability respectively. MDC values ranged from 50-62% with the seated method and 21-40% with the prone method.

Conclusion
Inter and intra-rater reliability were good to excellent for assessing knee flexion torque with hand-held dynamometry using both the seated and prone methods with clinically efficient clinician-stabilization approaches. The prone method may be more sensitive to detecting change over time due to lower MDC values.
Level of Evidence

INTRODUCTION

Sports medicine professionals utilize various clinical tests to determine capacity to produce force in patients. Isokinetic dynamometry is currently considered the gold standard for determining single joint muscle strength.1 However, this is not widely available in the clinical setting due to limitations of cost, space, and requisite time for testing. An alternative that is frequently used clinically is isometric testing with a hand-held dynamometer (HHD). This has been shown to be reliable for various joints when set up in a rigid and repeatable manner,2 and has been reported to be significantly correlated to isokinetic testing.3,4 Although previous work has demonstrated good to excellent reliability for clinician-stabilized HHD,4 belt stabilization is typically recommended.2 This may be more apparent when testing larger muscle groups capable of higher force production if the clinician or patient is not able to maintain a stable and rigid testing position.5,6 Further supporting this notion, the strength and sex of the examiner has been shown to influence reliability.5–7 Utilizing belt fixation or other forms of external fixation is one method that may mitigate the limitation of the clinician or patient’s strength.7–10 External fixation has been accomplished through various means clinically such as using gait belts, bracing against tables or walls, and using custom-built frames and devices.

One common HHD assessment includes knee flexion torque production. This measure may have utility in determining inter-limb deficits and comparing to normative data and also may allow a clinician to monitor progress throughout rehabilitation, determine effectiveness of interventions, and inform return-to-sport decision making.11,12 It should be acknowledged that this measure may not be directly used to infer (re)injury risk or sport performance. Prior literature has included a variety of methods with a HHD to obtain this measure.5,7,13–20 These studies collectively include a variety of patient positions, joint angles, and stabilization methods. It is important to note that knee flexion torque may vary depending on test position with potentially more torque producing capacity in longer muscle lengths (hip flexion and knee extension) possibly due to a muscle’s length-tension relationship.21,22 One should be cognizant of the testing positions and methods as it may be relevant when interpreting tests or comparing to previously reported data.

It is important to understand which clinically feasible positions and methods yield reliable measures as this gives insight to the force producing capacity of a muscle to aid in clinical decision making. In the clinical environment, it is also important to be efficient during testing as a measure of knee flexion torque represents only a portion of typical testing batteries. If reliable measures can be efficiently obtained during assessment of one physical quality, then this allows for more time to ensure appropriate and reliable measurement of other qualities, as well as provide the patient education on the interpretation of the results and possible interventions based on those results. It should be noted that many prior studies that support using belt fixation over clinician stabilization have been completed for the assessment of relatively strong and large muscle groups such as the knee and hip extensors.5–10 The knee flexors are typically capable of much less force production than the knee extensors, which is supported by a recent review including nearly 14,000 participants.22 Due to this, using clinician-stabilization when testing the knee flexors may be less susceptible to unacceptable reliability compared to the knee extensors. Therefore, the purpose of this study was to determine inter and intra-rater reliability of two clinically efficient methods of assessing isometric knee flexion torque using a HHD with clinician-stabilization. The hypothesis was that each method would yield good to excellent inter (between testers, within session) and intra-rater (within each tester, across sessions) reliability.

METHODS

SUBJECTS

Participants were recruited in this cross-sectional study as a convenience sample via an organizational email and word of mouth. Participants were assessed on two separate days (average seven days between sessions). Testing sessions were attempted to be completed as close as possible to the same time of day to account for potential circadian variation.23 Exclusion criteria included prior history of hip or knee injury requiring medical intervention and participants who were unable to understand testing procedures or provide consent. This study was approved by the Lawrence Memorial Hospital Institutional Review Board and participants were provided written informed consent and given the opportunity to ask any study-related questions prior to participating.

PROCEDURES

Participants began each session with a self-selected three to five minute warm up on a stationary bike, elliptical, or treadmill. Moment arm length was measured as the distance between the center of the lateral femoral condyle and the most lateral point of the lateral malleolus in the seated position using a standard measuring tape. This distance represents the knee joint axis of rotation and the point of force application for use in calculating torque. Dynamometry testing was completed in two positions, by two examiners, on both the dominant and non-dominant limb. Limb dominance was determined by asking “which leg would you prefer to kick a ball with?” The order of the tester, limb, and position were randomized on the first day and the same order was repeated for the second session. Figure 1 displays the process of testing among position, limb, and examiner. Each examiner was blinded to the results of the other examiner. The testing positions included 1) seated at
the edge of a table with the hips and knees flexed to 90° with hands gripping the sides of the table for stabilization with the examiner holding the dynamometer between the leg of the table and leg of the participant (posterior to the lateral malleolus) and 2) lying prone on the table with the hip at 0° and knee at 90° with hands gripping the table for stabilization while the examiner assumed a stride stance position with elbows locked in extension and hands overlapping (Figure 2). This position was chosen based on the experience of the examiners as it was believed to afford adequate stability for the test. The dynamometer used for testing was a Hoggan MicroFET2® HHD (Hoggan Health Industries, Salt Lake City UT, USA). This device has previously demonstrated good to excellent inter and intra-rater reliability, as well as concurrent validity compared to a fixed dynamometer for a knee flexion torque test. 15 "Make" tests were utilized meaning that the participant voluntarily produced as much force as possible during each test. Prior to testing trials for each session, one to three submaximal trials were completed for familiarization. Following this, three maximal effort trials were completed. The participant was instructed to gradually increase force during the first second of a three to five second max effort push into the dynamometer. Vigorous verbal encouragement was provided by the examiner to help ensure that maximal effort was achieved. Approximately 10 seconds rest was given between contractions as the examiner recorded the data, and two to three minutes rest was given between examiners. If an individual tester noted a trial to be greater than -20% different from the other two trials for that same session and tester, then an additional 30 second rest was given, and another trial was completed.

STATISTICAL ANALYSIS

Participant demographics were reported using descriptive statistics. Peak force (N) was recorded from each trial and converted to torque using the shank length. The average peak force of the three maximal attempts from each limb, position, and examiner was used for analysis. The intraclass correlation coefficient (ICC) and 95% confidence intervals were calculated in SPSS v.26 (IBM, Armonk, NY) to determine inter and intra-rater reliability. ICC values were classified as poor (<0.50), moderate (0.5-0.75), good (0.75-0.90), and excellent (>0.90). 25 An a-priori alpha of 0.05 was used for statistical analysis. The standard error of measurement (SEM) was calculated using the equation SD * √(1-ICC). 26 The minimal detectable change (MDC) was calculated as 1.96 * √(2) * SEM. 26 MDC was also reported as a percentage.

RESULTS

INTER-RATER RELIABILITY

Twenty healthy recreationally active individuals participated in this study (Table 1). Inter-rater reliability (between testers, within session) was good to excellent for both the seated and prone positions for both the dominant and non-dominant limbs. MDC ranged from 30-45% for the seated position and 21-40% for the prone position (Table 2).

INTRA-RATER RELIABILITY

Intra-rater reliability (within each tester, across sessions) was good for the seated position and excellent for the prone position for examiner 1, while it was good to excellent for both positions for examiner 2. MDC ranged from 43-62% for the seated position and 23-34% for the prone position (Table 3).

DISCUSSION

The purpose of this investigation was to determine inter and intra-rater reliability of isometric knee flexion torque production during two clinically efficient and pragmatic testing methods. The hypothesis that good to excellent inter-rater reliability (between testers, within session) and intra-rater reliability (within each tester, across sessions) would be found for both methods was supported.

These findings for inter-rater reliability are consistent with previous reports. Others that have investigated HHD assessment of knee flexion in a seated position (90° hip flexion, 90° knee flexion) have reported good to excellent ICC values for inter-rater reliability ranging from 0.82 – 0.99. 15,17 Specifically, Mentiplay et al. used perhaps the most comparable seated method to this study (90° hip flexion, 90° knee flexion, with clinician-stabilization) and reported ICC values of 0.82-0.92. 15 Others that used a seated position (90° hip flexion, 90° knee flexion, with external fixation) reported ICC values of 0.93-0.97 16 and 0.99. 17 In the prone position, prior work has investigated various degrees of hip and knee flexion with all included angles yielding good ICC values from 0.82 – 0.87. 19,20 None of these prior studies assessed in prone position used in this investigation (0° hip flexion, 90° knee flexion). The most comparable to the prone position in this study possibly was van der Made et al. (0° hip flexion, 15° knee flexion, with clinician-stabilization) who reported ICC values of 0.80-0.84. 19 Other studies utilizing a prone method reported ICC values of 0.84 (0° hip flexion, 0° knee flexion, with external fixation), 7 0.82 (0° hip flexion, 15° knee flexion, with external fixation), 7 0.82 (0° hip flexion, 15° knee flexion, with external fixation), 7 0.82 (0° hip flexion, 15° knee flexion, with external fixation).
Regarding intra-rater reliability, prior literature has been highly variable in the seated position with poor – excellent ICC values ranging from 0.49 – 0.98. As noted above, Mentiplay et al. had the most comparable seated method to this study and reported intra-rater ICC values of 0.89-0.96. Others that assessed the seated position at these same joint angles with external fixation reported ICC values of 0.77, 0.62-0.66, 0.98, and 0.49. The authors are not aware of a prior study reporting intra-rater reliability for the prone position at 0° hip flexion, 90° knee flexion. In the prone position (45° hip flexion, 30° knee flexion), Wollin et al. reported a good intra-rater ICC value of 0.86.

CLINICAL UTILITY

The importance of the findings in this study may be highlighted in that both testing approaches did not involve additional devices or set-up time due to external fixators or other equipment. Indeed, the inter and intra-rater reliability was shown to be generally high for both methods despite not utilizing external fixation for the dynamometer or participant and similar to values previously reported using fixed HHD for knee flexion torque. It may be argued that the seated position in this study offers a form of external fixation (the table) and therefore no longer is entirely clinician-stabilized by definition. The use of the table leg does add a novel aspect to this assessment while maintaining clinical pragmatism and offers another seated method available to the clinician in addition to the seated methods from prior studies further described above. Further, one should not interpret this study as a comparison of clinician-stabilization to external fixation, only as an investigation of reliability of two clinically efficient and pragmatic assessment methods. Most prior studies do not directly compare clinician stabilization to external fixation for knee flexion specifically, so it may not be directly concluded if the stabilization condition influenced reliability for this specific joint assessment. In one study that did compare belt stabilization of the dynamometer to clinician stabilization in the prone position (0° hip flexion, 15° knee flexion), the ICC values for inter-rater reliability were 0.82 and 0.84 respectively, suggesting that the belt stabilization did not influence reliability for that specific method of assessment. Further, utilizing external or belt stabilization does not necessarily mean that good or excellent reliability will be achieved. For example, Martins et al. reported only moderate reliability (ICC: 0.62 - 0.66) and Toonstra et al. reported poor reliability (ICC: 0.49) despite utilizing external fixation methods of the dynamometer when assessing knee flexion torque. Additionally, both van der Made et

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**Figure 2. Testing methods.**

A) The participant is seated at the edge of a table with the hip and knee flexed to 90 degrees and hands gripping the sides of the table while the clinician stabilizes the dynamometer between the participant’s leg and table. B) The participant is prone with the hip at 0 degrees and knee at 90 degrees and hands gripping the sides of the table while the clinician assumes a stride stance with elbows locked in extension to stabilize the dynamometer on the participant’s leg.

**Table 1. Participant demographics**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>±</th>
<th>StD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.4</td>
<td>±</td>
<td>8.9</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>173.2</td>
<td>±</td>
<td>14.4</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.5</td>
<td>±</td>
<td>17.7</td>
</tr>
<tr>
<td>Sex (male/female)</td>
<td>11/9</td>
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<td></td>
</tr>
</tbody>
</table>

cm=centimeters, kg=kilograms, StD=standard deviation, yrs=years
### Table 2. Torque and inter-rater reliability for each limb, position, and testing session

<table>
<thead>
<tr>
<th></th>
<th>Rater 1 Mean ± Std (Nm)</th>
<th>Rater 2 Mean ± Std (Nm)</th>
<th>ICC (95% CI)</th>
<th>SEM (Nm)</th>
<th>SEM (%)</th>
<th>MDC (Nm)</th>
<th>MDC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visit 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seated ND</td>
<td>65.0 ± 37.7</td>
<td>66.5 ± 33.3</td>
<td>0.92 (0.75,0.97)</td>
<td>9.8</td>
<td>15</td>
<td>27.3</td>
<td>41</td>
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<tr>
<td>Seated D</td>
<td>77.2 ± 34.0</td>
<td>73.8 ± 30.2</td>
<td>0.93 (0.78,0.98)</td>
<td>8.3</td>
<td>11</td>
<td>23.1</td>
<td>31</td>
</tr>
<tr>
<td>Prone ND</td>
<td>56.4 ± 22.7</td>
<td>63.9 ± 22.9</td>
<td>0.96 (0.87,0.99)</td>
<td>4.7</td>
<td>8</td>
<td>12.9</td>
<td>21</td>
</tr>
<tr>
<td>Prone D</td>
<td>53.1 ± 18.4</td>
<td>69.0 ± 22.6</td>
<td>0.84 (0.51,0.95)</td>
<td>8.8</td>
<td>14</td>
<td>24.3</td>
<td>40</td>
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<tr>
<td><strong>Visit 2</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seated ND</td>
<td>78.7 ± 36.5</td>
<td>70.1 ± 32.4</td>
<td>0.88 (0.62,0.96)</td>
<td>12.0</td>
<td>16</td>
<td>33.2</td>
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<tr>
<td>Seated D</td>
<td>85.3 ± 35.6</td>
<td>80.3 ± 39.0</td>
<td>0.94 (0.82,0.98)</td>
<td>8.8</td>
<td>11</td>
<td>24.5</td>
<td>30</td>
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<tr>
<td>Prone ND</td>
<td>59.1 ± 20.0</td>
<td>70.3 ± 26.3</td>
<td>0.94 (0.82,0.98)</td>
<td>5.7</td>
<td>9</td>
<td>15.9</td>
<td>25</td>
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<tr>
<td>Prone D</td>
<td>57.0 ± 17.6</td>
<td>73.1 ± 24.2</td>
<td>0.88 (0.62,0.96)</td>
<td>7.9</td>
<td>12</td>
<td>21.8</td>
<td>34</td>
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</tbody>
</table>

CI=Confidence Interval, D=dominant, ICC=intraclass correlation coefficient, MDC=minimum detectable change, ND=non-dominant, Nm=Newton meters, SEM=standard error of the mean, Std=standard deviation

### Table 3. Intra-rater reliability for each limb, position, and rater

<table>
<thead>
<tr>
<th></th>
<th>Intra-rater reliability (Rater 1)</th>
<th>Intra-rater reliability (Rater 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC (95% CI)</td>
<td>SEM (Nm)</td>
</tr>
<tr>
<td>Seated ND</td>
<td>0.89 (0.69,0.96)</td>
<td>12.5</td>
</tr>
<tr>
<td>Seated D</td>
<td>0.82 (0.53,0.94)</td>
<td>14.8</td>
</tr>
<tr>
<td>Prone ND</td>
<td>0.94 (0.82,0.98)</td>
<td>5.2</td>
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<tr>
<td>Prone D</td>
<td>0.94 (0.82,0.98)</td>
<td>4.6</td>
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</table>

CI=Confidence Interval, D=dominant, ICC=intraclass correlation coefficient, MDC=minimum detectable change, ND=non-dominant, Nm=Newton meters, SEM=standard error of the mean
al.\textsuperscript{19} and Mentiplay et al.\textsuperscript{15} showed good to excellent reliability for knee flexion torque assessment without a belt or external stabilization method. This may suggest that other aspects of the assessment method influence reliability, which may include but is not limited to the actual device used for stabilization, the dynamometer, the patient positioning, clinician positioning, characteristics of the clinician (i.e. sex, weight, strength), the instructions given, and both the patient and clinician’s familiarity with the assessment method. It should be made clear that this assumption of the lack of influence of external stabilization is only being suggested for isometric knee flexion torque assessment. Reliability of assessment of other joints and actions that are expected to produce greater torque such as knee extension and hip extension has been shown to generally be higher with an external stabilization method versus clinician stabilization.\textsuperscript{8–10,27} This is intuitive as a clinician would reasonably have more difficulty providing adequate stabilization against larger torque values.

Some clinicians may suggest that the extra time taken for HHD and patient fixation is a deterrent to obtaining the objective measurement. This deterring factor is mitigated with the methods of testing in this study, while still offering an acceptable form of stabilization. In the seated position, the participant’s own body weight stabilized the table providing for an immovable table leg to push the dynamometer against so that examiner strength is not a limiting factor. In the prone position, although the HHD is not fixated against an immovable object since it is held in place entirely by the examiner, the position assumed by the examiner (stride standing with elbows in full extension [Figure 2]) allowed for rigid enough stabilization to yield good to excellent reliability. Further, the participants were instructed to hold the table with both hands during each method to further provide some level of patient stabilization and limit compensatory mechanisms. It must be noted that sex, strength, and weight of the examiner and the patient could still be reasonably expected to influence reliability.\textsuperscript{5–7} Wikholm and Bohannon\textsuperscript{6} suggested reliability is more likely to be influenced by tester strength when participant force generation is greater than 120 Newtons. Below that value, reliability was not influenced by the strength of the tester. It is logical that this threshold may be variable among positions, joints, and actions assessed. It may be notable that both examiners in this investigation were males weighing >200 pounds that regularly participate in resistance training, which may have contributed to the observation of good to excellent reliability.\textsuperscript{5–7} Nonetheless, this study does provide options for clinically efficient and feasible methods of assessing knee flexion torque production.

One important observation in this investigation is the MDC values. MDCs include higher ranges for the seated position with values as high as 45% and 62% for inter and intra-rater reliability respectively. This is higher than intrarater MDCs previously reported up to 25 - 29\%,\textsuperscript{15,16} while previously reported intra-rater MDCs have been highly variable with the largest values ranging from 24 – 61\%.\textsuperscript{14,15,18} This represents a potential limitation of utilizing this testing method despite the good to excellent reliability. These high MDC values suggest that a reassessment would need to yield a relatively large change from the initial assessment for the clinician to be confident that a real change in knee flexion torque production capacity has occurred. If a change does not exceed this large MDC, then the clinician may just be observing expected variations in force output for the method of testing. This indicates a potential supporting element for testing in the prone position as MDC values were as low as 30% and 23% for inter and intra-rater reliability respectively. This is more comparable to prior studies which report inter-rater MDCs ranging from 15-25\%,\textsuperscript{7,19,20} and an intra-rater MDC of 14\%.\textsuperscript{20} The reason for the lower MDCs in the prone position may be mathematically due to lower standard deviations relative to the mean recorded with that method. The examiners subjectively noted that some participants in the seated position directed their line of force straight posterior into the dynamometer, while some appeared to direct their force in a slightly more superior oriented vector. This may have been due to the possibility of a slight compensation of concurrent hip flexion by the participants. Despite the dynamometer being held against an immovable table leg, the back of the dynamometer was a rounded surface that occasionally tended to slightly tilt against the flat leg of the table. This may have resulted in a relative decrease in the amount of force directed perpendicular to the dynamometer since their force vector was oriented slightly superior. As participants had varying degrees of force vector orientation, this may partially explain the larger relative standard deviations observed in the seated position and subsequently SEM and MDC calculations. If choosing to assess with the seated method utilized in this study, one should be cognizant to maintain the dynamometer directly perpendicular to the force vector produced by the patient. The clinician may improve this assessment by ensuring both hands firmly grasp both sides of the dynamometer and utilize adequate practice trials to ensure the participant is not adopting a compensatory hip flexion strategy.

The overall results of this study suggest that either of the clinically applicable assessment methods utilized in this study may be used to obtain a reliable measure of knee flexion torque production. The prone method may offer an advantage in that the MDC values are lower, indicating that this method may be more sensitive to detecting a true change when reassessing throughout the course of rehabilitation. Both methods provide the advantage of clinical efficiency as the only equipment required are a table and HHD, with no additional time and attention devoted to fixating the HHD or patient with external devices. When time and equipment restraints do not present as limitations, the authors still suggest utilizing any methods of patient and dynamometer fixation available that affords the most rigid and repeatable set up. This should especially be done if the clinician does not feel confident in their ability to stabilize the dynamometer, or the patient demonstrates compensations. Future research should identify clinically efficient and pragmatic reliable torque assessments for various joint angles and actions.
LIMITATIONS

There are several limitations of this investigation that should be acknowledged. First, there was no formal power analysis completed prior to commencement of the study which may have influenced the statistical results. Participants may not have achieved true maximal force production on all repetitions as an approximate 10 second break between trials may arguably have been inadequate. However, this testing protocol was chosen as it represents pragmatic testing during actual patient care when time may be a limiting factor. Additionally, the limb tested was alternated between positions to mitigate this and the examiners anecdotaly did not observe any consistent decrease in performance between trials. Regarding familiarization, there was not a true familiarization protocol in which the testing procedures were completed without data collection on a separate day. However, the same process of submaximal familiarization trials were used for each testing session for consistency. Both examiners were males weighing >200 pounds that regularly participate in resistance training, therefore these results may not generalize to clinician populations not sharing these characteristics. Further, the participants were all healthy individuals with no history of significant knee or hip injuries, and results in an injured population may differ. Finally, the observed results are specific to the particular methods of testing in this study, and should not be assumed to generalize across other testers, body positions, joint angles, etc.

CONCLUSION

The results of this study support that both the seated and prone positions with clinician stabilization may be utilized as a reliable means of determining knee flexion torque. The prone position yielded lower MDC values suggesting that it may be more sensitive in detecting actual change across multiple assessments. While it is suggested to use the most rigid and repeatable methods of stabilization available that time and equipment affords, the clinician stabilized methods utilized in this study offer a clinically efficient means of assessing knee flexion torque in a pragmatic clinical environment.

CONFLICTS OF INTEREST

None declared.

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REFERENCES


A Plague of Their Own: Injury Incidence Remains Elevated in the 2021 Major League Baseball Season Compared to Pre-COVID-19 Seasons

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Background

Significant increases in injuries were observed in the 2020 Major League Baseball (MLB) season; these were attributed to an increased acute to chronic workload due to the interrupted preseason and compressed season during the coronavirus disease of 2019 (COVID-19) pandemic. In 2021, the MLB resumed its regular schedule.

Hypothesis/Purpose

The purpose of this study was to determine the injury incidence and epidemiology of the 2021 MLB season compared to the injury incidence in the 2020 season and pre-COVID-19 seasons. The hypothesis was that, with the return to normal preseason training, injury incidence in 2021 would return to pre-COVID-19 rates. Additionally, it was hypothesized that injury list (IL) placements at midseason 2021 would be decreased relative to 2020 due to the uninterrupted preseason yet increased at full season 2021 due to increased overall workload from 2020.

Study Design

Descriptive epidemiology study

Methods

The MLB transactions database was searched for players placed on the IL between 2018 and 2021. Injuries were categorized by body part and player position. Incidence per 1000 athlete-exposures was calculated for the pre-COVID-19 (2018-2019), 2020, and 2021 seasons. The z test for proportions was used to determine significant differences between injury incidences.

Results

The injury incidence rate by midseason 2021 (9.32) compared to 2020 (8.66) was not significantly different (p=0.234). At full season 2021, injury incidence rate (8.69) was significantly higher than pre-COVID-19 seasons (5.15, p<0.001), but not 2020 (p=0.952). When comparing full season 2021 to 2020, increased foot/ankle (0.50 vs 0.14, respectively, p<0.001) and miscellaneous (1.92 vs 0.68, respectively, p<0.001) injuries were observed.
Conclusion

The overall injury incidence in 2021 was significantly higher than pre-COVID-19 seasons, and no significant difference was observed between both mid- and full season 2021 and 2020, refuting the hypotheses. This signifies that injury incidence remained elevated in the 2021 season despite resumption of preseason training and a regular season.

Level of Evidence

INTRODUCTION

The 2020 Major League Baseball (MLB) season was restructured due to the coronavirus disease 2019 (COVID-19) pandemic. Spring training was interrupted, and when play resumed, the season was shortened from 162 to 60 games.\textsuperscript{1,2} With an extended layoff between March and July and a shortened preseason, players had a habitually altered training schedule before beginning the regular season. The MLB resumed its normal schedule for the 2021 season, which ran from April 1\textsuperscript{st} through October 3\textsuperscript{rd}, and consisted of 162 games.\textsuperscript{3} Though MLB injuries are commonly frontloaded in the season, with high injury rates in April and May,\textsuperscript{4-6} there was an unprecedented number of injuries observed in the first half of the 2021 season with a rate/1000 exposures of 9.32. Platt et al. showed increased injury list (IL) placements during the 2020 season in both pitchers and position players.\textsuperscript{7} These injuries were likely attributable to a high acute to chronic workload ratio (ACWR) caused by a shortened preseason and a compressed game schedule.\textsuperscript{7} A high ACWR increases player injury risk.\textsuperscript{8} More doubleheaders in the 2020 season (45 seven-inning double-headers in an abbreviated season compared to 34 nine-inning double-headers in the full-season prior\textsuperscript{9,10}) further increased players’ acute workloads and is proposed to have contributed to the increased injury incidence observed,\textsuperscript{7} despite measures aimed at decreasing load placed on individual players, such as expanded rosters, taxi-squad availability, and a runner starting on second in extra-innings.\textsuperscript{11} Similar increases in injury incidence in 2020 following interruptions of play were observed in the National Football League (NFL)\textsuperscript{12,13} and an elite German soccer league,\textsuperscript{14} indicating that time away from formal training and competition due to COVID-19 has also affected injury rates in athletes of other professional sports. Baseball, in particular, does have other potential causes of the injury increase, namely a stylistic change to maximum effort,\textsuperscript{15} which is reflected in the increase in average fastball velocity\textsuperscript{16} and fewer average innings per start.\textsuperscript{15}

With a substantial increase in injuries games from the 2020 MLB season, it is possible that injury rates in 2021 would be higher than those in 2020 and may have continued to rise as volume accumulated. However, it is unknown whether the return to a traditional preseason timeline in 2021 successfully decreased injury incidence relative to 2020. The purpose of this study was to determine the injury incidence and epidemiology of the 2021 MLB season compared to the injury incidence in the 2020 season and pre-COVID-19 seasons. It was hypothesized that injury incidence in 2021 would return to pre-COVID-19 rates due to the return to normal preseason training. Additionally, it was hypothesized that IL placements in 2021 at midseason would be decreased relative to 2020 due to the uninterrupted preseason schedule yet increased in the second half of the season due to increased overall workload from 2020.

METHODS

Data from the 2018-2021 MLB transaction reports were extracted from \textit{mlb.com/transactions}.\textsuperscript{17} All injuries that resulted in a player being placed on the injured list (IL) were collected for analysis. Players are placed on the IL for 10 to 60 days after a physician’s determination that they are unable to play.\textsuperscript{18} In the 2020 season, the longer term on the IL was decreased to 45 days, and the shorter term was decreased from 15 to 10 days for pitchers.\textsuperscript{18} Multiple injuries that occurred in the same season at the same time were accounted for individually. From the database, publicly accessible information was collected, such as player name, date of IL placement, position, and body part injured. Specific type of injury beyond anatomical location of injury was not analyzed as the public database was limited on further injury details. Each injury was then categorized into the anatomic areas of upper extremity, lower extremity, spine/core, and other injuries. The “other” category consisted primarily of head injuries, medical reasons (upper respiratory infection, viruses including COVID-19, GI illnesses) for being unable to play, and unreported reasons for IL placement. Positions were sorted into pitchers and position players. Position players included all positions other than pitchers.

Utilizing \textit{fangraphs.com},\textsuperscript{19} the number of games played by each injured player four weeks and one week prior to placement on the IL was collected. The ratio between the game count of one week and four weeks was calculated as a measure of ACWR. A one-week training load is generally considered acute, while the average of the training load over four to six weeks is representative of chronic loads.\textsuperscript{20} Though pitch counts per game have been the primary variable collected to measure ACWR in baseball,\textsuperscript{20,21} game count was used in this study in order to employ a measurement that applies to both pitchers and position players, thus allowing for estimates of workload to be calculated amongst all players. ACWR at the time of injury was compared to the average ACWR for pitchers and position players overall in 2021. The overall ACWR was calculated for both pitchers and position players as a moving average in each week of the season. From this, a grand mean was calculated, which was compared to ACWR at time of injury with a t-test.
Injury incidence per 1000 player exposures was calculated using the same method described by Posner et al.\textsuperscript{6} One player exposure was defined as one game per athlete. Therefore, for the pre-COVID-19 cohort (2018 and 2019 seasons), total exposures were calculated using a 162-game season, 25-man active roster (of the 40-man potential player pool),\textsuperscript{18} and 30 teams in the MLB equating to 121,500 player exposures per year. Incidence rate for the pre-COVID-19 cohort was calculated using the cumulative number of injuries and exposures in both years. For 2020, player exposures were calculated using the 60-game season, 30-man roster for the first two weeks, 28-man roster for the second two weeks, and a 26-man roster for the remainder of the season (expanded in 2020 to include a 60-man potential player pool),\textsuperscript{22,23} and 30 teams in the MLB resulting in 48,960 player exposures. In the 2021 season, roster sizes were consistently 26 players. By the all-star break, the number of total games played by each team multiplied by the active roster size of 26 equaled 70,044 exposures. At the end of the regular season, with 162 games played by each team, total exposures in 2021 equaled 126,360. Because the IL is not used during the post-season, injuries past the regular season were excluded.

Incidence of injury was evaluated overall and for each anatomical zone. Subgroup analysis was performed to determine incidence of injury for pitchers and position players separately. Anatomic zones were then further subdivided to calculate incidence of injury for each specific body part. Incidence rate ratio (IRR) was calculated by dividing incidence in the 2021 group by incidence in the 2020 group and pre-COVID-19 group. Finally, the proportion of injuries occurring in each anatomical zone was analyzed overall and in the subgroups of pitchers and position players.

Differences in incidence for the overall group, as well as each subgroup, were statistically analyzed using the z-test for proportions, which is an ideal test to measure the statistical significance of the rate of IL placement for this descriptive study. R software version 4.0.2 (R Foundation for Statistical Computing, Vienna, Austria)\textsuperscript{34} was used for data analysis. Statistical significance was set at p ≤ 0.05.

RESULTS

TOTAL INJURIES

In the pre-COVID-19 seasons, there were 1246 injuries recorded on the IL. In 2020, there were 424 injuries recorded on the IL. By the end of season in 2021, 1098 injuries resulted in IL placement, and of those injuries, 653 were recorded by the all-star break (mid-season). Pitchers accounted for 55.0% (685/1246) of the injuries pre-COVID-19 and 56.8% (241/424) in 2020, compared to 50.7% (331/653) in 2021 by midseason and 52.6% (578/1098) by the end of the 2021 regular season.

2021 SEASON VERSUS PRE-COVID-19 SEASONS

The overall incidence rate per 1000 athlete exposures continued to be elevated in 2021 compared to pre-COVID-19 rates (5.13), both at midseason (9.32) and full season (IRR= 1.69, 8.69, p<0.001; Table 1). IL listing increases were present in all categories, including total, upper extremity, lower extremity, spine and core, and "other" categories (p<0.015, Table 1). Significant increases in pitcher IL listings were seen in all categories except spine/core by midseason 2021 compared to pre-COVID-19 (p=0.020) and all categories except lower extremity and spine/core for the full 2021 season (p<0.002, Table 1). Increases were seen in all categories in the position player cohort at both midseason 2021 (p<0.002) and full-season 2021 (p<0.015, Table 1).

A breakdown of specific injury locations showed increases by full-season 2021 compared to pre-COVID-19 in each of the following: foot/ankle, hamstring, groin, spine/core, hand/wrist, elbow/forearm, shoulder/chest, and miscellaneous (p< 0.016, Table 2). The lone decrease in incidence in 2021 compared to pre-COVID-19 was observed in the "other upper extremity" category (IRR 0.23, p<0.001, Table 2).

2021 MID-SEASON VERSUS 2020 SEASON

The overall incidence rate per 1000 athlete exposures by midseason 2021 (9.32) compared to 2020 (8.66) was not significantly different (IRR=1.08, p=0.234). Differences between 2020 and midseason 2021 included a significant increase in lower extremity injuries overall (IRR 1.58, p<0.001). Pitchers experienced fewer IL placements due to spine/core injuries by midseason 2021 (IRR 0.62, p=0.029) and increased placements in the "other" category (IRR 1.66, p=0.024). Furthermore, position players experienced more IL listings overall by midseason 2021 compared to 2020 (IRR 1.23, p=0.024).

Increases were further found between midseason 2021 and 2020 in the foot/ankle, hamstring, and miscellaneous categories (p<0.013). It is important to note that the miscellaneous category contained 245 injuries in 2021, of which 242 (99.6%) were listed as miscellaneous due to lack of reporting of the specific injury. Decreases, however, were seen in midseason 2021 compared to 2020 in the upper extremity and infection categories (p<0.001). Infection listing returned to their pre-pandemic levels.

2021 FULL SEASON VERSUS 2020 SEASON

The overall incidence rate per 1000 athlete exposures in full season 2021 (8.67) compared to 2020 (8.66) was not significantly different (IRR= 1.00, p=0.952, Table 1). The overall injury incidence in pitchers (9.15, p=0.337) and position players (8.20, p=0.265, Table 1) in full season 2021 was not significantly different from that of 2020. Pitchers in full season 2021 experienced fewer upper extremity (IRR=0.74, p<0.001) and spine/core injuries (IRR=0.65, p=0.016) compared to 2020, but experienced an increase in "other" injuries (IRR=1.86, p=0.002, Table 1). Position players in full season 2021 also experienced an increase in "other" injuries (IRR=1.82, p=0.002, Table 1) compared to 2020.

Significant increases in foot/ankle (IRR= 3.56 p<0.001, Table 2) and miscellaneous injuries (IRR=2.85, p<0.001, Table 2) were observed in full season 2021 versus 2020.
Table 1. Incidence comparison 2021 vs pre-COVID-19 and 2021 vs 2020 overall, pitchers, and position players

<table>
<thead>
<tr>
<th>Cohort</th>
<th>Pre-COVID-19</th>
<th>2020</th>
<th>2021</th>
<th>IRR 2021 vs. pre-COVID-19 (95% CI)</th>
<th>p-value</th>
<th>IRR 2021 vs. 2020 (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.13</td>
<td>8.66</td>
<td>8.69</td>
<td>1.69 (1.56-1.84)</td>
<td>&lt;0.001</td>
<td>1.00 (0.90-1.12)</td>
<td>0.952</td>
</tr>
<tr>
<td>Upper extremity</td>
<td>1.53</td>
<td>3.80</td>
<td>3.02</td>
<td>1.37 (1.20-1.56)</td>
<td>&lt;0.001</td>
<td>0.79 (0.67-0.95)</td>
<td>0.010</td>
</tr>
<tr>
<td>Lower extremity</td>
<td>1.63</td>
<td>1.98</td>
<td>2.33</td>
<td>1.40 (1.20-1.62)</td>
<td>&lt;0.001</td>
<td>1.18 (0.94-1.48)</td>
<td>0.159</td>
</tr>
<tr>
<td>Spine/core</td>
<td>0.88</td>
<td>1.47</td>
<td>1.21</td>
<td>1.30 (1.05-1.61)</td>
<td>0.015</td>
<td>0.78 (0.58-1.03)</td>
<td>0.077</td>
</tr>
<tr>
<td>Other</td>
<td>0.37</td>
<td>1.41</td>
<td>2.01</td>
<td>5.87 (4.64-7.44)</td>
<td>&lt;0.001</td>
<td>1.56 (1.20-2.03)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pitchers</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.87</td>
<td>9.84</td>
<td>9.15</td>
<td>1.56 (1.39-1.74)</td>
<td>&lt;0.001</td>
<td>0.93 (0.80-1.08)</td>
<td>0.337</td>
</tr>
<tr>
<td>Upper extremity</td>
<td>3.31</td>
<td>5.68</td>
<td>4.21</td>
<td>1.27 (1.09-1.49)</td>
<td>0.002</td>
<td>0.74 (0.60-0.91)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Lower extremity</td>
<td>1.42</td>
<td>1.27</td>
<td>1.61</td>
<td>1.27 (0.99-1.64)</td>
<td>0.060</td>
<td>1.61 (0.85-1.90)</td>
<td>0.234</td>
</tr>
<tr>
<td>Spine/core</td>
<td>1.10</td>
<td>1.76</td>
<td>1.11</td>
<td>1.12 (0.83-1.51)</td>
<td>0.441</td>
<td>0.63 (0.43-0.92)</td>
<td>0.016</td>
</tr>
<tr>
<td>Other</td>
<td>0.30</td>
<td>1.19</td>
<td>2.22</td>
<td>7.39 (5.10-10.70)</td>
<td>&lt;0.001</td>
<td>1.86 (1.25-2.78)</td>
<td>0.002</td>
</tr>
<tr>
<td>Position players</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.44</td>
<td>7.48</td>
<td>8.20</td>
<td>1.85 (1.65-2.09)</td>
<td>&lt;0.001</td>
<td>1.10 (0.93-1.30)</td>
<td>0.263</td>
</tr>
<tr>
<td>Upper extremity</td>
<td>1.19</td>
<td>1.92</td>
<td>1.82</td>
<td>1.37 (1.20-1.56)</td>
<td>&lt;0.001</td>
<td>0.95 (0.68-1.33)</td>
<td>0.757</td>
</tr>
<tr>
<td>Lower extremity</td>
<td>2.04</td>
<td>2.73</td>
<td>3.05</td>
<td>1.40 (1.20-1.62)</td>
<td>&lt;0.001</td>
<td>1.12 (0.85-1.48)</td>
<td>0.435</td>
</tr>
<tr>
<td>Spine/core</td>
<td>0.77</td>
<td>1.19</td>
<td>1.17</td>
<td>1.30 (1.05-1.61)</td>
<td>0.015</td>
<td>0.98 (0.64-1.51)</td>
<td>0.960</td>
</tr>
<tr>
<td>Other</td>
<td>0.44</td>
<td>1.63</td>
<td>2.18</td>
<td>5.87 (4.64-7.44)</td>
<td>&lt;0.001</td>
<td>1.82 (1.23-2.74)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

COVID-19=coronavirus disease 2019; IRR=Incidence rate ratio; CI= confidence interval. Bold font indicates statistically significant differences.

while significant decreases were observed in other lower extremity (IRR=0.41, p=0.005), elbow/forearm (IRR=0.65, p=0.005), other upper extremity (IRR=0.12, p<0.001), and infection (IRR=0.07, p<0.001, Table 2).

ACWR COMPARISON

Position players at the time of injury had a significantly higher ACWR (1.17 +/- 0.76) than position players overall (0.98 +/- 0.41, p=0.001). Pitchers also had a significantly higher ACWR at the time of injury (1.34 +/- 0.76) compared to the ACWR of pitchers overall (0.99 +/- 0.31, p<0.001).

DISCUSSION

2021 SEASON VERSUS PRE-COVID-19 SEASONS

The primary finding of this analysis is that the rate of placement on the IL in the 2021 MLB season was significantly higher than that of pre-COVID-19 seasons. This disproves the hypothesis that the overall 2021 injury incidence would not significantly differ from that of pre-COVID-19 seasons due to the return to regular preseason training. Furthermore, while injuries remained high in 2021, they did not increase as expected in the second half of the season suggesting the increase in injuries was not due to the return to a 162-game season from a 60-game season.

Many authors have examined the injury incidence in professional sports during the 2020 season following the disruptions to training and regular play,7,12–14,25 but to the best of the current authors’ knowledge, there are no studies to date examining the long-term effects of the COVID-19 layoffs on the subsequent season. This finding of increased injury incidence in 2021 may be surprising to the sports community at large; an expert opinion in regards to the effects of COVID-19 on professional soccer hypothesized that there would be no long-term effects on injury incidence after return to normal play because players would have the offseason to recover and regular preseason to train.26 This study’s findings may indicate that there were other unforeseen factors, such as accumulated load, locomotion activity and intensity, mood and sleep quality, previous fatigue and other situational factors,26 that may have influenced injury rates in 2021. The most notable of these factors is perhaps the massive increase in the accumulated load from
60 games in 2020 to 162 games in 2021. Since the COVID-19 pandemic presents an unprecedented situation, its long-term effects on injury risk in the MLB and professional sports at large should continue to be studied.

2021 MID AND FULL SEASON VERSUS 2020 SEASON

Comparing the first half of the 2021 season to the shortened 2020 season provides an interesting look at early season injury rates. There was no significant difference in overall injury incidence observed between the 2021 MLB midseason and 2020 season, indicating that injury incidence remained high in the first half of the 2021 season. This finding contrasts with the expected decrease in early season injury incidence as training and offseason routines were reestablished in 2021. One potential explanation for this finding is that the 2021 season once again began in early spring, making for colder weather on average compared to the July start in 2020. While primary literature supporting colder temperatures as a risk factor for soft tissue injury are scarce,27 some physicians and physical therapists anecdotally suggest this is the case.28,29 Additionally, offseason routines may not have been reestablished as assumed. It is possible that players may not have returned to performing pre-COVID-19 offseason training; however, this factor is uncontrolled for in this study. Furthermore, no significant difference was observed in overall injury incidence between full season 2021 and 2020.

Increases in early season injury were also observed in the NFL 2020-2021 season following the suspended pre-season due to COVID-19.15 The injury rate during weeks one to four of the regular season of 2020-2021 was significantly elevated compared to the injury rate of weeks one to four of the preseasons and regular seasons of 2016-2017, 2018-2019 and 2019-2020.13 The authors hypothesized that this increase in injury was due to deconditioning, muscle weakness, and fatigue, further emphasizing the importance of the NFL training camp for preparing athletes for the demands of regular season play.13 These findings parallel the increase in injuries observed in the 2020 MLB season due to the disrupted preseason training,7 but also underscore that the sustained high injury incidence in 2021 is unexpected since preseason training returned to normal.

An important secondary finding is that the distribution of injuries changed while injury incidence remained high. Lower extremity IL placements overall were significantly increased in early 2021 over 2020. Foot/ankle and "other" lower extremity injuries were significantly increased in the full 2021 season compared to 2020. Position players also experienced a significant increase in overall IL stints compared to 2020 values in early 2021. Infections played a significantly lesser role in increasing IL placements compared to 2020.

These previous findings make the increase in lower extremity injuries particularly notable in 2021. In 2020, overall injury incidence increased in all broad injury categories other than those listed as "lower extremity."7 In early 2021, lower extremity injuries significantly increased over both 2020 and pre-COVID-19 due to, primarily, significant increases in foot/ankle injuries and hamstring injuries.

Table 2. Detailed injury breakdown by body part 2021 vs pre-COVID-19 and 2021 vs. 2020

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Pre-COVID-19</th>
<th>2020</th>
<th>2021</th>
<th>IRR 2021 vs. pre-COVID-19 (95% CI)</th>
<th>p-value</th>
<th>IRR 2021 vs. 2020 (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot/Ankle</td>
<td>0.32</td>
<td>0.14</td>
<td>0.50</td>
<td>1.56 (1.12-2.17)</td>
<td>0.009</td>
<td>3.56 (1.62-7.83)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Knee</td>
<td>0.3</td>
<td>0.33</td>
<td>0.42</td>
<td>1.40 (0.98-1.99)</td>
<td>0.063</td>
<td>1.27 (0.73-2.22)</td>
<td>0.379</td>
</tr>
<tr>
<td>Hip</td>
<td>0.15</td>
<td>0.11</td>
<td>0.14</td>
<td>0.95 (0.54-1.67)</td>
<td>0.569</td>
<td>1.30 (0.49-3.39)</td>
<td>0.509</td>
</tr>
<tr>
<td>Hamstring</td>
<td>0.44</td>
<td>0.61</td>
<td>0.82</td>
<td>1.87 (1.43-2.45)</td>
<td>&lt;0.001</td>
<td>1.35 (0.90-2.03)</td>
<td>0.153</td>
</tr>
<tr>
<td>Groin</td>
<td>0.19</td>
<td>0.36</td>
<td>0.29</td>
<td>1.54 (1.00-2.37)</td>
<td>&lt;0.001</td>
<td>0.81 (0.46-1.43)</td>
<td>0.430</td>
</tr>
<tr>
<td>Other Lower Extremity</td>
<td>0.26</td>
<td>0.41</td>
<td>0.17</td>
<td>0.64 (0.39-1.05)</td>
<td>0.751</td>
<td>0.41 (0.22-0.75)</td>
<td>0.003</td>
</tr>
<tr>
<td>Spine/core</td>
<td>0.88</td>
<td>1.47</td>
<td>1.14</td>
<td>1.30 (1.05-1.60)</td>
<td>0.016</td>
<td>0.78 (0.58-1.03)</td>
<td>0.077</td>
</tr>
<tr>
<td>Head</td>
<td>0.21</td>
<td>0.18</td>
<td>0.23</td>
<td>1.09 (0.69-1.72)</td>
<td>0.704</td>
<td>1.28 (0.60-2.71)</td>
<td>0.562</td>
</tr>
<tr>
<td>Hand/wrist</td>
<td>0.51</td>
<td>0.78</td>
<td>0.86</td>
<td>1.69 (1.31-2.19)</td>
<td>&lt;0.001</td>
<td>1.11 (0.76-1.60)</td>
<td>0.575</td>
</tr>
<tr>
<td>Elbow/forearm</td>
<td>0.74</td>
<td>1.55</td>
<td>1.01</td>
<td>1.37 (1.09-1.72)</td>
<td>0.007</td>
<td>0.65 (0.49-0.87)</td>
<td>0.003</td>
</tr>
<tr>
<td>Shoulder/chest</td>
<td>0.78</td>
<td>1.15</td>
<td>1.10</td>
<td>1.41 (1.13-1.76)</td>
<td>0.002</td>
<td>0.96 (0.70-1.30)</td>
<td>0.80</td>
</tr>
<tr>
<td>Other upper extremity</td>
<td>0.17</td>
<td>0.34</td>
<td>0.04</td>
<td>0.23 (0.09-0.59)</td>
<td>&lt;0.001</td>
<td>0.12 (0.04-0.32)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Infection</td>
<td>0.05</td>
<td>0.55</td>
<td>0.04</td>
<td>0.79 (0.28-2.24)</td>
<td>0.674</td>
<td>0.07 (0.03-0.19)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.11</td>
<td>0.68</td>
<td>1.92</td>
<td>17.48 (11.73-26.07)</td>
<td>&lt;0.001</td>
<td>2.83 (1.97-4.06)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

COVID-19=coronavirus disease 2019; IRR=Incidence rate ratio for total cohort; CI= confidence interval. Bold font indicates statistically significant differences.
full 2021 season, lower extremity injuries significantly increased compared to pre-COVID-19 but only in the lower extremity subcategories of foot/ankle and "other" compared to 2020. Ankle, lower leg, and hamstring injuries have been shown in previous seasons to be highest in MLB players at the beginning of the season.5,30 consistent with the reported rates of other baseball injuries.6,7 This pattern suggests a potential influence of ACWR in affecting lower extremity injuries.

ACWR has been identified as a significant risk factor for soft tissue injury in a variety of professional sports.8 The rapid increase in workload necessitated by the interrupted 2020 preseason was hypothesized to be the main cause for increases in IL listings during the 60-game season.7 In 2021, both pitchers and position players had a significantly higher ACWR at time of injury than the average ACWR for the 2021 population. While both starting pitchers and relief pitchers were analyzed together, the ACWR calculation remains valid as it is a proportion of current work to previous work, therefore suggesting that increases in frequency of appearance in both starters and relievers was associated with IL placement. This finding is consistent with previous literature on the topic. A recent study of college baseball players found that players with an ACWR less than or greater than 33% were 8.3 times more likely to experience a throwing injury to the upper or lower extremity in the next week, indicating that an ideal ACWR is between 0.67-1.35.31 This study also identified a significant relationship between ACWR and upper extremity injuries.31 The mean ACWR for injured players in 2021 was shown to be significantly higher than the overall average ACWR for those in 2021, further supporting an elevated ACWR as a potential contributing factor to injury.

The continued increase in IL listing rates and the increases in lower extremity injuries despite the return to a normal preseason suggest the effects of deconditioning due to the 2020 layoff may be persisting longer than expected. One possible variable that may have contributed to the increased lower extremity injuries in 2021 is a delayed effect of alterations in both core strength and neuromuscular adaptation that began during the 2020 layoff. Core strength has been demonstrated to play a role in lower extremity injury prevention,32–35 and a lack of core strength and neuromuscular control leads to higher rates of lower extremity injury.33,35–38 In conjunction with this, posterior chain weakness may have also been a risk factor for the increase in lower extremity injuries observed. The posterior chain refers to the posterior musculoskeletal system, including the trunk, pelvis, hamstring and calf muscle complexes.39 The hamstring complex is the most frequently affected muscle of injuries within the posterior chain.39 Modifiable risk factors for posterior chain injury include: strength deficits, training overload, sprint performance and decreased range of motion.39 These risk factors suggest that, if deconditioning that began during the 2020 COVID-19 layoff persisted in the 2021 season, strength deficits, particularly of the posterior chain, may have contributed to the increase in lower extremity injuries observed in the 2021 season.

Taking all factors into account, it was surprising that lower extremity injuries did not significantly increase during the 2020 season. It is possible that lower extremity injuries were not as prevalent in 2020 because lower extremity conditioning may have been easier to accomplish during lockdown. The lower body can more easily be trained with body weight exercises and without extra equipment, as opposed to upper body, baseball-specific training, such as pitching and batting.7

Another difference between 2021 and 2020 was the significant decrease in infection as a reason for IL placement. COVID-19 infection was responsible for a substantial portion of IL placements in 2020.7 Notably, there were far fewer infectious causes for IL placement in 2021 compared to 2020. This finding supports the conclusion from the previous study7 that the increase in IL placements was largely not attributed to infection or exposure to COVID-19.

LIMITATIONS

As with all studies, this investigation has limitations. The IL is fundamentally a roster management tool. Therefore, using IL transactions is not a perfect secondary measure for injury. However, the continued increase in IL listings in 2021 compared to 2020 suggests many of the roster management factors that were particular to 2020 did not significantly influence the rate of IL placements. With the reinstatement of the minor leagues in 2021,40 and a more standard workflow pertaining to MLB rosters, these results show that the spikes in 2020 and 2021 were not likely due to these roster idiosyncrasies of 2020.

Additionally, the population of MLB players renders the results not generalizable to most athletes. Utilizing publicly accessible data also limits details available for each injury. In 2020 and 2021, many IL placements were made without a specific reason and are sorted as "miscellaneous," which is part of the broader "other" category. It is possible the COVID-19 protocol is responsible for many of these placements. Furthermore, only injuries that resulted in a placement on the IL were accounted for; therefore, this study did not capture injuries that did not result in an IL listing. Such a limitation suggests an underestimation of true injury incidence. In addition, in 2020 the 60-day injured list was reduced to 45 days.18 This time difference combined with the inadequate injury detail did not allow for an assessment of differences in injury severity between 2020 and 2021 and pre-COVID-19 seasons. Moreover, the epidemiologic nature of the study is not suited to propose a cause or explanation for the increase in IL placements. While hypotheses for potential causes are presented and supported, the current study is not designed to determine causation. Finally, utilizing games played to calculate ACWR is an imperfect measure since it does not account for differences in workload between different players per game. For example, a pitcher who throws multiple pitches per game may have a higher workload than a position player. Additionally, there are multiple intrinsic (e.g. rating of perceived exertion) and extrinsic (e.g. altitude and weather) factors that may contribute to workload that were unable to be measured in this study.
CONCLUSION

Incidence of placement on the IL increased significantly during the 2020 MLB season compared to pre-COVID-19 and remained elevated in 2021. Rate of IL placements attributed to every anatomic zone, including upper extremity, lower extremity, spine/core, and other injuries were significantly increased over pre-COVID-19 rates in 2021. Both position players and pitchers who experienced IL placement had a significantly higher ACWR than the average ACWR for the 2021 population, suggesting that elevated ACWR may be a risk factor for injury. This analysis suggests the interruption in sport in 2020 may have significant injury risk effects that persist longer than anticipated.

DISCLOSURES

BNP: None
BMS: None
SD: None
TLU: 3C-Meloq, 8-Shoulder and Elbow (British Journal), Sports Health, 9-American Shoulder and Elbow Surgeons, International Board of Shoulder and Elbow Therapists
ADS: None
WBK: 3B-NSC Showmotion, 3C-Alignmed, 4-Alignmed, 7-Springer
AVS: 3C-Allosource, Smith and Nephew, 5- Allosource, Flexion Therapeutics, 9-American Orthopaedic Society for Sports Medicine, Arthroscopy Association of North America

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REFERENCES


Ultrasound Measurement of Lateral Patellar Displacement: A Cadaveric Validation Study

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Keywords: cadaver study, patellar displacement, measurement, reliability, validity

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Background
Patellofemoral pain syndrome (PFPS) is one of the most common musculoskeletal complaints seen in outpatient settings. It has been suggested that hip adduction creates loads on the iliotibial band and causes lateral displacement of the patella (patellar tilt), which can lead to uneven patellofemoral joint loading, and hence, cause patellofemoral pain. In previous studies in the literature, ultrasound has been used to measure lateral patellar displacement. However, the method lacks validity data.

Purpose/Hypothesis
The aim of this study was to validate the use of ultrasound to measure lateral displacement of the patella, by comparing the position of the patella as measured first by ultrasound, and then by direct measurement.

Study Design
Descriptive Laboratory Study.

Methods
Nine soft-fixed cadavers were used in this study. The cadavers had been donated for anatomical examination and research under the Human Tissue Act (2004). The distance between the lateral femoral condyle and the lateral edge of the patella were measured by B-mode real-time ultrasound, and then by direct measurement, in two positions, neutral and at 20° hip adduction.

Results
The mean difference in the patella-to-lateral femoral condyle distance in the neutral position and at 20° adduction was 0.27 cm (ultrasound), and 0.34 cm (direct measurement), respectively. There were no significant differences between the measurements obtained by US and by direct measurement (Pearson correlation= 0.97, p=0.83).

Conclusion
Ultrasound is a valid and reliable method for measuring patellar position relative to the femoral condyle, and the validity data reported here suggest that it can be used with confidence in clinic to assess lateral patellar displacement.

Level of Evidence
3
INTRODUCTION

The patellofemoral joint (PFJ) consists of the posterior patella and the distal femur. The joint is widely studied due to the high prevalence of patellofemoral pain. While the etiology of patellofemoral pain (PFP) is multifactorial, patellar malalignment has been identified as one of the possible causes.\textsuperscript{1,2} The patella achieves the greatest stability beyond 45° knee flexion, where it is fully engaged in the trochlear groove.\textsuperscript{3} The joint capsule, patellofemoral ligament, iliotibial tract (ITB), and lateral patellar retinaculum all help to maintain the stability of the PFJ.\textsuperscript{4} Surrounding muscles, especially the distal portion of the vastus medialis, i.e., the vastus medialis obliquus, are important in the dynamic stability of the joint.\textsuperscript{5} Weakness or damage to these stabilizing structures may lead to patellar displacement,\textsuperscript{6} and hence, to patellofemoral pain.\textsuperscript{7}

Ultrasound (US) is an inexpensive and non-invasive imaging modality that has been widely used to investigate the knee joint.\textsuperscript{8–12} Results have been found to be consistent, and valid in comparison with magnetic resonance imaging (MRI).\textsuperscript{10} Ultrasound has also been found to be accurate and reliable when investigating patellar abnormalities\textsuperscript{13} and diagnosing fractures.\textsuperscript{14,15}

Previous real time US studies on asymptomatic subjects have shown that 20° hip adduction results in lateral displacement of the patella, compared to the neutral position.\textsuperscript{9,12} Although the results in these studies were statistically significant, the validity of the US method in assessing patellar position in relation to hip adduction was not reported. Consequently, it cannot be guaranteed that the patellar position measured by US was equivalent to the results that would have been obtained by direct measurement.

The aim of this study, therefore, was to validate the use of US to measure lateral displacement of the patella, by comparing the position of the patella as measured by US, and then by direct measurement.

MATERIALS AND METHODS

Nine soft-fixed cadavers (1 male, 8 females) donated for anatomical education and research under the UK Human Tissue Act (2004) were used in this study. Soft-fixed cadavers retain free movement of the joints and preserve a more life-like appearance. The mean age was 82.4± 6.02 years (range: 71-90). None of the cadavers had any noticeable lower limb pathology or deformity, and cause of death was unrelated to musculoskeletal pathology. However, three limbs had to be excluded from the study due to previous dissections of the knee area.

A SonoSite Edge II ultrasound machine (SonoSite, Bothell, USA) with a SonoSite H50x 15–6MHz linear-array probe (6 cm) was used for US imaging. The cadaver was positioned in the anatomical position with a block under the knee to maintain 20° flexion.\textsuperscript{9,12} The borders of the patella were palpated. The width and height were measured with a digital caliper, then a vertical line was drawn between the superior and inferior borders, and a horizontal line was drawn between the medial and lateral borders. The anterior superior iliac spine (ASIS) was palpated, and a steel ruler was placed on the cadaver, with one end on top of the ASIS and the other end on the mid-point of the patella. A straight line was then drawn from the mid-point of the patella to the ASIS. A standard 360° goniometer was used to position the lower limb. One arm of the goniometer was aligned with the left and right ASIS, while the other was aligned with the line drawn from the mid-point of the patella to the ASIS. Initial measurements were taken in the neutral position. The limb was then moved into 20° adduction and maintained in position using a block.

ULTRASOUND PROTOCOL

The ultrasound probe was covered with cling film for hygiene purposes. Water-soluble transmission gel was placed between the scanner head and the cling film, and on the skin of the knee. It has been shown that this method does not affect the measurements or the physical characteristics of the probe.\textsuperscript{16} The probe was positioned perpendicular to the skin, on the lateral side of the knee, in line with the previously marked horizontal line (Figure 1).

Minimal pressure was applied when placing the probe on the subject, sufficient to obtain a clear image without distorting the image or displacing the patella. Brightness mode (B-mode) real-time ultrasonography was then used to measure the patella-condyle distance in the neutral position and in 20° adduction (Figure 2). Three measurements were taken for each position. To minimize operator variability, all measurements were taken by the same operator, who had received US training from the Clinical Physics Department of the institution.

DIRECT MEASUREMENT PROTOCOL

Following ultrasound measurement, a scalpel was used to make a small, superficial, skin incision between the lateral
condyle of the femur and the lateral edge of the patella along the previous marked transverse line. Care was taken not to incise deeper than the superficial fascia. A self-retaining retractor was used to maximize visualization and access to the area. A digital caliper (resolution of 0.01 mm) was used to measure the patella-condyle distance at the apex of the lateral margin of the patella and the superior apex of the lateral femoral condyle (Figure 3). A measurement was first taken in the neutral position, then in 20° adduction. Again, three sets of measurements were taken in each position.

INTRA-RATER RELIABILITY STUDY

One subject was randomly selected for an intra-rater reliability study. This subject’s knees were assessed nine times over three different days for both US and DM measurements. All measurements were taken by the same investigator, using the same equipment, in order to standardize measurements.

STATISTICAL ANALYSIS

Measurements obtained were analyzed using Microsoft Excel. A paired t-test was used, with the significance set at p<0.05. Data points were plotted on a scatter graph, and the Pearson correlation and the coefficient of determination R² were calculated. A two-sample t-test was used to compare results obtained in this study with data previously reported from an ultrasound study on young, asymptomatic volunteers. Intra-rater reliability was assessed using the coefficient of variation (CV) and variance.

RESULTS

A total of 15 lower limbs from nine soft-fixed cadavers were examined. The mean and variance of the 3 repeated measurements for both methods showed close similarity, with low CV and variance (Tables 1 and 2).

The mean difference between the neutral and adducted positions in both left and right limbs combined was 0.24 cm. A paired t-test showed no significant difference in the measurements taken from the two different methods (p=0.83). A strong correlation between the methods was found (Pearson correlation=0.97, R²=0.9446) showing that the measurements obtained with US were valid and reliable (Figure 4). A two-sample t-test using the data reported here (mean difference 0.24 cm) compared to previously published ultrasound data obtained from an asymptomatic, in-vivo population (mean difference 0.18 cm) showed no significant differences between the mean patellar-condyle distance in the neutral and adducted positions, indicating that the data obtained from soft-fixed cadavers were comparable to that of a patient population.

The coefficient of variability (CV) for the intra-rater reliability test was 0.008 (0.8%) for US measurements and 0.045 (4.5%) for direct measurements in the neutral position; and 0.0057 (0.57%) and 0.003 (0.3%), respectively, in 20° adduction. These values were all <5%, indicating that the results were reliable.
Table 1. The mean, standard deviation (SD), coefficient of variation (CV), variance, and range of the lateral patellar-femoral condyle distance, as measured by ultrasound (US) and direct measurement (DM) in the neutral position.

<table>
<thead>
<tr>
<th></th>
<th>Mean (cm)</th>
<th>SD</th>
<th>CV (SD/Mean)</th>
<th>Variance</th>
<th>Range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>1.32</td>
<td>0.01</td>
<td>0.008</td>
<td>0.00007</td>
<td>1.31 - 1.33</td>
</tr>
<tr>
<td>DM</td>
<td>1.34</td>
<td>0.06</td>
<td>0.045</td>
<td>0.00004</td>
<td>1.33 - 1.34</td>
</tr>
</tbody>
</table>

CV: coefficient of variance, SD: standard deviation

Table 2. The mean, standard deviation (SD), coefficient of variation (CV), variance, and range of the lateral patellar-femoral condyle distance, as measured by ultrasound (US) and direct measurement (DM) in 20° hip adduction.

<table>
<thead>
<tr>
<th></th>
<th>Mean (cm)</th>
<th>SD</th>
<th>CV (SD/Mean)</th>
<th>Variance</th>
<th>Range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>1.05</td>
<td>0.006</td>
<td>0.0057</td>
<td>0.00002</td>
<td>1.04 - 1.05</td>
</tr>
<tr>
<td>DM</td>
<td>1.00</td>
<td>0.003</td>
<td>0.003</td>
<td>0.000006</td>
<td>0.99 - 1.00</td>
</tr>
</tbody>
</table>

CV: coefficient of variance, SD: standard deviation

DISCUSSION

Ultrasound has previously been used to evaluate patellar position,8–12 morphology,13 and fractures.15 However, the validity of the US method in assessing patellar position was not reported, and hence, it has not been confirmed that US is a reliable method of assessment of patellar position in comparison with direct measurement. It is important, therefore, to validate the methodology before its application in vivo to subjects in research, or in the clinic. This study fills the gap in the literature by comparing ultrasound results with direct measurements. It has previously been shown that good quality US images can be obtained from soft-fixed cadavers,6 therefore, this type of cadaver was used in this study.

To the authors’ knowledge, the study reported here is the first to demonstrate, by direct measurement, the validity of using US to measure the position of the patella in the neutral position and then in 20° of passive adduction. The current results showed a very small mean difference between the US measurement and the direct measurement (0.02 cm in the neutral position and 0.05 cm in 20° hip adduction, respectively), suggesting that the two methods produce very similar results. There was also a high level of
correlation between the two methods ($R^2=0.9446$, Pearson correlation=0.97), and there was no statistically significant difference in the results obtained ($p=0.85$). Therefore, the US technique used to measure patellar position is valid and can be used with confidence in clinical assessment of the position of the patella.

For both US and direct measurement, the intra-rater reliability test showed that the CV was <5%, which indicates that the results were reliable. The standard deviation (SD) of the US measurement and direct measurement was 0.01 and 0.06, respectively, in the neutral position, and 0.006 and 0.005, respectively, in hip adduction. The low SD also suggests that the measurements were reliable, and unlikely to be due to measurement errors.

It was found that in both US measurements and direct measurements (DM), hip adduction consistently produced a smaller patella-condyle distance than in the neutral position, and caused lateral displacement of the patella. The mean difference obtained by US and DM was 0.24 and 0.25, respectively. This is consistent with the in vivo study carried out by Herrington and Law, where 12 healthy males were recruited, and Kwan et al.’s study of a larger cohort of both males and females.12

While axial x-ray or CT images are currently used clinically to assess patellar tilt,17 real time US of lateral patellar displacement as described by Herrington et al.9 and Kwan et al.12 may present a potential alternative modality that could be easily applied in the clinic, although, since this was a cadaver study, more work will be necessary to validate the method in symptomatic patients.

Although the current results have shown US to be a valid method for measuring patellar position relative to the femoral condyle, some limitations must be taken into consideration. The sample size was relatively small, and the use of cadavers imposed its own limitations, as preserved tissue may not be completely comparable to living tissue. Also, the mean age of the cadavers was 82.4 ± 6.02 years, so it is likely that osteoarthritis, which affects more than 80% of the aged population,18 was present, which could have affected the results. Out of the nine cadavers used, eight were female, which may also have skewed the results. Although limbs with obvious damage or pathology were excluded, there is a possibility that the subjects had underlying knee or hip pathology that was not detected. Unfortunately, the donors’ medical records were not available, so the reliability of the results reported here could be compromised. However, the mean difference from both methods between the neutral and adducted positions recorded here (0.24 cm), is similar to the in vivo result (0.18 cm) reported in a much larger study of young, asymptomatic subjects,12 and furthermore, data analysis suggested that the results reported here are not significantly different. It should, however, also be borne in mind that these measurements were all non-weight-bearing and carried out after passive movement of the limb, so any direct comparison with patellar displacement in a living, weight-bearing subject should be treated with caution.

CONCLUSION

This study shows a high level of correlation between US and direct measurement of the position of the patella in neutral and adducted hip positions. This suggests that US is a valid method of assessing lateral displacement of the patella in vivo.

CONFLICT OF INTEREST STATEMENT

The authors confirm that they have no conflicts of interest to declare. The study was internally funded by St George’s, University of London

ACKNOWLEDGEMENTS

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REFERENCES


Original Research

Influence of Surveillance Methods in the Detection of Sports Injuries and Illnesses

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Background

Epidemiological data on sports injuries and illnesses depend on the surveillance methodology and the definition of the health problems. The effect of different surveillance methods on the data collection has been investigated for overuse injuries, but not for other health problems such as traumatic injuries and illnesses.

Purpose

The purpose of this study was to investigate the new surveillance method developed by the Oslo Sports Trauma Research Center (OSTRC), which is based on any complaint definition (new method), to identify health problems compared with the traditional surveillance method, which is based on time loss definition.

Study design

Descriptive epidemiology study

Methods

A total of 62 Japanese athletes were prospectively followed-up for 18 weeks to assess differences in health problems identified by both new and traditional methods. Every week, the athletes completed the Japanese version of the OSTRC questionnaire (OSTRC-H2.JP), whereas the teams’ athletic trainers registered health problems with a time loss definition. The numbers of health problems identified via each surveillance method were calculated and compared with each other to assess any differences between their results.

Results

The average weekly response rate to the OSTRC-H2.JP was 82.1% (95% CI, 79.8–84.3). This new method recorded 3.1 times more health problems (3.1 times more injuries and 2.8 times more illnesses) than the traditional method. The difference between both surveillance methods' counts was greater for overuse injuries (5.3 times) than for traumatic injuries (2.5 times).

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Conclusions
This study found that the new method captured more than three times as many health problems as the traditional method. In particular, the difference between both methods’ counts was greater for overuse injuries than for traumatic injuries.

Level of evidence
2b

INTRODUCTION

Epidemiological studies of injury and illness in sports are essential to protect the health of athletes.\(^1\) Definitions and methods of investigating the magnitude of injuries and illnesses have been published in consensus statements for specific sports\(^2\)–\(^4\) and multi-sport events by the International Olympic Committee.\(^1,5\) The following injury and illness definitions are recommended: all physical complaints regardless of their consequences (any complaint definition), injuries or illnesses leading to the athlete seeking attention from a qualified medical practitioner (medical attention definition), and injuries or illnesses leading to the athlete being unable to complete the current or future training session or competition (time loss definition).\(^1,6,7\) To date, most injury surveillance studies have used time loss, the narrowest of all consensus-recommended definitions.\(^8\)–\(^10\) However, this approach underestimates the full impact of overuse injuries because athletes often continue to participate in training and competitions despite persistent problems.\(^11,12\) To address these challenges, Clarsen et al.\(^6\) developed the Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire (OSTRC-O) in 2013 to record the extent of overuse injuries based on any complaint. Subsequently, the Oslo Sports Trauma Research Center Questionnaire on Health Problems (OSTRC-H) was developed in 2014 to record not only overuse injuries, but also traumatic injuries and illnesses.\(^13\)

Several authors have investigated the efficacy of the new surveillance methods in comparison with the traditional method, which uses the time loss definition.\(^6,14\) Clarsen et al.\(^6\) reported that the OSTRC-O captured 10 times more overuse injuries than the traditional method, with 75% rather than 11% of the athletes affected during the study period. Weiss et al.\(^14\) assessed professional basketball players throughout one season using the OSTRC-O, and reported 6.5 times more overuse injuries than were reported with the traditional method. Thus, while the efficacy of the new surveillance methods has been examined for overuse injuries, they have not been compared with the traditional surveillance method for other health problems, such as traumatic injuries or illnesses.

The OSTRC questionnaires, OSTRC-O and OSTRC-H, were updated in 2020 to the OSTRC-O2 and OSTRC-H2, respectively.\(^12\) These questionnaires have been translated into several languages and have been adopted in both sports injury research and clinical environments.\(^7,12,15–19\) It is therefore crucial to distinguish the differences between the new and the traditional methods, not only for overuse injuries, but also for other health problems. The purpose of this study was to investigate the new surveillance method developed by the OSTRC, which is based on any complaint definition (new method), to identify health problems compared with the traditional surveillance method, which is based on time loss definition. It was hypothesized that the new methods capture more health problems than the traditional method not only for overuse injuries, but also for traumatic injuries and illnesses.

METHODS

PARTICIPANTS AND RECRUITMENT

The university coaches and athletic trainers for a male handball team, a female soccer team, and a female lacrosse team were approached. After presenting the purpose of the study, athletes from the three teams were recruited individually. The inclusion criteria were as follows: 1) at least 18 years old and 2) able to speak and understand Japanese.\(^7,18\) Athletes were included regardless of whether they had current or previous injuries.\(^7,18\) This study was approved by the Ethics Committee of Osaka Electro-Communication University. All participants signed a written informed consent form. All methods were performed in accordance with relevant guidelines and regulations.

All athletes from each invited team (male handball, n = 27 athletes; female soccer, n = 14 athletes; female lacrosse, n = 23 athletes) consented to participate in the study. Of these, two female lacrosse athletes stopped playing lacrosse during the study period and were thus excluded from the analyses. The demographics of the participants are summarized in Table 1.

PROCEDURES

The study followed the participants prospectively for 18 weeks from April to August 2021. They were asked to complete the Japanese version of the OSTRC-H2 (OSTRC-H2-JP) weekly.\(^7\) The questionnaire was prepared using Google Forms, and the hyperlink was distributed via email.\(^7\) If no response was received from an athlete after two days at the end of each week, an automatic reminder email was sent.\(^7\) In parallel, each team’s athletic trainers registered injuries and illnesses using the traditional method, which is based on a time loss definition.\(^14\)

INJURY AND ILLNESS REGISTRATION USING THE NEW SURVEILLANCE METHOD

The OSTRC-H2-JP was used to record the athletes’ health problems based on any complaint.\(^7\) This questionnaire consisted of four key questions regarding the symptoms and consequences of injuries and illnesses during the previous
seven days. In case of any health problems, the athletes were asked to define whether the problems were an injury or illness. They were further asked to classify any injury as a traumatic or an overuse injury, and to disclose the body location. For an illness, they were asked to select the major symptoms that they experienced. For both injuries and illnesses, athletes also reported the number of days of complete time loss, which was defined as the total inability to train or compete. Based on the players’ responses to the four key questions, the severity score for each health problem was calculated on a scale of 0–100.

An any complaint health problem was defined as a health problem sustained by an athlete during a match or training, regardless of whether it received medical attention or necessitated time loss from sports activities. An illness was defined as a health complaint or disorder that is unrelated to an injury. An injury was defined as tissue damage or other derangement of normal physical function due to participation in sports, resulting from the rapid or repetitive transfer of kinetic energy. An injury was further classified as a traumatic or overuse injury; a traumatic injury was defined as caused by a single, clearly identifiable energy transfer, and an overuse injury was defined as caused by multiple accumulative bouts of energy transfer without a single, clearly identifiable event responsible for the injury.

**INJURY AND ILLNESS REGISTRATION USING THE TRADITIONAL METHOD**

The athletic trainers were asked to register health problems based on the time loss definition. For each injury, the registration form requested information about whether it was a traumatic or overuse injury, the injury location, the type of injury, the number of time loss days, and the diagnosis. For an illness, the form requested information about major symptoms, the number of time loss days, and the diagnosis. The severity of each health problem was classified as minimal (1–5 days), mild (4–7 days), moderate (8–28 days), or severe (>28 days) based on the number of time loss days.

A time loss health problem was defined as a health problem sustained by an athlete during training or a match that caused the athlete to be unable to participate fully in future training or matches. Both surveillance methods used the same definitions of injury, illness, traumatic injury, and overuse injury.

**STATISTICAL ANALYSIS**

The participants’ basic information was presented as the mean and standard deviation. The weekly response rate of the OSTRC-H2.JP was presented as a percentage and 95% confidence interval (95% CI) for all athletes and each team. The prevalence of health problems based on the OSTRC-H2.JP responses was calculated weekly by dividing the number of athletes reporting any type of problem by the number of questionnaire respondents.

To assess the differences between data collected by the new and traditional surveillance methods, the numbers of health problems were calculated and compared. Statistical analyses were performed using Microsoft Excel for Mac (version 16.54, Microsoft Corporation, Redmond, WA, USA) and SPSS (version 26.0, IBM Corporation, Armonk, NY, USA), with the significance level set at \( p < 0.05 \).

**RESULTS**

**THE NEW SURVEILLANCE METHOD**

During the 18 weeks, the average weekly response rate to the OSTRC-H2.JP among all participants was 82.1% (95% CI, 79.8–84.3); responses were provided by 72.9% (95% CI, 68.9–76.8) of the male handball team, 90.1% (95% CI, 86.4–93.8) of the female soccer team, and 88.6% (95% CI, 85.4–91.8) of the female lacrosse team.

From the responses to the OSTRC-H2.JP, 120 health problems were identified in 48 athletes (77.4%), of which 106 were injuries and 14 were illnesses (Table 2). Of these injuries, 64 were classified as traumatic injuries and 42 as overuse injuries. The average weekly prevalence of health problems was 31.2% (95% CI, 28.2–34.2) among all three teams. The average weekly prevalence of injuries and illnesses was 28.0% (95% CI, 25.1–30.9) and 3.8% (95% CI, 2.6–5.1), respectively. The average weekly severity score for health problems was 56.1 (95% CI, 54.7–57.6). The sever-

**Table 1. Participants’ characteristics. Data are presented as mean and standard deviation.**

<table>
<thead>
<tr>
<th></th>
<th>Male handball (n = 27)</th>
<th>Female soccer (n = 14)</th>
<th>Female lacrosse (n = 21)</th>
<th>Total (n = 62)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>19.3 ± 0.7</td>
<td>20.4 ± 1.4</td>
<td>20.1 ± 0.9</td>
<td>19.8 ± 1.0</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.72 ± 0.06</td>
<td>1.59 ± 0.04</td>
<td>1.60 ± 0.04</td>
<td>1.65 ± 0.08</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>69.2 ± 6.4</td>
<td>52.3 ± 4.0</td>
<td>56.4 ± 5.6</td>
<td>61.1 ± 9.2</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>23.3 ± 1.9</td>
<td>20.8 ± 1.1</td>
<td>22.0 ± 1.9</td>
<td>22.3 ± 2.0</td>
</tr>
<tr>
<td>Sports experience, years</td>
<td>8.4 ± 2.3</td>
<td>11.2 ± 4.5</td>
<td>1.8 ± 1.1</td>
<td>6.8 ± 4.6</td>
</tr>
<tr>
<td>Training volume, hours/week</td>
<td>18.1 ± 2.1</td>
<td>13.3 ± 2.0</td>
<td>16.1 ± 2.7</td>
<td>16.4 ± 3.0</td>
</tr>
</tbody>
</table>

BMI: body mass index
ity score for injuries was 51.6 (95% CI, 50.1–53.2), and the severity score for illnesses was 81.0 (95% CI, 72.4–89.7). Table 3 shows the average weekly prevalence and the severity scores of health problems during the course of the study.

THE TRADITIONAL SURVEILLANCE METHOD

A total of 39 health problems that resulted in time loss were identified from 31 athletes (50.0%) by athletic trainers from all three teams (Table 2). Of these, 34 were classified as injuries and five as illnesses. Among the injuries, there were 26 traumatic injuries and eight overuse injuries. The most affected body parts were the ankle (n = 11), the knee (n = 7), and the lumbo-sacral spine/buttock (n = 5) (Table 4).

COMPARISON BETWEEN THE NEW AND TRADITIONAL SURVEILLANCE METHODS

Throughout the study period, the new method recorded 3.1 times more health problems than the traditional method (new method: n = 120, traditional method: n = 59). These health problems were reported by 48 athletes (77.4%) using the new method and 31 athletes (50.0%) using the traditional method. For injuries and illnesses, the new method found 3.1 times more injuries (new method: n = 106, traditional method: n = 34) and 2.8 times more illnesses (new method: n = 14, traditional method: n = 5) than the traditional method. For injuries, the difference between methods was greater for overuse injuries (new method: n = 42, traditional method: n = 8) than for traumatic injuries (new method: n = 64, traditional method: n = 26). The differences between the new and the traditional method are shown in Table 2 and Figure 1.

Among injuries, the greatest difference between the new and traditional methods was for the head/face (6.0 times), followed by the shoulder (4.0 times) and the hand (4.0 times) (Table 4).

DISCUSSION

In this study, Japanese athletes were prospectively followed to assess differences in the number of health problems identified with the new method, which used an any complaint definition, and the traditional method, which used a time loss definition. The new method recorded more than three times as many health problems as the traditional method. Overuse injuries were identified as much as five times more often with the new method compared with than with the traditional method.

Throughout the study, 120 health problems were identified using the new method, which was 3.1 times more than when using the traditional method. Among the health problems, the differences between the two methods were similar for injuries and illnesses. A study investigating the characteristics of injuries and illnesses among elite Norwegian athletes using the new method reported that out of 262 recorded injuries, 124 injuries resulted in time loss. This indicates that 2.1 times more injuries were identified when using the any complaint definition than when using only the time loss definition. Although this is the first study to investigate differences between the new and traditional methods for determining health problems, not only for overuse injuries, but also for traumatic injuries and illnesses, the results obtained from this study are comparable to those of previous studies on both injuries and illnesses.

The differences in injuries identified when using the new and the traditional methods were greater for overuse injuries (5.3 times) than for traumatic injuries (2.5 times). Overuse injuries are caused by repeated microtraumas without a single, identifiable event, and in many cases, do not result in time loss with absence from training or competition. Symptoms such as pain or functional limitation often appear gradually and may be transient; thus, it is likely that at least in the early stages, the athlete will continue to train and compete despite having overuse conditions. In fact, the severity scores for overuse injuries in this study were significantly lower than those for traumatic injuries and illnesses, and overuse injuries were less likely than traumatic injuries and illnesses to be accompanied by an absence from training or competition.

The difference between the two methods among overuse injuries in this study was similar to that of for targeted male professional basketball players, but lower than that of for targeted Norwegian athletes. Weiss et al. examined overuse injuries in professional basketball players using the new and the traditional methods, and showed that the new method recorded 6.5 times more overuse injuries than the traditional method. Clarsen et al. also investigated overuse injuries using both methods, and found that the new method identified 10.1 times more overuse injuries than the traditional method. The study included athletes participating in handball, floorball, volleyball, cycling, and cross-country skiing. While the majority of participants (66.5%) were involved in non-contact sports such as volleyball, cycling, and cross-country skiing, the majority of participants in our study (66.1%) were involved in contact sports such as handball and soccer. It has been reported that overuse injuries occur more frequently in non-contact sports than in contact sports. Hence, it is possible that the differences between the previous and current study are due to the characteristics of the sports in which the athletes participated.

This is the study to investigate the differences between quantification of health problems, such as traumatic injuries and illnesses, by the new and traditional surveillance methods. The study does have some limitations. First, as the participants from only three university teams were enrolled; thus, it was not possible to extract a sufficient numbers of health problems for detailed examination of the differences between their quantification by the new and traditional methods in terms of the locations of injuries and illnesses. Additionally, although the questionnaires are intended to be used for a variety of sports, only responses from athletes participating a few sports (handball, soccer, and lacrosse) were analyzed. In particular, the results might differ between contact and non-contact sports. Furthermore, the athletes self-reported their injuries and illnesses in the new method. As most athletes do not have adequate medical knowledge, erroneous information regarding their
Table 2. Differences of health problems identified between the new and traditional surveillance methods. Data are presented as the number of health problems and multiples in difference.

<table>
<thead>
<tr>
<th></th>
<th>Male handball</th>
<th>Female soccer</th>
<th>Female lacrosse</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health problems</td>
<td>27</td>
<td>11</td>
<td>2.5</td>
<td>41</td>
</tr>
<tr>
<td>Injury</td>
<td>26</td>
<td>10</td>
<td>2.6</td>
<td>36</td>
</tr>
<tr>
<td>Traumatic injury</td>
<td>17</td>
<td>9</td>
<td>1.9</td>
<td>26</td>
</tr>
<tr>
<td>Overuse injury</td>
<td>9</td>
<td>1</td>
<td>9.0</td>
<td>10</td>
</tr>
<tr>
<td>Illness</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3. Average weekly prevalence and severity scores of health problems. Data are presented as mean and 95% confidence interval.

<table>
<thead>
<tr>
<th></th>
<th>Male handball</th>
<th>Female soccer</th>
<th>Female lacrosse</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevalence (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Health problems</td>
<td>20.4% (16.2, 24.6)</td>
<td>44.0% (37.5, 50.4)</td>
<td>33.5% (28.5, 38.6)</td>
<td>31.2% (28.2, 34.2)</td>
</tr>
<tr>
<td>Injury</td>
<td>19.5% (15.4, 23.7)</td>
<td>35.4% (29.1, 41.6)</td>
<td>31.8% (26.8, 36.8)</td>
<td>28.0% (25.1, 30.9)</td>
</tr>
<tr>
<td>Traumatic injury</td>
<td>15.3% (11.6, 19.1)</td>
<td>24.9% (19.3, 30.6)</td>
<td>15.9% (12.0, 19.8)</td>
<td>17.9% (15.4, 20.4)</td>
</tr>
<tr>
<td>Overuse injury</td>
<td>4.5% (2.3, 6.6)</td>
<td>10.9% (6.8, 14.9)</td>
<td>19.2% (15.0, 23.4)</td>
<td>11.5% (9.5, 13.6)</td>
</tr>
<tr>
<td>Illness</td>
<td>0.9% (-0.1, 1.9)</td>
<td>9.5% (5.7, 13.3)</td>
<td>2.9% (1.1, 4.7)</td>
<td>3.8% (2.6, 5.1)</td>
</tr>
<tr>
<td>Severity score</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Health problems</td>
<td>68.6 (63.6, 73.5)</td>
<td>54.9 (51.3, 58.6)</td>
<td>54.3 (50.5, 58.0)</td>
<td>56.1 (54.7, 57.6)</td>
</tr>
<tr>
<td>Injury</td>
<td>66.8 (61.5, 72.1)</td>
<td>44.9 (41.1, 48.7)</td>
<td>51.7 (47.8, 55.5)</td>
<td>51.6 (50.1, 53.2)</td>
</tr>
<tr>
<td>Traumatic injury</td>
<td>71.5 (65.2, 77.7)</td>
<td>49.2 (41.2, 57.2)</td>
<td>59.2 (51.6, 66.9)</td>
<td>57.3 (54.6, 60.0)</td>
</tr>
<tr>
<td>Overuse injury</td>
<td>33.2 (15.6, 50.8)</td>
<td>27.3 (17.4, 37.2)</td>
<td>43.3 (39.3, 47.2)</td>
<td>41.6 (39.9, 43.2)</td>
</tr>
<tr>
<td>Illness</td>
<td>19.9 (-24.5, 64.3)</td>
<td>70.9 (51.6, 90.2)</td>
<td>9.9 (-4.2, 23.9)</td>
<td>81.0 (72.4, 89.7)</td>
</tr>
</tbody>
</table>
Table 4. Location and severity of injuries and illnesses. Data are presented as the number of health problems and multiples in difference.

<table>
<thead>
<tr>
<th>Location of injury</th>
<th>Non time loss</th>
<th>Time loss</th>
<th>Total</th>
<th>Difference (Times)‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimal</td>
<td>Mild</td>
<td>Moderate</td>
<td>Severe</td>
</tr>
<tr>
<td>Injury*†‡</td>
<td>72</td>
<td>8</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Head/face</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thoracic spine/upper back</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lumbo-sacral spine/buttock</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Shoulder</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Elbow</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Forearm</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wrist</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Hand</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hip/groin</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thigh</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Knee</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Lower leg/Achilles tendon</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ankle</td>
<td>18</td>
<td>3</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Foot</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Illness</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

*One injury included two body parts (lower leg/Achilles tendon and foot)
†Four body parts (neck/cervical spine, chest, abdomen, upper arm) had no injury case and were excluded from the table.
‡Data show the difference in the number of health problems identified by the new method (total) and traditional method (all time loss).

conditions might have been reported. To minimize erroneous responses, the athletes were familiarised with the definitions of health problems during the pre-study meeting.

CONCLUSION

This study found that the new surveillance method, which uses an any complaint definition, could capture more than three times as many health problems, including traumatic injuries, overuse injuries, and illnesses, as the traditional method, which uses a time loss definition. In particular, the methods differed more in their quantifications of overuse injuries than they did for traumatic injuries.

CONFLICT OF INTEREST

The authors have no conflicts of interest to report.

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Figure 1. Venn diagram of the number of health problems captured by the new and traditional surveillance methods.

The Gray circle indicated the number of health problems captured by the traditional surveillance method and the white circle that of captured by the new surveillance method.
REFERENCES


Original Research

Roles And Responsibilities Of The Physical Therapist In Collegiate Athletics: Results Of A National Survey

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Keywords: sports medicine, rehabilitation, physical therapy, collegiate athletics, collaborative care

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Background
Over the past decade, there has been an increased focus on collaboration within collegiate athletics based sports medicine. Specifically, athletic trainers (ATs) and physical therapists (PTs) are working together, often side-by-side, to provide optimal care for the injured athlete. However, the roles and responsibilities of the PT within this model are currently not well described.

Purpose
The purpose of this study was to identify educational training, credentials, roles, and responsibilities of the PT working with collegiate athletes.

Study Design
Cross-sectional survey

Methods
An anonymous, descriptive online survey focusing on the demographic and occupational characteristics of PTs providing care for collegiate athletes was created and distributed electronically through the American Academy of Sports Physical Therapy (AASPT), a subgroup within the American Physical Therapy Association (APTA).

Results
One hundred forty eligible responses were included. Sixty-four percent (90/140) of the respondents were male; 86% of the respondents (120/140) reported working in the National Collegiate Athletic Association (NCAA) Division I setting. Half (70/140) of respondents were also ATs, and 60% (85/140) were board-certified sports clinical specialists (SCS). All respondents (140/140) provide rehabilitation exercises; nearly all provide sports performance enhancement and manual therapy (97%, 136/140 and 96%, 135/140, respectively). Other identified roles and responsibilities included communication with the athletic training staff, event coverage, and personnel management.

Conclusions
The role of the PT within collegiate athletics sports medicine is highly varied; years of experience, certification, credentials, and location of patient care are also variable.

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Clinical Relevance

PTs working in a collegiate athletics sports medicine setting have many paths to entry and diverse job duties. PTs interested in working in this setting should prioritize developing relevant experience and communication skills.

Level of Evidence

Level 3b

INTRODUCTION

The past decade has brought a paradigm shift in collegiate athletics sports medicine. In order to provide optimal outcomes and best practice, there has been an effort to elevate the provision of medical services and increase interprofessional practice and collaboration.1,2 A hallmark of collaborative care is multiple caregivers from different professions utilizing best practices to improve patient outcomes.3,4 When this model is superimposed upon collegiate athletics, the athlete (patient) may be supported by the athletic trainer (AT), primary care physician, orthopedic surgeon, physical therapist (PT), mental health counselor, strength and conditioning coach, dietician, and many others.5

The field of physical therapy traverses a broad continuum relating to age, gender, impairments, and functional limitations. By definition, a sports PT specializes in the health care management of the physically active individual who has been injured or aspires to return to athletic endeavors; they use evidence-based sports science to create and execute a customized plan of injury prevention, performance enhancement, management of an acute care injury, and return to sport.6 This includes earning the designation Sports Clinical Specialist (SCS) by the American Board of PT Specialties (ABPTS) which demonstrates competence in the field of sports physical therapy. To date, board specialization is not mandatory, nor does it directly affect the ability to practice PT in any setting. Specific to sports, the collegiate setting is an environment in which a PT can utilize their skill set to care for student athletes by working collaboratively with the AT and the rest of the sports medicine team. Support for the collaboration between the PT and AT professions has been aided in-part by the American Physical Therapy Association (APTA) and National Athletic Trainers’ Association (NATA) stating a partnered agenda via professional addresses and collaborative educational conferences.7,8

At present, in the collegiate athletics sports medicine setting, the fundamental roles and responsibilities of ATs and physicians have been well-defined.9 The AT is responsible for overseeing and directing care for student athletes while team physicians provide additional medical diagnosis and treatment. However, the roles and responsibilities of the PT working in a collegiate environment are not well known. Therefore, the purpose of this study was to identify educational training, credentials, roles, and responsibilities of the PT who provides care as a member of the collegiate athletic sports medicine teams. The hypotheses were that the PT will have additional certifications and/or credentials beyond that of an entry-level PT; and that their role as a member of the collegiate athletic sports medicine team will extend beyond rehabilitation services.

METHODS

SURVEY DEVELOPMENT

The survey tool was initially developed by a group of PTs who are also American Academy of Sports Physical Therapy (AASPT) members (MZ, JTN, and JS) and provide physical therapy for collegiate athletes in the athletic training room at their respective universities. The group has over 20 years of experience working with collegiate athletes. The initial survey draft was piloted to seven additional AASPT members with experience in collegiate athletics or research methodology. The pilot group completed the electronic survey via an email link; they were not compensated. 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 a final document was prepared and reviewed by all authors. The survey was uploaded to Google Forms (Alphabet Inc, Mountain View, CA), which has previously been demonstrated to be an appropriate electronic survey system for medical questionnaires.10 The survey was designed to take less than 10 minutes to complete. This study was approved by the University of Maryland, Baltimore Institutional Review Board prior to survey distribution.

An invitation email to AASPT members and a post on the AASPT website announced the purpose of the survey, emphasized anonymity through aggregate-only reporting, and informed individuals that voluntary consent was designated by responding to the survey. The link to the survey was available on the AASPT website for four weeks; two email reminders were sent to membership during that timeframe, encouraging them to complete the survey and to share the link with non-AASPT members who were known to treat collegiate athletes. Inclusion criteria required respondents to be licensed PTs with a formal, established, working relationship with a United States collegiate athletic department. Responses were excluded from PTs who worked with collegiate athletes on a volunteer basis only or who worked with collegiate athletes in an unaffiliated outpatient office.

The survey asked about demographic and educational background, such as age, gender, years of experience, residency completion, and information regarding other credentials or certifications. Specific roles and responsibilities of the PT were also identified. Lastly, information relating to employer (athletics, contract work, or other) was obtained.
Data regarding whether renumeration was utilized (insurance or other reimbursement) was also acquired.

**DESCRIPTIVE STATISTICS**

Descriptive statistics were used to summarize the sample population using frequency counts for categorical variables and means and standard deviations for continuous variables. Responses that were written in by respondents were manually coded. Exploratory analysis consisted of several group comparisons related to work history and number of job duties. Specifically, the number of years in college athletics between self-identifying female and male respondents and between PTs and dual PT/ATs were compared. Additionally, the number of job duties between self-identifying female and male respondents, between PTs and dual PT/ATs, and between respondents with more or less than 15 years of PT experience were compared.

Prior to comparison, normality of data was assessed by visually observing the histograms of variables and performing a Shapiro-Wilk test. In the instance of non-normal data, a Wilcoxon signed rank test was used. Ninety-five percent confidence intervals (95% CI) were computed for all comparisons. Alpha was set a priori at 0.05. Data were analyzed using R Version 3.6.1 (R Foundation for Statistical Computing, Vienna, Austria).

**RESULTS**

**GENERAL DEMOGRAPHICS**

Of the 6,106 AASPT members who the survey was emailed to in 2020, 183 completed surveys for a 2.91% response rate. Of the responses, 140 met the inclusion criteria and were included in the final analysis. A summary of demographic information of the respondents is presented in Table 1. The mean number of years in practice was 15.7 years; nine years were spent working with collegiate athletes. The majority of respondents [64% (90/140)] identified as male. Most respondents [86% (120/140)] reported working with NCAA Division I athletes; various additional credentials (SCS) or certifications (AT) were held by the respondents.

**OPERATIONAL CHARACTERISTICS**

The employer category, location of service, financial model, and hours per week are presented in Table 2. Forty-three percent (60/140) of respondents reported working for a healthcare company that contracted with the athletic department. Of the respondents, 50% (42/140) provided some and 61% (85/140) provided all their care on-site at an athletic department facility. Fifty-six percent (79/140) respondents indicated they worked less than 50% of the work week with the athletic department. Regarding reimbursement, 39% (54/140) of respondents reported seeking insurance reimbursement for their services.

**JOB RESPONSIBILITIES AND TREATMENTS PROVIDED**

Daily job responsibilities and treatments rendered by survey respondents are presented in Table 3 and Table 4, respectively. Ninety percent (126/140) of the sample indicated they communicated directly with athletics staff and 44% (61/140) of the sample indicated they were involved with event coverage. One hundred percent (140/140) respondents reported providing rehabilitation exercise.

**GROUP COMPARISONS**

The summary statistics for the variables in the group comparisons are displayed in Table 5. No data for group comparisons were normally distributed. Respondents with more than 15 years of PT experience had significantly more job duties than those with less than 15 years of PT experience (p=0.031; 95% CI: -1.0, -0.01). Given that less than 1% (n=1) of respondents did not self-identify as male or female, this group was not able to be included in the following group comparisons. There was no significant difference in years in collegiate athletics between self-identifying males and females (p=0.418; 95% CI: -2.99, 1.00) or respondents who PT/ATs compared to those who were PTs (p=0.110; 95% CI: -3.99, 0.001). There was also no significant difference in the number of job duties between individuals self-identifying as male or female (p=0.988; 95% CI: -1.00, 1.00) or those who were PTs or PT/ATs (p=0.080; 95% CI: -1.0, 0.001).

**DISCUSSION**

The purpose of this study was to identify patterns and themes in the educational training, credentials, roles, and responsibilities of the PT working in collegiate athletics. The results of the survey suggests that these PTs possess additional credentials beyond entry level PTs and their responsibilities extend beyond rehabilitation care alone. Although varied educational background, years of experience, and responsibilities were identified, common practice themes emerged from the survey results that warrant further discussion.

**DEMOGRAPHICS**

Of the respondents, 35% (49/140) identified as female, and 64% (90/140) identified as male, while <1% preferred not to answer. Presently, the AASPT is comprised of 6,298 PT members, 38% of which identify as female, 57% as male, and 5% whom preferred not to answer. As such, the findings are reflective of the AASPT demographic data. In a similar study of the gender composition of team physicians in select NCAA Division I and professional teams, women comprised 18.1% of all team physicians and 7.7% of orthopaedic surgeon team physicians, a lower percentage than observed in the current study. While the gender demographics in this survey may be equitable when compared to AASPT membership, this cannot be generalized to all PTs or the medical field.

In the 2020-2021 academic year, 44% of collegiate student athletes identified as female. The NCAA reporting of
athlete participation does not provide information for non-binary gender classification. Based on this data, female PTs are likely underrepresented in collegiate athletics sports medicine when compared to the percentages of female student athletes. Although not represented in NCAA participation data, individuals with non-binary identification may also be underrepresented by PTs in collegiate athletics. As such, increasing the number of females and individuals identifying with a non-binary gender on the collaborative health care team should be considered.

As demonstrated in Table 5, the number of years in college athletics as well as the number of job duties were similar between male and female genders. This implies that both male and female PTs have had similar roles and responsibilities in collegiate sports and have had a presence for approximately the same length of time. However, when compared to the percentage of female athletes in collegiate sports, the number of female PTs is lacking.

CREDENTIALS AND CERTIFICATIONS

Of the survey respondents, 60% reported being board certified in sports physical therapy, whereas only 24% reported completing a sports residency (Table 1). As such, over half of the respondents completed eligibility requirements and successfully passed the SCS examination without completing a sports residency. In addition, half of the respondents reported that they were also ATs (Table 1) and 44% of all respondents reported that they were responsible for athletic event coverage (Table 3). It cannot be determined if those individuals who provide athletic event coverage were also dual credentialed PT/ATs. The fact that AT or post-professional PT training was not a universal finding suggests many viable paths to careers in collegiate athletics exist.

Interestingly, there were a greater number of respondents who identified as being a SCS (60%) then being an AT (50%). This finding may be based on numerous factors. First, the prevalence of the dual PT/ATs may be declining due to changes in AT education. Most recently, there has been a transition of the bachelor’s degree to an entry level master’s degree in athletic training education programs. Given the likely rise in tuition costs and time commitments, individuals may be less likely to complete both a master’s degree in athletic training and a doctorate degree physical therapy. Second, the role of the PT only clinician in collegiate athletics may be sufficient as specialty PT training

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Table 1. Sample Demographics

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Percent of sample</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>49</td>
<td>35%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>90</td>
<td>64%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefer not to answer</td>
<td>1</td>
<td>&lt;1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Years as PT</strong></td>
<td>140</td>
<td>100%</td>
<td>15.7</td>
<td>11.6</td>
</tr>
<tr>
<td><strong>Years in college athletics</strong></td>
<td>140</td>
<td>100%</td>
<td>9.4</td>
<td>9.1</td>
</tr>
<tr>
<td><strong>Years in current position</strong></td>
<td>140</td>
<td>100%</td>
<td>7.7</td>
<td>8.4</td>
</tr>
<tr>
<td><strong>Athletic level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCAA Division I</td>
<td>120</td>
<td>86%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCAA Division II</td>
<td>16</td>
<td>11%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCAA Division III</td>
<td>20</td>
<td>14%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAIA</td>
<td>8</td>
<td>6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Specialty training</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sports residency</td>
<td>34</td>
<td>24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sports fellowship</td>
<td>10</td>
<td>7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthopedic residency</td>
<td>3</td>
<td>2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Professional credentials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCS</td>
<td>84</td>
<td>60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT</td>
<td>70</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSCS</td>
<td>42</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCS</td>
<td>33</td>
<td>24%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAAOMPT</td>
<td>11</td>
<td>8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AASPT member</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>129</td>
<td>92%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>11</td>
<td>8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Terminal degree</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bachelor’s</td>
<td>27</td>
<td>19%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master’s</td>
<td>28</td>
<td>20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doctorate</td>
<td>66</td>
<td>47%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PhD/EdD</td>
<td>19</td>
<td>14%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N: Number of participants who responded yes to that category; SD: standard deviation; NCAA: National Collegiate Athletic Association; NAIA: National Association of Intercollegiate Athletics; SCS: sports certified specialist; AT: athletic trainer; CSCS: certified strength and conditioning specialist; OCS: orthopedic certified specialist; FAAOMPT: Fellow of the American Academy of Orthopedic Manual Physical Therapists; PhD: Doctor of Philosophy; EdD: Doctor of Education.
Table 2. Occupational Characteristics

<table>
<thead>
<tr>
<th>Employer Category</th>
<th>N</th>
<th>Percent of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthcare company</td>
<td>60</td>
<td>43%</td>
</tr>
<tr>
<td>Academic department</td>
<td>38</td>
<td>27%</td>
</tr>
<tr>
<td>Athletic department</td>
<td>32</td>
<td>23%</td>
</tr>
<tr>
<td>Independent contractor</td>
<td>10</td>
<td>7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Service location</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>On site</td>
<td>85</td>
<td>61%</td>
</tr>
<tr>
<td>Off site</td>
<td>13</td>
<td>9%</td>
</tr>
<tr>
<td>Combination</td>
<td>42</td>
<td>30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Financial model</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wage-based</td>
<td>67</td>
<td>48%</td>
</tr>
<tr>
<td>Insurance reimbursement</td>
<td>54</td>
<td>39%</td>
</tr>
<tr>
<td>Mix of wage/insurance reimbursement</td>
<td>4</td>
<td>3%</td>
</tr>
<tr>
<td>Fee per visit</td>
<td>4</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>8%</td>
</tr>
<tr>
<td>&lt;25%</td>
<td>52</td>
<td>37%</td>
</tr>
<tr>
<td>26-50%</td>
<td>27</td>
<td>19%</td>
</tr>
<tr>
<td>51-75%</td>
<td>14</td>
<td>10%</td>
</tr>
<tr>
<td>76-100%</td>
<td>47</td>
<td>34%</td>
</tr>
</tbody>
</table>

N: Number of participants who responded 'yes' to that category.

Table 3. Job Responsibilities

<table>
<thead>
<tr>
<th>Job Responsibilities</th>
<th>N</th>
<th>Percent of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication with athletics staff</td>
<td>126</td>
<td>90%</td>
</tr>
<tr>
<td>Teaching</td>
<td>83</td>
<td>59%</td>
</tr>
<tr>
<td>Event coverage</td>
<td>61</td>
<td>44%</td>
</tr>
<tr>
<td>Research</td>
<td>54</td>
<td>39%</td>
</tr>
<tr>
<td>Rehabilitation coordinator</td>
<td>52</td>
<td>37%</td>
</tr>
<tr>
<td>Management of athletics personnel</td>
<td>43</td>
<td>31%</td>
</tr>
<tr>
<td>Sports science data management</td>
<td>32</td>
<td>23%</td>
</tr>
</tbody>
</table>

N: Number of participants who responded 'yes' to that category.

Table 4. Interventions provided by the sports PT

<table>
<thead>
<tr>
<th>Intervention</th>
<th>N</th>
<th>Percent of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rehabilitation exercises</td>
<td>140</td>
<td>100%</td>
</tr>
<tr>
<td>Sports performance enhancement</td>
<td>136</td>
<td>97%</td>
</tr>
<tr>
<td>Manual therapy</td>
<td>135</td>
<td>96%</td>
</tr>
<tr>
<td>Modalities</td>
<td>106</td>
<td>76%</td>
</tr>
<tr>
<td>Dry needling</td>
<td>78</td>
<td>56%</td>
</tr>
</tbody>
</table>

N: Number of participants who responded 'yes' to that category.

formed by >95% of the respondents; dry needling was performed by 56% of the respondents (Table 4). Perhaps collegiate athletics sports medicine teams are seeking individuals to perform these skills, thereby allowing ATs to focus on other responsibilities, such as sideline and event coverage, emergency care for the injured athlete, and practice preparation. In the case of dry needling, the AT may be unable to perform this skill due to their respective state AT practice act. Therefore, PTs may demonstrate value in collegiate athletics sports medicine settings by excelling in the services they provide.

Roles and Responsibilities, Interventions Performed

An important finding is that nearly all respondents (90%, 126/140) reported that they regularly communicated with the athletics staff. This finding is critical as communication is necessary to promote interprofessional collaboration and successful outcomes for the student-athlete. Developing and maintaining a high-performance sports medicine team includes incorporation of best practices from within each profession, ongoing communication, operating in unison, incorporating diversity, and maintaining proper perspective.

In addition, the number of job duties did not differ between self-identified male and female genders or between PTs and PT/ATs (Table 5). The only difference regarding the number of job responsibilities was related to years of experience. Those PTs with greater than 15 years of experience had statistically more job responsibilities than those with less than 15 years of experience, suggesting cumulative experience may influence career advancement more than gender or credentials.
### Table 5. Summary statistics and results from group comparisons between males and females

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
<th>p-value (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean (SD)</td>
<td>mean (SD)</td>
<td></td>
</tr>
<tr>
<td>Years in college athletics</td>
<td>10.51 (10.48)</td>
<td>7.37 (5.43)</td>
<td>0.418 (-2.99, 1.00)</td>
</tr>
<tr>
<td>Number of job duties</td>
<td>3.23 (1.57)</td>
<td>3.20 (1.70)</td>
<td>0.988 (-1.0, 1.0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>PT/AT</th>
<th>PT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Years in college athletics</td>
<td>11.25 (10.49)</td>
<td>7.62 (7.09)</td>
<td>0.110 (-3.99, 0.001)</td>
</tr>
<tr>
<td>Number of job duties</td>
<td>3.47 (1.65)</td>
<td>2.97 (1.53)</td>
<td>0.080 (-1.0, 0.001)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>PTs &gt;15 years</th>
<th>PTs &lt;15 years</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of job duties</td>
<td>3.56 (1.66)</td>
<td>2.96 (1.52)</td>
<td>0.031 (-1.0, -0.01)</td>
</tr>
</tbody>
</table>

SD: standard deviation; CI: confidence interval; PT: physical therapist; AT: athletic trainer; PT/AT: PT who is also an AT

### OCCUPATIONAL CHARACTERISTICS

The data from the present study demonstrate that most PTs provide care for NCAA Division I athletes rather than other NCAA divisional levels or NAIA programs (Table 1). This finding mirrors previous studies that Division I programs staff significantly more full-time and part-time ATs than Division II, Division III, and NAIA programs; specifically, the average number of full-time ATs per department at the Division I, Division II, Division III, and NAIA levels were 10.4, 3.8, 3.3, and 2.4 respectively. In addition, the ratio of student-athletes to AT increases significantly between Division I and Division III. In Division I, the ratio of student-athletes to AT averages 58:1. In Division II and III, the ratio of student-athletes to AT increases to 118.3:1 and 137.5:1, respectively. As such, one could argue that the Division II and III levels present an opportunity for PTs wishing to support college athletes with potentially fewer resources.

The results found that PTs in collegiate athletics are employed in various ways. Half of all respondents are employed within the academic institution, either as an employee of the athletic department or employee of an academic department (Table 2). Forty-three percent of respondents reported being employed by a health care company. As such, the respondents are nearly split equally between being employed by a health care company or being employed by the academic institution. This variation in employer category suggests that each athletic department may have unique resources and relationships that dictate their staffing models and that a variety of models may be viable.

Interestingly, 91% of respondents provide care for the athlete in the athletic training room either exclusively (61%) or in a combined on-site/off-site model (30%) (Table 2). However, to collaborate effectively across the team and raise the visibility of physical therapy, the ability to provide on-site care may be an important trend to facilitate real-time communication and collaboration.

### LIMITATIONS

This survey has several limitations that should be addressed. First, the survey was disseminated via the AASPT website and electronic communication; therefore, identifying non-AASPT members practicing in the collegiate setting was difficult. Further, it is likely that all genders of PTs working in collegiate athletics were not fully accounted for in the survey. The survey question requesting self-identification was developed in line with how demographics are reported for the AASPT but are not in keeping with current best practices, i.e. using questions that use gender confirmatory language to permit self-identification of gender in a more inclusive manner. Individuals who do not identify as male or female may have not responded to the survey for that reason alone and are therefore under-represented in the results. Further, no demographics of race or ethnic background were accounted for in the study. This information would be helpful to further identify areas for growth and inclusion in the collegiate athletics settings. Doing so would likely improve outcomes amongst the diverse population of collegiate athletes served by PTs. Lastly, the survey was conducted during the COVID-19 pandemic, which may have affected the response rate or altered the roles of those participating in the study at the time. Further research should include deeper insights into demographic information (gender, race, ethnicity, education), specific interventions performed, detailed job descriptions, and service locations. A qualitative study seeking deeper understanding of these aspects of practice as well as monitoring these data longitudinally will provide useful information on how PTs can improve care in collaboration with collegiate sports health care teams.

### CONCLUSIONS

The results of this survey research highlight demographic, occupational characteristics, roles, and responsibilities of PTs providing care in collegiate athletics sports medicine in...
the United States. Themes that appeared were the under-representation of female professionals, variability of credentials and post-professional PT education, and a smaller presence in Division II, III, and NAIA institutions. Commonality was found regarding use of treatment methods such as rehabilitation exercise, sports performance enhancement, and manual therapy. Given the rising emphasis of interprofessional collaboration within collegiate athletics sports medicine teams, it appears PTs provide a unique skillset that can support student athletics and their healthcare colleagues. Further research into other team members’ perspective of PTs in collegiate athletics sports medicine may help to define and maximize the efficacy of PT practice in this setting. Financial and administrative models need to be better understood to ensure long term sustainability of these roles. As the field of sports medicine evolves to improve collaborative care, this survey highlights the current roles and responsibilities of the PT working in the collegiate athletics sports medicine setting and serves as a starting point for further understanding and development of the sports PT specialty.

CONFLICTS OF INTEREST

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Exploring Force Production Reliability across Different Levels of Clinical Experience during a Simulated One-handed Instrument-Assisted Soft Tissue Mobilization Treatment: A Pilot Study

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**Background**

Instrument-assisted soft tissue mobilization (IASTM) is a commonly utilized intervention for musculoskeletal pain and dysfunction. However, little is known regarding the reliability of forces applied by clinicians of different experience levels during an IASTM intervention.

**Purpose**

The purpose of this pilot study was to assess intra-clinician reliability of IASTM force (i.e., mean normal force) during a simulated, one-handed stroke IASTM intervention across different levels of IASTM clinical experience.

**Design**

Descriptive laboratory study.

**Methods**

The researchers conducted a repeated measures trial in a laboratory setting with a convenience sample of ten participants who had previously completed professional IASTM training. Participants performed 15 one-handed sweeping strokes with an IASTM instrument on a skin simulant attached to a force plate for a standardized hypothetical treatment scenario. The participants performed the treatment on two separate days, 24-48 hours apart. The researchers examined the intra-rater reliability for average (mean) normal forces using Bland-Altman (BA) plots and Coefficient of Variation (CV) values.

**Results**

The BA plot results indicated all participants (professional athletic training students = 4, athletic trainers = 6; males = 5, females = 5; age = 32.60 ± 8.71 y; IASTM experience = 3.78 ± 4.10 y), except participant D (1.9N, 190g), were consistently reliable within 1N (100g) or less of force for mean differences and within the maximum limits of agreement around 3.7N (370g). Most participants’ CV scores ranged between 8 to 20% supporting reliable force application within each treatment session.

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Conclusion

The data indicated that IASTM trained clinicians could produce consistent forces within and across treatment sessions irrespective of clinical experience.

Level of Evidence

INTRODUCTION

Instrument-assisted soft tissue mobilization (IASTM) is a commonly utilized intervention for musculoskeletal pain and dysfunction.1–4 The use of instruments is thought to provide a mechanical advantage to transmit greater, and more controlled load to mobilize soft tissue restriction or myofascial adhesion than manual massage.1–3 The more targeted force transmission is thought to result in soft tissue healing, collagen repair, resolution of scar tissue, and connective tissue remodeling.1–7 Further, IASTM is also thought to minimize clinician fatigue and enhance clinician detection of soft tissue anomalies.1–7

Multiple theories regarding the mechanism of effect of IASTM have been proposed, with mechanical and neuro-physiological theories often being cited. Mechanical theory advocates often suggest that IASTM provides pressure and shearing forces to release and address adhesions, fascial restriction, and scar tissue facilitated through the inflammatory phase of the tissue healing process.6–9 Neurophysiological theory advocates, in contrast, propose IASTM causes stimulation of both the high and low threshold mechanoreceptors.10–12 The stimulation also activates the ascending afferent pathways that signal the natural physiological response of the body, causing blood flow changes and mechanoreceptor activity after an IASTM session.10–12 The selected IASTM approach or tools may also activate different mechanoreceptors (e.g., Pacinian corpuscles, Meissner corpuscles, Merkels disks) based on force applied, instrument weight, bevel or angle degree, or stroke variations (e.g., stroke speed).10–12

Clinicians have several IASTM instruments and training programs available to them, including, but not limited to, Técnica Gavilán®, RockBlades®, Edge Mobility System™, Fascial Abrasion Technique™, and the Graston Technique®.2,7 Several IASTM companies offer training programs with specific protocols, while others do not promote specific protocols or require training for instrument purchase.2,7 Little is known regarding how differences in manufactured IASTM instruments (e.g., instrument weight, beveling, number of edges, etc.), variations in IASTM training, or proposed manufacturer IASTM treatment protocols influence force production during treatment or patient outcomes.2–7 The lack of evidence-based guidelines, inconsistencies in required IASTM clinician training prior to instrument purchase, irregularities across training programs, and variations within IASTM treatment variables (e.g., force applied, instrument weight, instrument bevel, treatment goals, etc.) may lead to inconsistencies in IASTM application in research and clinical practice.1,2,7

Currently, research is limited in determining the amount of force and the reproducibility of that force during the IASTM application. Researchers6,8,9,12–14 have more commonly quantified IASTM force application in animal model studies. Studies conducted on rodent ligaments with short durations of approximately 250–300 grams (g; ~2–3 newtons [N]) of downward force have demonstrated enhanced soft-tissue healing.8,9 Gehlsen, Cannon, and Helfst14 also reported short durations of increased forces ranging from 0.5N (50g) to 1.5N (150g) enhanced fibroblast proliferation. However, it is not well understood how the forces used in the animal model studies compare to IASTM forces used in clinical practice, how these published results have influenced clinical practice, or how different forces influence treatment outcomes.

To date, the IASTM forces used in human trials have been less commonly quantified or estimated, and the forces reported have varied more widely than those used in the animal model studies. Light force, as estimated by the weight of an IASTM tool (i.e., ~208g, ~2N) without assessment of the actual force applied during treatment, has been used as an estimate for pressure during treatment; the light pressure was concluded to have improved pain pressure threshold in participants with delayed onset muscle soreness.5 In contrast, Vardiman et al.13 documented force production and reported large treatment force ranges (mean and peak pressure) varying from 2–9N (200–900g) within a treatment session; the use of IASTM in this scenario did not result in significant changes in range of motion, maximum voluntary contraction peak torque, and change in inflammatory markers in healthy participants. As minimal research regarding force used during IASTM exists in human trials to guide evidence-based guidelines for IASTM application, clinicians may be challenged to select an appropriate treatment force and may rely on their IASTM training or personal preference to guide treatment application. Recently, IASTM trained clinicians indicated that it is common to deviate from the recommendations of their IASTM training or to not consider the amount of force applied during IASTM treatment.15 Thus, it may also be challenging to confirm that IASTM force application is consistent within a treatment session or across treatment sessions.

Currently, few researchers have examined the amount of force clinicians utilize while treating patients, the consistency of IASTM force application within or across treatments, or how IASTM force application consistency may vary by clinician experience. Given the lack of IASTM force research, the variability of forces reported in the literature, and the clinician-noted deviations from training recommendations, it is valuable to evaluate clinician-applied IASTM force and the reliability of those forces across treatment sessions. Therefore, the purpose of this pilot study was to assess the intra-clinician reliability of IASTM forces (i.e., mean normal force) during a simulated, one-handed...
stroke IASTM intervention among clinicians with different levels of IASTM and professional experience.

METHODS

DESIGN

The University of Idaho Institutional Review Board approved the pilot study and informed consent was provided by participants prior to study participation. A repeated measures trial was conducted at a university research biomechanics laboratory. All participants were provided with an identical standardized treatment scenario and instructed to perform the IASTM treatment using the Técnica Gavilán® instrument Ala (Tracy, CA; Ala, mass: 196g) as they would in clinical practice. A total of 15 one-handed strokes were completed across two data collection days; the average normal forces (i.e., the average force perpendicular to the treatment plane from the beginning to end of a single stroke) in newtons (N) were recorded for each IASTM stroke applied.

PARTICIPANTS

This study included a convenience sample of ten participants (five females and five males; six certified athletic trainers and four athletic training students) who had completed at least one professional IASTM course prior to study participation. All participants had completed the introductory course offered by Técnica Gavilán®, while one of the participants had also completed additional IASTM courses (e.g., RockBlades® courses). Participants had a mean age of 32.60 ± 8.71 years and a mean IASTM experience of 3.78 ± 4.10 years.

Participant experience was classified into five categories: 1st Year Professional Student (i.e., student in their 1st year of professional program who completed their first IASTM course within the prior six weeks), 2nd Year Professional Student (i.e., student in their 2nd year of professional program with one year of IASTM experience after completing their first IASTM course), Early Career Clinician (i.e., credentialed clinician with less than five years of IASTM experience post-completion of their first IASTM course), Intermediate Experienced (Exp.) Clinician (i.e., credentialed clinicians with five to nine years of IASTM experience post-completion of their first IASTM course), and Established Clinician (i.e., credentialed clinician with 10 + years of IASTM experience post-completion of their first IASTM course).

INSTRUMENTATION

Participants applied IASTM forces to a skin simulant (Complex Tissue Model, Simulab Corporation®, Seattle, WA) of 1-inch thickness designed to replicate skin, subcutaneous fat, fascia, and pre-peritoneal fat that was attached to a 6’x6’ force plate (HE6x6, AMTI®, Watertown, MA). The force plate was calibrated between each participant and raw data from the force plate were recorded at a rate of 500Hz using NetForce software (v. 3.5.3, AMTI®, Watertown, MA). Data were processed in MATLAB (v. 2019b, Natick, MS) and filtered using a 10Hz low-pass Butterworth filter to determine the beginning and end of each stroke. The skin simulant attached to a force plate was then stabilized on a treatment table for data collection (Figure 1).

The Técnica Gavilán® instrument Ala has also been used in prior studies. The weight of the instrument is 196g. The Técnica Gavilán® instrument is a stainless-steel tool with a single beveled edge which allows unilateral strokes by the clinician (Figure 2). The same instrument was used for consistency among clinicians and sessions.

PROCEDURES

All participants completed a familiarization protocol (i.e., practiced five one-handed strokes with the instrument on the skin simulant) before beginning the testing protocol. Participants were allowed to add their desired amount of emollient to the skin simulant and to practice strokes on the simulant/force plate until the participant reported feeling comfortable applying an IASTM treatment on the apparatus. Participants were then provided with a standardized treatment scenario for the medial gastrocnemius: an otherwise healthy patient experiencing gastrocnemius tightness who they examined to confirm that an IASTM application was indicated.

Once the familiarization protocol was completed, participants then applied five one-handed, unilaterally directed sweeping strokes (distal to proximal) to the skin simulant with the IASTM instrument, emulating as closely as possible a typical patient treatment application for the simulated scenario. Participants lifted the instrument off the simulant between strokes to identify individual strokes more efficiently during data processing. The participant selected the direction (i.e., distal-to-proximal or proximal-to-distal) that felt most natural to them, and ultrasound gel could be added as emollient as needed during treatment.

The testing protocol was repeated three times, for 15 total strokes with the Técnica Gavilán® instrument (Figure 2) on two testing days. A total of 30 complete treatment strokes per participant were collected over the two treatment sessions. The second treatment session occurred between 24 and 48 hours after the initial testing session for all participants.

STATISTICAL ANALYSIS

Coefficient of variation (CV) and descriptive statistics were calculated in Excel 16.46 (Microsoft®, 2021). The mean force (Newtons N) was defined as the average of the vertical forces produced across the entire length of a single stroke and divided by the number of trials (Table 1). Coefficient of variation (SD/Mean*100) was calculated over two days for individual participants and the total strokes with the Técnica Gavilán® instrument (Table 1). Lower CV values corresponded to higher reliability; CV values ≤ 20% were preferred, but values ≤ 30% were also considered low enough to indicate data homogeneity. Box and whisker plots were created to compare average (mean) forces between two treatment session days (Figure 3).
Bland-Altman (BA) plots (Figure 4) were constructed for each participant to determine the agreement between the average (mean) forces applied over the two-day treatment sessions. The BA plots were created with data points from the Técnica Gaviláná instrument. The BA plots were constructed with R 3.6.2 (The R Foundation for Statistical Computing Platform, 2019) and the BlandAltmanLeh (v0.5.1; Lehnert, 2015) software package. The BA plots were presented with mean differences, 95% limits of agreement (LOA), and the precision of those limits (e.g., 95% confidence intervals).

RESULTS

The average forces produced across all 10 participants ranged from 1.6 to 9.0N (~160-900g). The highest average force was produced by Participant D (7.1-9.0N; 720-900g). The sample of participants demonstrated relatively small standard deviations (SD) in their mean force application for day one (~1.2N; 120g) and day two (~1.6N; 160g). The highest mean differences value for average force was also found with Participant D (1.9N; 190g), while the other participants had mean differences of 1N (100g) or less. Box and whisker plots also support similar force application among participants across Day 1 and Day 2 (Figure 5).

Only one CV value was above 20% (i.e., 23%) for any participant across either of the two treatment sessions, with the other 19 values ranging between 8 to 20% (Table 1). The CV values indicate acceptable consistency among the forces within an IASTM treatment session. The BA plot analysis suggested that all ten participants demonstrated agreement with average force production over Day 1 and Day 2 treatment sessions. Forces from all participants reflect that 98% of the data points are within the LOA. When assessing each participant, the LOA for average forces were narrowest for participant E (~0.6N, 0.3N; 60g, 30g) and widest for participant D (~3.7N, ~0.2N; 37g, 20g). The consistent findings within the box and whisker plots in a simulated model with a single stroke, combine with low CV values and acceptable BA plot results supports acceptable IASTM force application reliability.

DISCUSSION

The researchers investigated the ability of clinically experienced (i.e., licensed professionals) and non-clinically experienced (i.e., professional-level student) participants to reliably apply IASTM forces during a simulated treatment scenario. Participants who had at least completed the same IASTM training courses (i.e., the introductory IASTM Técnica Gaviláná basic training course) were able to produce consistent treatment forces within and across the two treatment sessions. The box and whisker plots, CV values, and BA plots indicated the IASTM trained clinicians in this

Figure 1. Skin simulant Setup.
Complex Tissue Model (Simulab Corporation©, Seattle, WA) attached to a force plate (HE6X6, AMTI©, Watertown, MA)

Figure 2. Técnica Gavilán® Instrument Ala (Tracy, CA; Ala, mass: 196g) (Front & Back)
Table 1. Participant Reliability

<table>
<thead>
<tr>
<th>Participant Category</th>
<th>Mean Force (N)</th>
<th>SD (N)</th>
<th>CV (%)</th>
<th>BA Mean Diff. (N)</th>
<th>BA Avg. Forces (N) 95% CI Upper/Lower</th>
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<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
<td>Day 1</td>
<td>Day 2</td>
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<tr>
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<td>Student</td>
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<tr>
<td>Participant C</td>
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<td>2.5</td>
<td>0.5</td>
<td>0.4</td>
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<tr>
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<td>1.2</td>
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<td>Participant E</td>
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<td>1.8</td>
<td>0.1</td>
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<td>0.4</td>
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<tr>
<td>Intermediate Exp. Clinician</td>
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<td>Participant G</td>
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<tr>
<td>Participant H</td>
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<td>Established Clinician</td>
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<td>Participant J</td>
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<tr>
<td>Participant K</td>
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<td>4.9</td>
<td>0.7</td>
<td>0.5</td>
<td>14</td>
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</tbody>
</table>

Mean Force equals the average force from all 15 strokes from all participants for Day 1 and Day 2. Coefficient of variation (CV) was calculated as the ([SD/Mean]*100). Bland-Altman (BA) analysis, mean differences and 95% confidence intervals for the limits, are also presented. For reference: 2.5 newtons (N) = 250 grams (0.55 lbs), 2N = 204 grams (0.45 lbs), 1.0 newtons (N) = 100 grams (0.22 lbs) and 0.02N = 2 grams (0.004 lbs).

Figure 3. Box and Whisker Plots.

Box and whisker plots for average force (F_{mean}) in Newtons for each of the 15 strokes for each participant over Day 1 (dark box) and Day 2 (light box) treatment sessions. Black dots indicate potential force outliers from an individual stroke.
Figure 4. Mean Forces (N).
Bland-Altman plots for mean forces (N) for all participants. Mean force equals the average force from each of the 15 strokes for Day 1 and Day 2. Each data point plotted denotes the vicinity to zero of a given difference plotted relative to the average value of the Day 1 and Day 2 measurements.
sample developed and maintained sufficient force consistency after completing an IASTM training course irrespective of their clinical experience levels. The IASTM force ranges found in the study of 1.6N (160g) to 9N (900g) are similar to prior reported ranges of 2N (200g) to 9N (900g) to the posterior leg of human participants.\textsuperscript{13} The force ranges are also consistent with a descriptive study where researchers analyzed IASTM forces using similar methodology (i.e., analyzed IASTM stroke application on a skin simulant affixed to a force plate for mean and peak normal forces) and reported an average mean normal forces of 6N (600g) and peak normal forces of 8.9N (890g) across various instruments and professional clinicians.\textsuperscript{16} Evidence elucidating how IASTM force differences (e.g., force range, force peaks) influence physiological outcomes in human trials is not available. Animal models\textsuperscript{8,9,14} suggest a relationship between increased tissue healing and higher levels of force; however, the scenarios (e.g., enzyme induced injuries, smaller and more superficial tissue) and the IASTM forces (i.e., substantially lower) may not serve as good models for potential human trial results.

These pilot study results provide initial support that clinicians who complete similar IASTM training may produce similar force across IASTM treatment sessions. However, these results are limited to similarly trained IASTM clinicians. Thus, it would be beneficial to confirm IASTM force consistency in a larger sample of clinicians and to examine how different training influences IASTM force production ranges and consistency. Determining how IASTM force treatment ranges and IASTM training differences may or may not result in different physiological responses or patient outcomes at different IASTM dosages (e.g., amount of force, length force is applied) would help guide best-practice recommendations for IASTM application.

The pilot study results also expand on previous findings\textsuperscript{13,16} that provided insight into the amount of force that may be produced during an IASTM intervention to the medial gastrocnemius in otherwise healthy people by reporting the reliability of those forces and if clinician experience substantially influenced force reliability. The current data suggests that trained Técnica Gavilán IASTM clinicians produce consistent forces within 1N (100g) of force application without requiring extensive experience post-IASTM training. Although current research is indeterminate regarding an optimal force application for IASTM, the current findings and previous research\textsuperscript{13,16} indicate that IASTM trained clinicians may produce similar and consistent forces within and across IASTM treatment sessions. While clinicians have indicated that they may not try or know how to quantify forces during an IASTM treatment,\textsuperscript{15} the results provide some data to indicate that clinicians may still be able to apply a relatively consistent force during the treatment session.

There were a few limitations identified in the pilot study. One limiting factor was the relatively small sample size of ten participants with similar training background (i.e., Técnica Gavilán\textsuperscript{a} basic course), which may have influenced the forces participants applied during treatment sessions. Another limitation was using a single IASTM instrument and a single IASTM stroke; using different treatment strokes or IASTM instruments may influence force production and reliability. Additionally, the researchers methodology included the use of a simulated tissue on a force plate versus actual patients; while force measurement may be more accurate with the use of force plate technology, the amount of force used on the skin simulant may differ from human tissue that is pathological or healthy. Further, force application may vary by other clinical variables (e.g., table height, treatment goals, etc.) and the reported values may not be representative of all clinical scenarios or all clinicians. Future research should explore how different IASTM training, length of experience using IASTM, and clinicians’ perceptions of IASTM mechanisms or treatment effects influences IASTM force production and reliability. Finally, as a standardized IASTM optimal force recommendation does not exist in practice, future research should also explore the ranges described in the literature to determine how different amounts of IASTM force application and instrument technique affect treatment outcomes in clinical practice. This exploratory study provides insight and guidance for future studies on IASTM force application with patients.

CONCLUSION

The results of this pilot study provide insight into the amount of force and the consistency of forces during IASTM applied by trained clinicians with different levels of professional experience within a simulated treatment scenario. The participants demonstrated acceptable consistency within and across the two treatment sessions. Thus, clinicians who complete similar IASTM training may be able to quickly develop consistent force production during IASTM treatments and may be able to maintain that consistency across their careers.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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REFERENCES


Case Reports

The Effect of Blood Flow Restriction Therapy on Shoulder Function Following Shoulder Stabilization Surgery: A Case Series

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Keywords: Blood Flow Restriction, Shoulder Instability, Shoulder Strength

International Journal of Sports Physical Therapy

Background

Traumatic shoulder instability is a common injury in athletes and military personnel. Surgical stabilization reduces recurrence, but athletes often return to sport before recovering upper extremity rotational strength and sport-specific abilities. Blood flow restriction (BFR) may stimulate muscle growth without the need for heavy resistance training post-surgically.

Hypothesis/Purpose

To observe changes in shoulder strength, self-reported function, upper extremity performance, and range of motion (ROM) in military cadets recovering from shoulder stabilization surgery who completed a standard rehabilitation program with six weeks of BFR training.

Study Design

Prospective case series

Methods

Military cadets who underwent shoulder stabilization surgery completed six weeks of upper extremity BFR training, beginning post-op week six. Primary outcomes were shoulder isometric strength and patient-reported function assessed at 6-weeks, 12-weeks, and 6-months postoperatively. Secondary outcomes included shoulder ROM assessed at each timepoint and the Closed Kinetic Chain Upper Extremity Stability Test (CKQUEST), the Upper Extremity Y-Balance Test (UQYBT), and the Unilateral Seated Shotput Test (USPT) assessed at the six-month follow-up.

Results

Twenty cadets performed an average 10.9 BFR training sessions over six weeks. Statistically significant and clinically meaningful increases in surgical extremity external rotation strength (p < 0.001; mean difference, .049; 95% CI: .021, .077), abduction strength (p < 0.001; mean difference, .079; 95% CI: .050, .108), and internal rotation strength (p < 0.001; mean difference, .060; CI: .028, .093) occurred from six to 12 weeks postoperatively. Statistically significant and clinically meaningful improvements were reported on the Single Assessment Numeric Evaluation (p < 0.001; mean difference, 17.7; CI: 9.4, 25.9) and Shoulder Pain and Disability Index (p < 0.001; mean difference, -31.1; CI: -44.2, -18.0) from six to 12 weeks postoperatively. Additionally, over 70 percent of participants met reference values on two to three performance tests at 6-months.

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Conclusion
While the degree of improvement attributable to the addition of BFR is unknown, the clinically meaningful improvements in shoulder strength, self-reported function, and upper extremity performance warrant further exploration of BFR during upper extremity rehabilitation.

Level of Evidence
4, Case Series

INTRODUCTION

Traumatic shoulder instability is a common upper extremity injury. Incidence rates range from 23.9 per 100,000 person-years in the general population to 435 per 100,000 person-years in military cadets. Surgical stabilization reduces recurrence and improves self-reported function compared to conservative management for active young adults. Return to sport typically occurs six months postoperatively, with time from surgery used as the primary measure of readiness. However, athletes often lack rotational strength and upper extremity performance, with only 80% of athletes and 68% of overhead throwing athletes reaching their pre-injury play level. Since the rotator cuff stabilizes the humeral head within the glenoid, incomplete recovery of rotational strength may contribute to recurrent instability and failure to return to sport following shoulder stabilization surgery.

Exercising with loads at 70-85% of one-repetition maximum improves muscle strength but is challenging, symptom-producing, or sometimes contraindicated following surgery. Blood flow restriction (BFR) training uses a tourniquet to impede arterial inflow while occluding venous return, stimulating anaerobic metabolism without heavy resistance. Blood flow restriction training is safe and well-tolerated in the acute phase of tissue healing. Local physiologic adaptations from BFR training primarily occur in muscles distal to tourniquet placement. However, increased metabolite accumulation, selective recruitment, cellular swelling, and myostatin down-regulation may activate a systemic release of anabolic hormones – growth hormone and insulin-like growth factor-1 – suggesting BFR training may stimulate muscle growth proximal to tourniquet placement. Long occlusion times with combined aerobic and anaerobic exercise may add to the systematic release of anabolic hormones, further contributing to proximal muscular adaptations seen with BFR training.

Exercising with BFR is gaining popularity for upper extremity injuries but its effectiveness following shoulder stabilization surgery requires additional exploration. Therefore, the purpose of this case series was to observe changes in shoulder strength, self-reported function, upper extremity performance, and range of motion (ROM) in military cadets recovering from shoulder stabilization surgery who completed a standard rehabilitation program with six weeks of BFR training.

METHODS

This study was a prospective case series. Eligible participants were current military cadets, fluent in English, and within six weeks of shoulder stabilization surgery. Shoulder stabilization was defined as any procedure to tighten or repair the glenoid labrum or glenohumeral ligaments. Participants were excluded if they were immunocompromised; required general anesthesia for another medical procedure within six weeks of consent; underwent concomitant rotator cuff repair; had a humeral neck or shaft fracture; or had a history of deep vein thrombosis, endothelial dysfunction, or bleeding disorders.

Twenty-three military cadets, status-post shoulder stabilization surgery were screened for eligibility and enrolled in the study (Figure 1). The most common surgical procedure performed was a Bankart repair of the anterior-inferior glenoid labrum. Of the 23 participants, three dropped from the study, with two failing to follow up within the required time points and one unable to receive BFR treatments after enrollment due to COVID-19-related illness. Eighteen participants completed all follow-up assessments, with two graduating before the six-month evaluation.

PHYSICAL THERAPIST

A single physical therapist recruited, treated, and assessed the outcomes on all participants. The physical therapist was board certified in orthopedic physical therapy and a fellow in training at a Division 1 sports physical therapy fellowship program. The physical therapist provided tailored manual therapy and home exercise programs addressing individual impairments as needed as part of standard rehabilitation.

BLOOD FLOW RESTRICTION

Blood flow restriction treatments began post-op week six when participants were cleared from ROM restrictions and permitted to begin isotonic resistance exercises. Participants performed two to three BFR treatments per week in addition to a standard rehabilitation protocol. A Delfi Personalized Tourniquet System (Delfi Medical Innovations Inc., Vancouver, Canada) was used to automatically regulate pressure with the tourniquet (18 x 4.5-inch contour cuff) applied to the upper brachium of the surgical extremity (Figure 2). Inflation time was set to 30 minutes, and limb occlusion pressure was set to 50%. The tourniquet remained inflated during all exercises but did not exceed 30 minutes per session.
Figure 1. Flow diagram of patient recruitment and retention

Abbreviations: NPRS, Numeric Pain Rating Scale; SANE, Single Assessment Numeric Evaluation; SPADI, Shoulder Pain and Disability Index; QuickDASH, Quick Disabilities of Arm Shoulder and Hand; ROM, Range of Motion; USMA, United States Military Academy

DETERMINING INTENSITY AND RESISTANCE

Perceived exertion is a good indicator of physical strain and is used to help prescribe and regulate intensity during aerobic and anaerobic training.25–29 Participants were given a Rating of Perceived Exertion (RPE) scale at the beginning of each treatment.29 Before applying the tourniquet, participants performed a few repetitions of each exercise without BFR on both extremities to determine the load-RPE for their working sets.26 For their surgical extremity, participants selected a resistance at an RPE between seven (extremely light) to nine (very light), corresponding to 30% of a one-repetition maximum effort.26 This was used as
the starting resistance for their surgical extremity. On their non-surgical extremity, participants performed the same procedure but selected a resistance at an RPE between 15 (hard) to 17 (very hard), corresponding to between 70% to 90% of a one-repetition maximum effort.26 Participants were permitted to adjust the resistance as needed but were instructed to keep pre-BFR resistance within the predetermined RPE ranges.

AEROBIC EXERCISE

Participants began treatment with an upper body cycling exercise on a Biodex Upper Body Cycle (UBC) (Model 950-138, Shirley, New York). Participants cycled forward at their self-selected pace for five minutes at a pre-BFR resistance RPE between nine (very light) to eleven (light).27

STRENGTH EXERCISES

Participants performed three strengthening exercises targeting the rotator cuff and periscapular musculature: resisted external rotation, scapular retraction with shoulder extension, and scapular plane abduction. A Keiser Functional Trainer (Keiser Corp model 003025.15, Fresno, CA) was used to adjust resistance and transition between extremities and exercises easily. For the surgical extremity, four sets of each exercise were performed using the 30-15-15-15 repetition method recommended by Patterson et al.14 For the non-surgical extremity, four sets of 12 repetitions were performed without BFR. Participants alternated between extremities completing one exercise before moving to the next. If participants failed to complete all exercises in the allotted 30 minutes, the tourniquet was removed, and participants finished the remaining exercises without BFR.

OUTCOME MEASURES

Primary outcomes included shoulder isometric strength and patient-reported function measured from the surgical date at three follow-up assessments: six weeks, 12 weeks, and six months. Secondary outcomes included physical function assessed by performance tests during the six-month follow-up and shoulder active range of motion measured at six weeks, 12 weeks, and six months postoperatively.

ISOMETRIC STRENGTH

The physical therapist assessed isometric shoulder external rotation, internal rotation, and abduction strength using a hand-held dynamometer (Microfet 2, Hoggan Health Industries Inc. Draper, UT, USA). Hand-held dynamometry is reliable and has concurrent validity with isokinetic testing while being practical in a clinical setting.30 Participants performed a submaximal effort at 50% before performing two test efforts in each position. Test efforts consisted of a five-second maximal contraction. The surgical extremity was tested before the non-surgical extremity. Strength was normalized by dividing the average force in kilograms produced by kilograms of body mass and then compared to the contralateral extremity. For analysis, a percent change of 15% is considered clinically meaningful.31

External and internal rotation strength was assessed in the supine position with the shoulder in 45 degrees of abduction (Figure 3). This position stabilizes the scapulothoracic articulation and is described as the optimal position to reduce the coefficient of variation.32–34 A bolster was placed under the elbow to maintain neutral shoulder flexion and extension and between the arm and trunk to maintain 45 degrees of abduction.34 The hand-held dynamometer was positioned proximal to the styloid process of the wrist joint.

Abduction strength was assessed with the participant seated on the plinth with their shoulder abducted 45 de-
Degrees in the scapular plane.\textsuperscript{34} The hand-held dynamometer was placed proximal to the elbow.

\textbf{PATIENT-REPORTED FUNCTION}

Participants completed the Numeric Pain Rating Scale (NPRS), the Single Assessment Numeric Evaluation (SANE), the Shoulder Pain and Disability Index (SPADI), and the modified Disability Arm Shoulder Hand (QuickDASH) at each follow-up assessment. The NPRS assessed pain intensity on an 11-point scale (zero being no pain and ten being the worst). The NPRS is reliable, valid, and responsive, with a change of two or more considered clinically meaningful.\textsuperscript{35} The SANE assessed shoulder function as a percentage of normal (zero being no function and 100\% being normal). The SANE is reliable, valid, and responsive, with a change of 15\% considered clinically meaningful.\textsuperscript{36,37} The SPADI and QuickDASH are reliable, valid, and responsive for assessing pain and disability for multiple shoulder conditions. A change of 18 points was considered clinically meaningful for the SPADI\textsuperscript{38,39} and 16 points for the QuickDASH.\textsuperscript{40–42}

\textbf{PERFORMANCE TESTS}

Participants performed the CKUEST (Figure 4a), the UQYBT (Figure 4b), and the USPT (Figure 4c) following isometric strength testing at the six-month follow-up assessment. The surgical shoulder was assessed before the non-surgical shoulder for all tests.

The CKUEST is a reliable measure of upper extremity closed kinetic chain function.\textsuperscript{43} Participants assumed a standard push-up position with their hands placed inside two pieces of athletic tape measured 36 inches apart and their feet no more than 12 inches apart. When instructed, participants reached, alternating hands, touching the athletic tape under the opposite hand. The total number of cross-body touches in 15 seconds was recorded. Participants performed a submaximal trial before performing three test efforts. An average of three efforts was used for analysis. Results were compared to reference values with a score of greater than or equal to 21 touches considered above average for healthy college-aged students.\textsuperscript{8,43–45}

The UQYBT is a reliable measure of unilateral upper extremity closed kinetic chain excursion.\textsuperscript{44,46} Participants assumed a standard push-up position with their feet no more than 12 inches apart. Participants reached as far as possible in three directions with their free hand. Participants performed three practice trials before performing three test efforts.\textsuperscript{44} A total excursion score was calculated by summing the average of each reach direction. A composite score was calculated to normalize for limb length, taking the total excursion distance and dividing it by three times the upper limb length.\textsuperscript{44} Limb symmetry index (LSI) was then calculated by dividing the composite score of the surgical extremity by the composite score of the non-surgical extremity and then multiplying by 100. Scores were compared to reference values from a cohort of military cadets, with an LSI of 95\% considered normal.\textsuperscript{44}

The USPT is a functional test of upper extremity power with good test-retest reliability in college male and female athletes.\textsuperscript{47,48} Participants sat with their back against a wall, feet flat on the floor, knees at a 90\/-degree angle, and their non-testing hand across their chest. In a pushing motion, participants maximally tossed a 2.72-kilogram medicine ball from shoulder height as far forward as possible while keeping their head, non-tested scapula, and back in contact with the wall. Participants performed three submaximal practice tosses before performing three test efforts. Using the methods described by Chmielewski et al., average scores were allometrically scaled (\(\text{distance (cm)/body mass (kg)}^{0.35}\)) with body mass as the anthropometric measure.\textsuperscript{48} The exponent 0.35 removed the influence of body mass, yielding a body size-independent measure.\textsuperscript{48} An LSI of 90\% accounted for limb dominance and was considered normal.\textsuperscript{48}

\textbf{ACTIVE RANGE OF MOTION}

Before isometric testing, the physical therapist measured active flexion, external rotation, and internal rotation using a digital inclinometer (Baseline Digital Inclinometer 12-1057; Fabrication Enterprises INC, New York, USA). Participants were positioned supine with their knees flexed, feet flat, and low back flush on a standard treatment plinth.
Table 1. Demographics, mean (SD)

<table>
<thead>
<tr>
<th>n</th>
<th>Age (yrs)</th>
<th>Sex (M/F)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Surgical Limb (R/L)</th>
<th>Dominant Limb (R/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>21.3 (1.9)</td>
<td>17 / 3</td>
<td>178.3 (8.1)</td>
<td>79.9 (11.8)</td>
<td>13 / 7</td>
<td>19 / 1</td>
</tr>
</tbody>
</table>

Abbreviations: M/F, male / female; R/L, right / left

Measurement was recorded at the end of available active ROM (loss of test position or limitation due to pain). Two trials were completed bilaterally, with the average used for analysis.

Shoulder flexion was measured with the digital inclinometer positioned on the arm between the olecranon process and axilla for flexion. External and internal rotation were measured in 90 degrees shoulder abduction, 90 degrees elbow flexion, and neutral forearm rotation. The distal half of the humerus was positioned off the plinth to allow for full ROM. The therapist applied manual anterior-posterior pressure to the humeral head to decrease compensatory movements. The digital inclinometer was placed on the forearm between the ulnar styloid process and the olecranon process.

DATA ANALYSIS

Descriptive statistics, including central tendency and variability measures, were the primary means of analyzing data. A one-way, repeated-measures analysis of variance was used to analyze changes in all outcome measures over time. An alpha of .05 was set with time as the within-subject factor. A Bonferroni correction was used for three planned pairwise comparisons to examine the differences between the various time points (α = .0167), with 95% confidence intervals (CIs) calculated for mean differences. All data were analyzed using SPSS Version 28 for Windows software (SPSS Inc, Chicago, IL).

OUTCOMES

Participant characteristics are summarized in Table 1.

ISOMETRIC STRENGTH

Participants experienced statistically significant improvements in surgical extremity external rotation strength (F = 10.0, p < 0.001), abduction strength (F = 25.8, p < 0.001), and internal rotation strength (F = 11.3, p < 0.001). Post hoc comparisons revealed statistically significant increases in external rotation strength, internal rotation strength, and abduction strength from six to 12 weeks (Table 2). From six weeks to 12 weeks, 17 of 20 participants achieved clinically meaningful improvements in surgical extremity external rotation strength (Figure 5), 17 of 20 for abduction strength, and 14 of 20 for internal rotation strength. No statistically significant strength increases occurred in the non-surgical extremity.

PATIENT-REPORTED FUNCTION

Participants experienced statistically significant improvements in reported function measured by the SANE (F = 19.7, p < 0.001), the SPADI (F = 24.8, p < .0001) and the QuickDASH (F = 61.8, p < 0.001). Post hoc comparisons revealed statistically significant improvements and clinically meaningful improvements on the SANE and SPADI from six to 12 weeks and statistically significant improvements on the SANE, the SPADI, and QuickDASH from six weeks to six months (Table 3). From six to 12 weeks, 16 of 20 participants achieved clinically meaningful improvements on the SANE and 17 of 20 on the SPADI.

PERFORMANCE TESTS

Five of 18 participants met or exceeded reference values on all three performance tests, nine of 18 passed only two tests, three passed only one test, and one participant failed to pass a single test (Table 4). Only three of 18 participants met or exceeded reference values on all performance tests and had 90% limb symmetry for each isometric strength measure at the 6-month assessment. No performance test had a higher pass rate, as 12 of 18 participants met the reference value for each test.

ACTIVE RANGE OF MOTION

Participants experienced statistically significant improvements in surgical extremity external rotation ROM (F = 40.02, p < 0.001), flexion ROM (F = 33.56, p < 0.001), and internal rotation ROM (F = 16.7, p < 0.001). Post hoc comparisons revealed statistically significant improvements in surgical extremity ROM across all timepoints (Table 5).

DISCUSSION

This case series aimed to observe changes in shoulder strength, self-reported function, upper extremity performance, and shoulder ROM in military cadets recovering from shoulder stabilization surgery who completed a standard rehabilitation program with six weeks of BFR training. To the authors’ knowledge, this is the first study to explore the addition of upper extremity BFR training to rehabilitation following shoulder stabilization surgery. Statistically significant and clinically meaningful improvements in shoulder strength and self-reported function were observed in participants who performed BFR training twice a week, beginning six weeks postoperatively. Most participants met or exceeded reference values on two upper extremity performance tests. No adverse events occurred, and no participant discontinued BFR treatments.
Table 2. Surgical Extremity Isometric Strength, mean difference (95% CI)

<table>
<thead>
<tr>
<th>Isometric Strength</th>
<th>Assessment Time</th>
<th>Within-Group Difference†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External Rotation</td>
<td>6 weeks - 12 weeks</td>
<td>.049 (.021, .077)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>.002 (.042, .046)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>.051 (.006, .108)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 12 weeks</td>
<td>.079 (.050, .108)*</td>
</tr>
<tr>
<td>Abduction</td>
<td>12 weeks - 6 months</td>
<td>.011 (-.060, .082)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>.068 (-.015, .151)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 12 weeks</td>
<td>.060 (0.28, .093)*</td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>12 weeks - 6 months</td>
<td>.016 (-.043, .075)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>.045 (-.024, .113)</td>
</tr>
</tbody>
</table>

*Significant post hoc comparisons, p<.0167
†Normalized by body mass (strength in kg/body mass in kg)

Figure 5. Surgical Extremity External Rotation Isometric Strength Measures by Participant at 6 and 12 weeks

Abbreviations: ER, external rotation
*Significant Post hoc comparisons<.0167
*Represents the 15% improvement needed to reach a clinically meaningful change for each participant

Table 3. Patient-Reported Outcomes, mean difference (95% CI)

<table>
<thead>
<tr>
<th>Patient-Reported</th>
<th>Assessment Time</th>
<th>Within-Group Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SANE</td>
<td>6 weeks - 12 weeks</td>
<td>17.7 (9.4, 25.9)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>12.2 (-9.2, 25.2)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>29.8 (15.1, 44.6)*</td>
</tr>
<tr>
<td>SPADI</td>
<td>6 weeks - 12 weeks</td>
<td>-31.1 (-44.2, -18.0)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>-6.4 (-15.1, 2.3)</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>-24.7 (-34.0, -15.5)*</td>
</tr>
<tr>
<td>QuickDASH</td>
<td>6 weeks - 12 weeks</td>
<td>-6.9 (-9.2, -4.6)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>-3.2 (-6.3, -2.2)*</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>-10.2 (-12.9, -7.6)*</td>
</tr>
</tbody>
</table>

Abbreviations: SANE, Single Assessment Numeric Evaluation; SPADI, Shoulder Pain and Disability Index; QuickDASH, Disability Arm Shoulder Hand
*Post Hoc Comparisons, p<.0167

Few studies have examined BFR training for the upper extremity, and even fewer have examined BFR training following an upper extremity musculoskeletal injury. In a randomized study of 32 healthy adults, Lambert et al. compared BFR training to low-intensity exercise alone on rotator cuff strength and endurance. After eight weeks of BFR training, the only statistically significant between-group change was increased internal rotation strength for participants in the BFR group. Likewise, Brumitt et al. found no between-group difference in rotator cuff strength in 46 healthy participants who performed BFR training compared to those who performed exercise alone.
In contrast, Bowman et al. found BFR training to be more beneficial than exercise alone in improving shoulder strength in 24 healthy adults.22 After six weeks of training, participants in the BFR group averaged 48%, 39%, and 53% improvement in shoulder scaption, flexion, and abduction isometric strength, respectively.22 Regarding rotational strength, participants in the BFR group averaged a peak torque improvement of 11% for internal rotation and 15% for external rotation.22 Participants in the BFR cohort performed exercises with continuous BFR on one extremity and without BFR on the contralateral extremity, whereas Lambert et al. and Brumitt et al. had participants perform exercises on one extremity.22–24

In the current study, surgical extremity external rotation, abduction, and internal rotation strength improved by an average of 42%, 44%, and 40% from six weeks to 12 weeks, whereas, the non-surgical extremity had a percent change of six percent, seven percent, and minus seven percent respectively. Our BFR parameters were consistent in training frequency, tourniquet pressure, and restriction method outlined by a panel of experts in occlusion training.14 The protocol followed methods outlined by Cancio et al., who found 30 minutes of low load continuous BFR training at 50% limb occlusion pressure more beneficial in improving self-reported function than standard care alone in participants recovering from distal radius fractures.20 Like Cancio et al., no participant in the current study discontinued BFR treatments. However, five participants in our study needed the limb occlusion pressure reduced from 50% to 40% during the initial BFR treatment due to moderate discomfort in the surgical extremity.

Studies investigating a return to sport criteria following shoulder stabilization surgery have identified time from surgery as the most common indicator of readiness, with athletes typically cleared for sport between five to six months postoperatively.7,51 Wilson et al. used a battery of tests consisting of isokinetic strength testing and two functional tests to assess return to play readiness in competitive athletes six months following shoulder stabilization surgery.5 Only 20 of 43 athletes had an LSI of 90% for internal rotation strength, and only 12 of 43 had an LSI of 90% for external rotation strength.8

The current study observed an LSI of 90% in 15 of 20 participants for internal rotation strength and nine of 20 for external rotation strength at 12 weeks postoperatively. At six months, an LSI of 90% was observed in 12 of 18 participants for internal rotation strength and 11 of 18 for external rotation strength. While Wilson et al. did not assess abduction strength, an LSI of 90% for abduction was observed in 14 of 20 participants at 12 weeks and 13 of 18 at six months postoperatively. Despite the observed improvements, only three of 18 participants had 90% limb symmetry on all strength measures and met reference values on all performance tests at the six-month assessment, suggesting the need for further research to define the best return to sport criteria after shoulder stabilization surgery.

Although the authors are uncertain of the mechanism of action and contribution that BFR had to the observed improvements in the current study, the results are promising and, at minimum, provide preliminary data for future studies.

LIMITATIONS

While statistically significant and clinically meaningful changes in shoulder strength and self-reported function were observed, a causal relationship between intervention and outcome cannot be assumed. The small sample size and lack of a control group mean observed changes may have been a product of time, the natural progression of the condition, or standard rehabilitation. The participants were homogenous regarding age, health, and activity level limiting generalizability to populations outside of young athletes. Furthermore, home exercise programs and manual

Table 4. Number of Participants who met or exceeded Reference Values on the Performance Tests

<table>
<thead>
<tr>
<th>CKCUEST, UQYBT, USPT</th>
<th>CKCUEST, UQYBT</th>
<th>CKCUEST, USPT</th>
<th>UQYBT, USPT</th>
<th>2 of 3 Tests</th>
<th>Only 1 Test</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>14</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Abbreviations: CKCUEST, Closed Kinetic Upper Extremity Stability Test; UQYBT, Upper Quarter Y-Balance Test; USPT, Unilateral Seated Shoulder Test

Table 5. Surgical Extremity Active Range of Motion, mean difference (95% CI)

<table>
<thead>
<tr>
<th>Range of Motion</th>
<th>Assessment Time</th>
<th>Within-Group Difference (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Rotation</td>
<td>6 weeks - 12 weeks</td>
<td>24.56 (13.20, 35.91)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>20.94 (12.36, 25.53)*</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>45.50 (32.11, 58.89)*</td>
</tr>
<tr>
<td>Flexion</td>
<td>6 weeks - 12 weeks</td>
<td>20.94 (14.00, 27.70)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>9.28 (2.37, 16.19)*</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>30.22 (19.90, 40.55)*</td>
</tr>
<tr>
<td>Internal Rotation</td>
<td>6 weeks - 12 weeks</td>
<td>15.11 (6.04, 24.18)*</td>
</tr>
<tr>
<td></td>
<td>12 weeks - 6 months</td>
<td>10.5 (2.86, 18.14)*</td>
</tr>
<tr>
<td></td>
<td>6 weeks - 6 months</td>
<td>25.61 (14.18, 37.04)*</td>
</tr>
</tbody>
</table>

*Significant post hoc comparisons, p<0.0167
therapy were tailored to participants, possibly confounding the BFR-specific effects.

CONCLUSION

After shoulder stabilization surgery, significant improvements in shoulder strength, self-reported function, and ROM were observed with six weeks of BFR training in 20 military cadets. No participant discontinued the BFR treatments, and no adverse events occurred. While the degree of improvement attributable to the addition of BFR is unknown, the clinically meaningful improvements in shoulder strength, self-reported function, and upper extremity performance warrant further exploration of BFR during upper extremity musculoskeletal rehabilitation. Future studies should include randomized control groups with and without BFR and explore varying occlusion times to determine the effectiveness of adding BFR to standard postoperative rehabilitation.

DISCLOSURE/DISCLAIMER

The authors have no relevant or material financial interests that relate to this study. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the United States Army or Department of Defense.

ETHICS APPROVAL

Study was approved by the Naval Medical Center Portsmouth Institutional Review Board

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REFERENCES


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The Management of Valgus Extension Overload Syndrome Experienced with Hitting in a High School Baseball Player: A Case Report

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Keywords: Baseball, Movement System, Valgus Extension Overload, Batting

Background
Valgus extension overload syndrome (VEOS) of the elbow is a condition associated with overhead athletes. However, the non-surgical management of these individuals is not well documented.

Purpose
To discuss the unique presentation, management, and outcomes of an adolescent baseball player with a chronic history of VEOS experienced during hitting.

Case Description
A 15-year-old right-handed high school baseball catcher presented with a six-month history of right-sided ulnar elbow pain. Elbow MRI w/ contrast was consistent with VEOS. The initial examination demonstrated excessive resting right-sided humeral external rotation compared to his left. Valgus stress testing in the subject’s hitting position reproduced symptoms, which were alleviated with retest while correcting excessive humeral external rotation. Weakness of the humeral internal rotators and stiffness/shortness of the posterior shoulder were found and thought to relate to the humeral contribution to his elbow movement dysfunction. Rehabilitation emphasized addressing impairments contributing to excessive humeral external rotation with reintegration into batting.

Outcomes
After five weeks of physical therapy, the subject returned to soft toss hitting at approximately 75% velocity for the first time since symptom onset, without pain. At seven months after discharge, a phone conversation confirmed that the subject had returned to baseball without limitations.

Discussion
Despite the concept of 'regional interdependence', common proximal impairments are often assumed to contribute to elbow pain without a clear biomechanical rationale. Future research demonstrating the specific biomechanical effects of the shoulder on the elbow is needed, in addition to more accessible examination strategies to assess their relationship.
Level of Evidence

BACKGROUND AND PURPOSE

Valgus extension overload syndrome (VEOS) is a condition that results from impingement of the posteromedial tip of the olecranon process on the posteromedial wall of the olecranon fossa. VEOS is common among overhead athletes such as baseball pitchers. During pitching, the elbow is said to be exposed to angular velocities up to 5000°/sec with valgus forces of 64 Nm, during late cocking, and compressive forces of 500 N experienced at the lateral radiocapitellar joint as the elbow rapidly moves from 120° of flexion to 25° at ball release.

In 20–120° of flexion, the anterior bundle of the ulnar collateral ligament (UCL) is the primary restraint to valgus forces, when the elbow is moving into extension. Repeated valgus forces upon the UCL can lead to micro instability, resulting in excessive stress where the posteromedial portion of the olecranon contacts the olecranon fossa. This stress can create osteochondritis dissecans (OCD) of the capitulum, UCL injuries, and pathology at the posteromedial compartment of the humeroulnar joint (i.e. osteophyte formation, olecranon stress fractures, chondromalacia).  

Osteochondritis dissecans occurs at the anterolateral or central capitulum almost exclusively, comprising 97.5% of OCD lesions of the elbow and is correlated with valgus stress and axial loading. Stable lesions (those with patency of the articular cartilage and subchondral bone) often respond well to conservative treatment. Unstable lesions typically require procedures such as osteochondral autograft transplantation (OAT) or internal fixation. Return to sport is extremely variable after surgery, ranging from 62–100%.

Conservative treatment for associated UCL injury focuses on restoring glenohumeral internal rotation and strength of the axioscapular, rotator cuff, and flexor-pronator musculature. Should conservative intervention be unsuccessful, UCL reconstruction (Tommy John) surgery is preferred with an approximate 85% return to play for adolescent baseball players.

Little is documented on conservative treatment for posteromedial impingement without frank compromise of the articular cartilage, subchondral bone, or UCL. Surgical outcomes for adolescents with posteromedial impingement has not been documented. In adults, surgical outcomes for posteromedial impingement are mixed, with greater success rates (72%) for those with isolated posteromedial compartment pathology compared to those with combined lesions or UCL insufficiency (42%). There have been no case reports of adolescent baseball players with persistent VEOS symptoms and difficulty returning to hitting. Therefore, the purpose of this case report is to describe a movement-focused examination and treatment strategy for such an individual, emphasizing the role of the physical therapist as a movement expert.

Figure 1. Elbow MRI with intra-articular contrast demonstrating bone marrow edema of the medial epicondyle (red circle).

CASE DESCRIPTION

A 15-year-old right-handed male high school catcher presented to physical therapy with an approximate six-month history of medial elbow pain of gradual onset, having had an MRI with contrast. The accompanying radiologic report confirmed no presence of osteochondral lesion, fracture, or compromise of the anterior band of the ulnar collateral ligament. The report noted “marrow edema pattern of the distal humerus, medial epicondyle, olecranon, and proximal ulna involving the sublime tubercle and coronoideal process most consistent with stress reaction in the setting of valgus extension overload.”

The subject denied a specific mechanism of injury, but reported a gradual increase with throwing, after which he began to experience “sharp” pain at the medial elbow with right-handed hitting. He initially underwent an initial set of six weeks (12 sessions) of physical therapy with another clinician at the same clinic, approximately three months after onset, consisting of forearm pronator strengthening at 90° of elbow flexion, scapular stabilizer, trunk, and sagittal plane lower extremity exercise (e.g. squats). Throwing improved significantly with treatment without any recurrence reported during follow-up with his orthopedic surgeon approximately 2.5 weeks after discharge. However, he reported a return of his medial elbow symptoms when resuming hitting.

He followed up with his hitting coach for several weeks, hitting off a tee, while continuing his home exercise program from previous physical therapy treatment. However,
pain continued to persist with ball contact during hitting. He elected to take a break from throwing and hitting. He consulted his orthopedist, who referred him for further physical therapy. The subject of this case report was informed of the case would be submitted for publication and consented to the release of information.

EXAMINATION

The subject was 5'10", weighing 155 lbs., with an ectomorphic body build. Subject's static posture was significant for the discrepancy between the subject’s right humeral position in comparison to his scapula. The right scapula was relatively depressed and abducted in comparison to the left, which may have been expected given the subject's right-handed dominance. However, despite greater right scapular internal rotation, the right humerus appeared to rest in greater external rotation and extension. The increased observed right scapular internal rotation suggested external humeral rotation was especially prevalent (Figure 2).10

Movement observation consisted of overhead elevation and simulation of subject’s hitting position in combination with single leg squat due to the gluteal demand required during optimal hitting.11 Overhead elevation demonstrated early right scapular upward rotation and greater internal rotation, a pattern associated with posterior shoulder mobility deficits.12 The subject's hitting motion was simulated during the examination, with marked right humeral external rotation observed during the drive phase. The humeral alignment appeared to compensate for the expected forearm supination of the trailing upper extremity, with the medial and lateral epicondyle near-parallel to the predicted line of force that would occur during ball contact. Sudden valgus force applied to the elbow in this position to simulate sudden ball contact reproduced the subject’s symptoms. Manually internally rotating the humerus and then reapplying valgus force to the elbow made the motion pain free (Figure 3). No laxity was appreciated during valgus stress testing. At this point in the examination it was hypothesized the subject’s primary movement dysfunction was excessive humeral external rotation resulting in increased valgus force at the elbow on the trailing upper extremity during ball contact. Additional impairments that could contribute to the preference for this hitting strategy were also assessed.

Shoulder and elbow range of motion were evaluated. Primary deficits included loss of bilateral shoulder internal rotation, although significantly more limited on the right (L 30°, R 10°; measured at 90° of abduction). Although humeral retroversion is common in overhead athletes, the total arc of motion on the subject's symptomatic side was 125°, well below previously established estimates (e.g. 160°).13 Forearm supination was more limited on the left (L 80°, R 90°), while pronation was more limited on the right (L 80°, R 60°).

Key muscles involved in scapulohumeral and elbow mechanisms were tested (strength measures are noted in table) using manual muscle testing (MMT). The subject's right serratus anterior, middle, and lower trapezius were graded equal or greater than the strength of the left. However, the subject's humeral internal rotators including the subscapularis and pectoralis major were a full grade weaker (L 5/5, R 4/5). Muscles were all tested by the same examiner using MMT, which has been found to have acceptable intrarater reliability.14

Lower extremity and trunk movement patterns were also screened, as the gluteal and trunk musculature are crucial for force development during hitting. Rolling was chosen as a transverse plane trunk stability pattern based on prior implementation in athletes and the absence of an established gold standard assessment for transverse plane lumbopelvic control,15 which was symmetrical and negative for trunk and extremity dissociation. The single leg squat was chosen to functionally assess gluteal performance, as it has been shown to correlate to weakness of the hip extensors.16–18 Observational analysis during the single leg squat demonstrated greater hip adduction and internal rotation on the right.

ASSESSMENT

The subject demonstrated signs and symptoms consistent with valgus extension overload syndrome, confirmed on MRI and during physical examination. During both static standing and simulation of the batting position during the drive phase, the subject’s humerus (and therefore elbow joint) appeared to be in excessive external rotation. This external rotation appeared to be a significant contributor to the loads sustained at the right medial elbow. Symptom reproduction during the rapid applications of valgus force with complete resolution with medial rotation of the

Figure 2. Standing alignment posterior view.
Reproduction of subject's initial posture demonstrating scapular asymmetry and increased humeral external rotation.
There exists a paucity of data regarding elbow forces sustained during hitting or ball contact during baseball. However, during a baseball swing, the rear forearm must supinate to optimize bat contact with a pitch while the elbow rapidly extends at approximately 1200 to 1500°/sec.\(^\text{19}\) If the humerus excessively externally rotates instead of forearm supination occurring, then the valgus moment at the humeroulnar joint significantly increases. Of significance was the subject's posterior shoulder stiffness. During swing, the rear humerus horizontally adducts to make ball contact. Flexibility impairments of the posterior shoulder are more profound in horizontal adduction and would contribute to increased humeral external rotation during swing as the humerus adducts,\(^\text{20}\) driven by stiffness of the posterior cuff and external rotators.

Although very little is known about upper extremity muscle activation during baseball hitting, it is known key humeral internal rotators such as the pectoralis major and latissimus dorsi are active during ball contact.\(^\text{21}\) Strength has also been correlated to upper quarter alignment.\(^\text{22}\) The combination of excessive stiffness or shortness of the posterior shoulder with inadequate humeral internal rotator strength and activation during hitting would contribute to the excessively externally rotated humeral position and valgus stress at the elbow during ball contact. Although the lack of pronounced weakness (when tested via MMT) of the subject’s right scapular stabilizers and posterior cuff musculature was somewhat surprising, the subject had previously completed a six-week physical therapy program focused on improving strength of these muscle groups.

Signs of weakness of the right gluteus maximus (e.g., during MMT and single leg squat)\(^\text{16–18}\) were also thought to contribute to decreased pelvic rotation induced through the rear limb during the swing. This would result in a need for increased humeral horizontal adduction, placing further strain on the subject’s stiff and short posterior shoulder.

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**Figure 5. Initial painful varus stress test (left) vs. painless varus stress test (right) with a red line to denote position of the humeral epicondyles.**

Note original test position was performed in a position simulating hitting, although modified above for clarity to the reader.

**Table. Objective Examination Data**

<table>
<thead>
<tr>
<th>Examination Measure</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder PROM</td>
<td>ER (0° abduction): L 90°, R 95° ER (90° abduction): L 100°, R 105° IR (90° abduction): L 30°, R 10°</td>
</tr>
<tr>
<td>Elbow PROM</td>
<td>Extension (forearm supinated): L 10° of hyperextension, R 5° of hyperextension Supination: L 80°, R 90° Pronation: L 80°, R 60°</td>
</tr>
<tr>
<td>Flexibility Assessment</td>
<td>Wrist flexor-pronator flexibility (wrist and elbow extended with palm supinated): Stiffness throughout mid and end-range on right only</td>
</tr>
</tbody>
</table>

humerus assisted in confirming a movement diagnosis of excessive humeral external rotation and the interpretation of relevant impairments to kinesiopathology.
musculature and exacerbating humeral external rotation induced through the flexibility deficits of the posterior glenohumeral structures.

Although the subject's supination range of motion was slightly greater on the right, this could be explained through decreased pronator teres strength, which would also contribute to decreased dynamic resistance to valgus force.\textsuperscript{23,24} The discrepancy between sides was minor and falls within the standard error of measure for goniometry at the elbow, which has been reported up to 11.5°.\textsuperscript{25} As several thousand pounds of force occur during bat ball contact,\textsuperscript{26} the primary focus of treatment was to prevent excessive humeral external rotation placing the coronal axis of the humeroulnar joint in-line with ball contact rather than attempting to improve dynamic elbow stability through pronator strength alone.

The above findings suggested a final movement diagnosis of excessive humeral external rotation contributing to the subject's symptoms and limitations during baseball.

INTERVENTION

The treatment plan for this subject was focused on improving posterior shoulder flexibility, increasing strength and stiffness of the humeral medial rotators, and progressively integrating the concept of slightly increased humeral medial rotation into hitting maneuvers to decrease valgus stress at the medial elbow. The subject was provided insight regarding the underlying hypothesis and singular goal of treatment based on the excessive humeral external rotation movement diagnosis throughout the examination process. This was intended to empower him early on to correct any daily habits that may contribute to excessive humeral external rotation. Recent literature suggests in regard to rehabilitation, activity performance changes result in longer lasting and more meaningful change than exercise alone.\textsuperscript{27}

Kinesiology tape was applied in a novel method, originating at the right medial antebrachial and elbow regions, and then spiraling proximally across the humerus to the right scapular region (Figure 4). The purpose of this taping was primarily to provide medial elbow support while reducing external humeral rotation throughout the day. Only one study has investigated the use of kinesiology tape for medial elbow pain,\textsuperscript{28} which improved forearm control over that of sham taping. However, multiple studies have found benefits for the use of kinesiology tape for treatment of lateral epicondylitis regarding decreasing pain and improving grip strength.\textsuperscript{28,29} Multiple authors have found that the direction of kinesiology tape does not change outcomes.\textsuperscript{30,31}

Soft tissue mobilization to the posterior shoulder musculature was also performed early to treat movement improvement of the subject's ability to perform humeral internal rotation exercise through a larger range. Soft tissue mobilization has been shown to improve posterior shoulder flexibility in multiple populations\textsuperscript{32,33} including baseball players. Humeral internal rotation at 90° of abduction improved 30° after a single session of soft tissue mobilization. The subject was instructed on soft-self tissue mobilization to preserve these gains, an intervention which has been shown to be effective at improving humeral internal rotation.\textsuperscript{34}

Manual therapy was combined with exercises to decrease posterior shoulder stiffness while concurrently increasing humeral internal rotator strength and stiffness. Prone (Figure 5) and supine (Figure 6) humeral rotation exercise in 90° of abduction was prescribed. Rotation with the humerus in 90° of abduction has been found to result in a relatively high percentage of subscapularis activation.\textsuperscript{35}

Supine shoulder internal rotation with a dumbbell was also prescribed to eccentrically activate the humeral external rotators (Figure 6). Eccentric exercise was chosen to decrease actual stiffness and shortness of the posterior shoulder contributing to inadequate humeral internal rotation, as this contraction type has been shown to add sarcomeres in series.\textsuperscript{36} Although very short-duration stretching programs may improve stretch tolerance and ROM, their ef-

Figure 4. Novel kinesiology taping technique to promote humeral internal rotation.

Figure 5. Prone shoulder internal rotation exercise to promote subscapularis use while inducing a stretch to the posterior shoulder.
As the subject advanced, neuromuscular reeducation during gripping was added to train the subject to allow for forearm supination without compensatory external rotation of the humerus (Figure 8). A two-pound bar was used, which the subject could simulate using his aluminum bat. The subject stood with the humerus flexed to 90° and observed his cubital fossa. He was instructed to grip the “bat” and then first rotate his humerus medially. He then rotated the “bat” outward, ensuring he did not also externally rotate the humerus during forearm supination. This was aimed to both teach control of the humerus during horizontally adducted positions that would be required during batting while also activating the flexor-pronator forearm musculature to assist in providing dynamic stability against elbow valgus. 24,40

Integration of the gluteal musculature in a transverse pattern using a heavy resistance band was prescribed to improve pelvic and trunk rotation during batting, therefore reducing the requisite amount of horizontal humeral adduction (and therefore decreasing posterior shoulder flexibility demands that could induce external humeral rotation), during this movement. It is important to note the subject reported an improvement in symptoms prior to any specific intervention to address the trunk and pelvis, which were implemented at visit 4. The specific effect of the lower limbs on shoulder and elbow positioning and force are not well studied. However, it is known that the gluteus maximus is active during the earlier portions of swing41 and that pelvic rotation is crucial for generating force to achieve ball contact.42

The subject’s daily activities and existing exercise regimens were reviewed and modified to augment gains from the above program. For example, bench pressing was modified with cueing to adduct the scapula and avoid scapular protraction during the concentric phase of the press (Figure 9). This position would not only encourage humeral horizontal adduction for high-load pectoralis major activation, but also contribute to stretch of the posterior shoulder musculature under load. Exercises such as Pallof pressing were integrated into the subject’s standard gym routine to op-
strenthening
return
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aging
timize
humeral
reeducation

Figure 8. Forearm supination neuromuscular reeducation exercise to teach dissociation from humeral external rotation.

timize transverse plane trunk stability while also encouraging humeral horizontal adduction for posterior shoulder flexibility.

After this time, focus was placed on returning to hitting while the subject continued the above exercises. Interval return to sport programs exist as suggested by Reinold et al.42 as well as return to hitting suggested by Monti in 2015.43 Similar guidelines were utilized for this subject's return to sport. Return to hitting was conducted in three phases; hitting from a tee, soft toss, then from a pitch at moderate effort behind L-screen in batting cage. Swings were complete at subject perceived effort of 75-80%. Each phase consisted of progressive swing repetitions with at least 1 day rest in between to assess tolerance. The subject remained at one step in each phase until he could bat without symptoms before progressing, a similar methodology to those utilized in previously established return to play interval programs.

Two drills also were performed to specifically address the trailing elbow position to improve maintenance of the elbow posterior to the knob of the bat, and therefore to decrease the magnitude of external rotation of the humerus and during the acceleration and follow through phases of the bat swing.43 During the first drill, a 10 lbs. dumbbell was utilized while the subject moved the weight through the 1st half of the swing with an isometric hold at what would be the contact point of the swing (Figure 10). The second drill was completed with a PVC pipe, maintaining the same position as the first drill with the isometric hold, then carrying out the remainder of the swing (Figure 11). Video analysis with the subject's phone was utilized as biofeedback.

OUTCOMES

After four physical therapy sessions, the subject had returned to practice and resumed all throwing activities. He denied any recurrence of symptoms with throwing and humeral internal rotation PROM at 90° of abduction had

Figure 9. Bench press neuromuscular reeducation activity modified to promote a posterior shoulder stretch while strengthening the pectoralis major (left). Incorrect performance (right) with scapular internal rotation.
improved from 10° to 30°. After 9 physical therapy sessions, he reported a 100% alleviation of symptoms with hitting. At the conclusion of physical therapy treatment, he continued to be able to throw without any limitations and had returned to hitting from live arm without pain at full effort. Follow-up via phone at seven months after discharge revealed that the subject had returned to play at full-capacity without any symptom recurrence.

DISCUSSION

The subject presented to physical therapy with chronic medial elbow pain and confirmed MRI evidence of VEOS. Although he noted mild symptoms with throwing, he reported his primary aggravating activity was hitting. He had participated in 12 physical therapy sessions earlier during the year including traditional scapular stabilizer strengthening exercises (e.g. shoulder taps, Ys and Ts), but had experienced a recurrence of symptoms upon return to hitting. After completing nine physical therapy visits over five weeks, he was able to return to all activities such as hitting without any pain.

Regional interdependence has been discussed for two decades and adapted to encompass the general interactions between various physiologic systems. The prevalence of scapular dysfunction in overhead athletes and comprehensive rehabilitation programs for the elbow that include exercises for the rotator cuff, lower and middle trapezius, and serratus anterior may contribute to a profession-wide assumption that these exercises will address the underlying movement problems in this population.

This case exemplifies the importance of a systematic movement examination and assessment of potential relevant contributing impairments for individuals who do not fall in the majority regarding common movement dysfunctions that lead to a given condition. For example, the subject did not present with any findings suggestive of remarkable scapular stabilizer (serratus anterior, middle, and lower trapezius) weakness or dyskinesis that could contribute to his elbow dysfunction. Grip strength, tested to determine function of the medial elbow stabilizers such as the flexor digitorum superficialis and profundus measured at 100–110 lbs. of force (symmetrical between hands) in multiple positions and elbow angles, well above the 75th percentile for a 15 year-old male. The subject had previously participated in a strengthening program consisting of exercises to address the scapular and medial elbow stabilizers with little success, and thus determining an underlying aberrant movement cause of continued pain was the focus upon the subject’s return to physical therapy.

Although medial elbow pain in relation to throwing is relatively well researched, there exists a paucity of literature regarding its incidence with hitting. Furthermore, unlike throwing, the contribution of the lower extremities, trunk and the scapula to forces at the elbow during hitting have not been studied. Dissimilar to pitching, batting is a reactive movement pattern that changes significantly in response to the pitcher. This makes the study of an optimal movement pattern for batting difficult, as multiple strategies may be ideal based on the location and velocity of the ball.

However, the general phases of batting have been well-defined and include preparatory, stance, stride, drive, bat acceleration, and follow-through phases. The preparatory phase describes the initial batting stance preferred by each hitter. This transitions into the stance phase, during which the batter lifts their front leg, shifting their weight to the rear leg while coiling their trunk and upper extremities in reverse of the pitcher. This coiling continues as the batter then brings the front leg forward (stride phase) and then makes lead leg contact with the ground (drive phase). During drive phase, maximal energy storage is achieved through a further 12° of reverse arm motion. At the end of the drive phase, the trailing elbow should be flexed with the shoulder adducted. The goal of these initial phases is to capitalize on the stretch-shortening cycle to generate optimal force during the swing. This kinetic
energy is transferred during the bat acceleration phase through rapid uncoiling beginning at the lower extremities, and then transitioning to the pelvis, trunk, shoulder, and elbows.\footnote{61} The final follow-through phase allows the batter to optimize pelvic rotation.

The moment of ball contact during the bat acceleration phase in relationship to the subject’s pattern of humeral rotation is of specific relevance to this case. Bat velocity is assisted through rapid elbow extension just prior to ball contact, previously estimated at 948\(^\circ\)/sec.\footnote{61} The rapid elbow extension to accelerate the bat combined with excessive humeral external rotation would increase valgus force on ball contact and replicate forces that occur during VEOS often seen in pitchers.\footnote{62}

Based on these phases of batting, a reasonable comprehension of movement requirements (e.g. rapid pelvic rotation, rear upper extremity horizontal adduction, rapid elbow extension) can be established by a physical therapist and systematically tested. The importance of beginning a physical examination with movement observation and tests confirming specific hypotheses of an underlying movement cause cannot be overstated. For example, for this subject, excessive right humeral external rotation was noted both at rest and with functional movements. The valgus stress test was positive for symptom reproduction when the subject replicated upper extremity position simulating ball contact and rapid valgus force was applied manually by the physical therapist. This test was implemented to simulate forces experienced by the subject during ball contact.

The hypothesis that excessive humeral external rotation was resulting in the subject’s pain and pathology viewed on MRI was supported by then manually rotating the humerus into slightly greater internal rotation and repeating the same valgus stress test. For many subjects, multiple movements that are symptom provoking could be used with systematic modification of the movement to establish a pattern suggesting an underlying movement dysfunction. This is analogous to prior research that has found a battery of tests in physical examination is generally more useful in establishing a diagnosis than a single test.\footnote{63,64}

Impairments were then systematically assessed based on the movement diagnosis and movement observations. Factors relevant to their contribution to excessive humeral external rotation with batting were examined. For example, inadequate participation or stiffness of the humeral internal rotators such as the subscapularis, pectoralis major, and latissimus dorsi, or excessive stiffness of the humeral external rotators (especially those which would be placed in tension with forward humeral flexion) could contribute to the subject’s preferred but painful hitting strategy. These impairments were all tested based on the initial standing static postural, movement, and functional testing examination. For example, during forward reaching and shoulder elevation, excessive early scapular upward rotation was noted. This is a pattern suggestive of inadequate mobility of the glenohumeral joint\footnote{12} and therefore, posterior shoulder stiffness contributing to excessive humeral external rotation was hypothesized to be a relevant contributing factor to the movement syndrome. This was then tested in more isolation during measures such as humeral internal rotation mobility and palpation to the posterior shoulder musculature. Using this strategy, the clinician was able to systematically establish relevant impairments to the subject’s movement dysfunction.

This case exemplifies the unique role of physical therapists as movement experts who are well equipped to address specific kinesiology on physical examination. Although the profession has more recently transitioned to various classification models that match intervention to specific presentations in regions such as the lumbar spine,\footnote{65} programs in the upper quadrant trend toward consistently addressing the rotator cuff and axioclavicular musculature.\footnote{48,66} The prevalence of scapular dysfunction in overhead athletes\footnote{47} and comprehensive rehabilitation programs for the elbow that include exercises for the rotator cuff, lower and middle trapezius, and serratus anterior\footnote{48} may contribute to the assumption that these exercises are beneficial for all subjects with elbow or shoulder movement conditions. For the above subject, previous treatment including traditional scapular stabilization exercise was not effective in reducing his symptoms upon return to hitting, suggesting the importance of customizing intervention to specific patterns of movement dysfunction.

LIMITATIONS

The presented case report has notable limitations, including the inability to generalize and non-experimental nature of this study. Furthermore, due to a lack of normative data regarding humeral rotation during batting and subject privacy logistics, actual video analysis of upper quarter position throughout the hitting maneuver was not obtained. Pelvic and lower quarter normative data exist for batting,\footnote{61,67} and therefore video analysis may have revealed whether the integration of specific pelvic and trunk retraining during physical therapy was actually needed. Additionally, certain physical examination measures such as manual muscle testing in the shoulder possess questionable inter-rater reliability and reproducibility\footnote{68} and should be interpreted with caution.

CONCLUSIONS

This case report exemplifies the importance of a systematic movement examination to establish an underlying movement diagnosis with which to efficiently guide treatment. The subject presented with continued signs of VEOS and limitations with baseball batting despite prior participation in physical therapy including exercises typically cited in a regional interdependence model. A systematic evaluation established an atypical movement diagnosis of excessive humeral external rotation contributing to valgus force during ball contact. This diagnosis guided all subsequent intervention. After nine physical therapy visits over five weeks, the subject was able to return to soft toss hitting, confirming a 100% return to play without recurrence at seven month follow-up. These outcomes demonstrate the successful implementation of a movement-based intervention.
program. Furthermore, they imply the importance of a specific application of human movement knowledge rather than generally implementing the concept of regional interdependence.

DISCLOSURES

The authors of this case report have no conflicts of interest.

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Maximizing Recovery in the Postpartum Period: A Timeline for Rehabilitation from Pregnancy through Return to Sport

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Keywords: pregnancy, postpartum, physical therapy, strength and conditioning, female athlete

Increased participation and duration in sport has become commonplace for women with their involvement often including the transition to motherhood in the peak of their athletic careers. No rehabilitation models that assess the full spectrum of pregnancy to postpartum have been developed for women to assist in safe exercise progressions that reduce postpartum symptoms and optimize performance during the return to full activity. Referral to physical therapy both in the prenatal and postnatal period is currently not considered standard of care to reduce prevalence of symptoms such as musculoskeletal pain, diastasis recti, and pelvic floor dysfunction which may ultimately interfere with physical activity and performance. This commentary presents a timeline and suggested progression for exercise participation to improve awareness of the musculoskeletal changes that occur after labor and delivery. The concepts covered may increase the understanding of how to manage pregnant and postpartum athletes from a musculoskeletal perspective and serve as a starting point for establishing appropriate and guided rehabilitation for safe return to sport after childbirth.

INTRODUCTION

Musculoskeletal parameters in pregnancy and postpartum care have been an area of much debate and scrutiny, with continuous changes in these recommendations being inconsistent at best and conflicting at worst. The ability to stay active during and after pregnancy provides significant physiological benefits, regardless of prior training status.1–5 From a medical perspective, physical activity during pregnancy decreases risk of developing conditions such as gestational diabetes, pre-eclampsia, hypertension, depression, and both prenatal and postpartum incontinence.1 Physical activity also been shown to not increase the likelihood of adverse outcomes including low birth weight, miscarriage, or perinatal mortality.1 Despite the known benefits of physical activity in this population, there is little guidance on how to safely progress programming during pregnancy or how to return to sport performance postpartum.6,7 The six-week postpartum check is largely agreed upon as a point where medical clearance to return to normal activity occurs – however, it is becoming more clear that appropriate musculoskeletal interventions could safely begin in the immediate postpartum period. Discussions with the mother surrounding what types of exercise are safe to perform and what symptoms are normal/abnormal are not commonly included at this time, and musculoskeletal exams are rarely performed despite pregnancy and delivery being both medical and musculoskeletal events.8,9 Delaying guided rehabilitation until the six-week postpartum mark may compromise safe return to activity as many women work to navigate this phase independently. Currently, no peer-reviewed return to sport protocols for postpartum women exist despite the fact that 75% of postpartum runners return to running within eight weeks after delivery.10 Thus, women may be missing the benefit of guided rehabilitation and targeted exercise in a time frame where they can minimize postpartum symptoms and adequately prepare for return to sport.

Peak athletic performance has been shown to coincide with the predicted peak fertility years.1 As such, female athletes frequently sustain careers spanning these years, which often includes managing the physical transition from pregnancy to motherhood. Prevalent postpartum conditions including musculoskeletal pain, urinary incontinence,
abdominal separation, and pelvic organ prolapse are factors that may limit physical performance and safe return to sport.\textsuperscript{11} Christopher et al. and de Mattos Lourenco et al. have found that more than one-third of postpartum runners experience pain upon their return as well as some form of urinary incontinence.\textsuperscript{10,12} While these symptoms may be present prior to or immediately upon return to activity, they may also demonstrate a delayed onset over time, as return to exercise may not consider the potential for dysfunctional pelvic floor and/or abdominal musculature. In addition, postpartum symptoms such as urinary incontinence or hip and knee pain appearing with return to activity may be dismissed as "normal", potentially leading to continued deferral of treatment until the athlete is often several years postpartum. The lack of distinction between common versus normal symptoms in the first three months postpartum often delays appropriate management despite evidence that physical therapy can be beneficial in preventing and resolving these symptoms.\textsuperscript{15–15}

Exercise guidance through the postpartum period is warranted for athletes to return to full activity safely and effectively. This clinical commentary proposes and outlines guidelines to encourage recreational and other elite athletes to engage in early physical activity in a progressive manner. Safe return to sport guidelines would allow women to address the facets of the musculoskeletal system that have been affected by pregnancy and return to sport and impact activity safely, using the first six weeks to their advantage.

ADAPTATIONS TO PREGNANCY AND POSTPARTUM

A wide variety of physiologic changes occur during pregnancy, which often can be managed with thorough musculoskeletal assessment and intervention. Weight gain, ligamentous laxity, postural changes, and center of gravity changes that occur during pregnancy all require different demands on strength, endurance, and postural control. The abdominal musculature is stretched to 115% of its resting length by 38 weeks of pregnancy.\textsuperscript{16} Cardiac output increases by 50–50%, (driven by increasing heart rate and stroke volume) by mid-pregnancy, along with a 10–20% increase in baseline oxygen consumption. Together, these cardiovascular alterations result in decreased available oxygen for aerobic activity.\textsuperscript{17,18} Pregnant athletes are often still anecdotally encouraged to stay below a target heart rate (formerly recommended as <140 bpm) and avoid lifting more than 25 pounds, conflicting with the more recent evidence that indicates these heart rate monitoring and absolute limits on weight lifting are no longer appropriate restrictions for low risk pregnancies.\textsuperscript{4,5}

During labor and delivery, pelvic floor musculature is stretched to 250% of its resting length during delivery.\textsuperscript{9} Recovery of the pelvic floor muscles (levator ani and associated connective tissue) is thought to be maximized by four to six months postnatal, although unrestricted clearance to activity is typically obtained well before this point.\textsuperscript{9} Bladder neck mobility postpartum remains higher than when measured at 37 weeks gestation and can require increased musculoskeletal support to limit symptoms such as incontinence.\textsuperscript{19} With cesarean section delivery, uterine scar thickness is still increased at the six-week postnatal point indicating continued remodeling despite the fact that many women are told that they may begin unrestricted activity at this point, and notable pelvic floor dysfunction including weakness or difficulty with coordination may also still be present associated with the pressure of the growing uterus throughout pregnancy.\textsuperscript{20}

"CORE CANISTER" HEALTH AND DYSFUNCTION

Pregnant and postpartum women may have limited education on their own bodies and the musculoskeletal adaptations that occur. They may also not realize that many of the symptoms that they may experience in pregnancy and postpartum are common but not normal. In the United States, pelvic floor rehabilitation is not currently recommended for women as a standard of care requiring many to self-advocate for such treatment. Prevalence of pelvic floor dysfunction (urinary stress incontinence, urgency urinary incontinence, overactive bladder, pelvic organ prolapse, and fecal or anal incontinence) is high, with over one in four women experiencing at least one of these conditions.\textsuperscript{21} The presence of incontinence during pregnancy may be indicative of the presence of incontinence in postpartum. Those who have persistent incontinence at three months postpartum have a significantly greater likelihood of continued incontinence at the five-year postpartum mark compared to the general population.\textsuperscript{22} Postpartum urinary incontinence creates a barrier to exercise, and may limit athletes from completing their desired sport or exercise program.\textsuperscript{13} The total number of women including female athletes who will undergo surgery for correction of pelvic organ prolapse alone is expected to increase by ~48% over the next four decades.\textsuperscript{23} Despite many of the commonly experienced signs and symptoms of pelvic floor dysfunction being improved or prevented with rehabilitation, there is little discussion of a guided protocol to limit the likelihood of onset such dysfunction during pregnancy and postpartum.\textsuperscript{19,24–27}

As would be expected, given the duration and intensity of change imparted upon the pelvic floor musculature, followed by the largely musculoskeletal event of labor and delivery, the pelvic floor muscles are typically dysfunctional postpartum with regard to strength, motor control, and endurance.\textsuperscript{9} For many women who were unaware of how to utilize pelvic floor muscles appropriately prior to delivery or for women who have had multiple babies without adequate rehabilitation and recovery, there may be significant dysfunction in attempts to self-train these muscles.\textsuperscript{2} Recommendations for musculoskeletal intervention postpartum vary from no activity until medical consult to full clearance to self-guided exercise at six weeks, suggesting discussions of varying types of delivery and tearing or injury may not be included when assessing return to activity/sport.\textsuperscript{25} When prescribed appropriately, performance of deep core exercises during pregnancy results in significantly fewer incontinence symptoms during late pregnancy and the postpartum period.\textsuperscript{8}
DEMands of Returning to Sport

Running is a specialized skill requiring very specific muscular endurance and strength demands. While it is common to use physical therapy to restore running mechanics in the post-operative and post-injury populations, the use of physical therapy in postpartum women looking to safely return to running is less commonly utilized. Optimizing postnatal recovery is a critical factor given the pregnant and postpartum musculoskeletal changes that occur as physical therapist’s accommodate these athletes and their desire to return to previous levels of activity.

There is considerable demand on the pelvic floor musculature during a task such as running. High impact activities are associated with a sudden rise in intra-abdominal pressure as well as ground reaction forces of 1.6-2.5x bodyweight.\(^{28,29}\) Given the structure and location of the pelvis as a force transmission site from the lower to the upper body, it is expected that the attaching musculature would be required to quickly contract and relax repeatedly throughout a task such as running. If the pelvic floor musculature is unable to contract and relax on demand in a supervised setting such as pelvic floor rehabilitation, it would be expected that the ability to perform that role during an often subconscious task such as running would be diminished and as such could result in potential activity-related dysfunction associated with that lack of ability including incontinence and prolapse.\(^{28}\)

High impact exercise has been found to increase risk of pelvic floor dysfunction nearly five-fold as compared to low impact exercise, further warranting additional healing time prior to resuming high impact tasks.\(^{12}\) Just as physical therapists typically defer return to running in post-operative cases where notable anatomical healing must occur, perhaps physical therapists should also advocate for a return to running protocol that corresponds both to a time and criterion-based approach in the postpartum phase.\(^{25}\) A recommendation of this nature was initially made by Goom and colleagues,\(^{2}\) who advised that return to running be considered at or around the three months postpartum period. Based on the baseline demands of running as a power, endurance, and strength movement, the aim of the following recommendations is to restore asymptomatic tolerance for return to running. For most athletes, clearance for return to running ready them to participate in a more sport-specific training program as desired.

Rehabilitation Timeline Recommendations

In the absence of absolute or relative contraindications, pregnant women should be encouraged to participate in a regular, moderate intensity exercise program supported by the American College of Sports Medicine (ACSM) as well as the American College of Obstetricians and Gynecologists (ACOG) guidelines.\(^{5,30}\) General physicians have self-reported that they do not typically feel that they have adequate training in postpartum exercise prescription, and variations in regards to anecdotal recommendations are common.\(^{31}\) From a physical therapy perspective, Table 1 outlines a rehabilitation timeline with suggested goals and criterion for exercise participation to encourage a timely and safe full return to sport. As with any protocol, parameters may be adjusted to some extent depending on the individual, but these are best adjusted under the guidance of an appropriately trained professional.\(^{32}\) Such professionals should be well versed in the warning signs during exercise as well as contraindications to exercise when working with pregnant and postpartum clients.\(^{5,31}\)

Each phase of the following protocol should ideally be monitored by a pelvic health physical therapist who can best make determinations on readiness to progress to the next phase and ensure that the pelvic floor muscles are contracting and relaxing correctly. Working with trained individuals in the area of pelvic health may also help to reduce fear avoidance behaviors and increase compliance during the pregnancy period.\(^{35}\) Understanding that high-impact tasks like running are necessary and appropriate for maximizing performance allows increased focus on safe movement with core and pelvic floor control, posture, and mobility.

FisT TO Third trimester

Initially, cardiovascular activity should be kept at a conversational pace, but is no longer limited to the 140 beats per minute metric.\(^{7}\) When a patient is self-assessing intensity, clinicians should discuss how to use the rate of perceived exertion (RPE) modified scale (0-10), aiming for between 1-4 for light to moderate.\(^{22}\) Occasional higher intensity cardiovascular tasks may be completed for short time periods, but time spent exceeding the RPE ranges of 5-7 should be limited due to the added pressure on the pelvic floor muscles as a fetus develops. Exercises may include running, stationary biking, low impact aerobics, step aerobics, swimming, or walking may be encouraged, which may vary day to day with specific symptoms of the mother.\(^{5,34}\) Contact sports, activities that increase likelihood of falls (horseback riding, cycling, downhill skiing, etc.), scuba diving, and/or hot yoga should be avoided.\(^{1,2,36}\) Incorporation of rest periods throughout cardiovascular effort (walking, stopping, stretching, etc.) should be considered to reflect the metabolic needs of the mother as pregnancy progresses.

Risk versus benefit analysis should be performed with continued impact work, as some athletes will be able to continue running and jumping during this phase but should closely monitor symptoms to determine whether this should be modified or eliminated. In similar fashion, running may be continued but duration can be reduced to limit the amount of stress on the pelvic floor and changes to gait with changing posture and growing fetus. Incline jogging/running and interval runs, for example, can be encouraged in bouts to reduce the volume of repetitive impact and assist with maintenance of running if desired. For athletes training for an upcoming race or needing to return quickly to an elite athlete level, continued safe impact work may be warranted and monitored closely. Other forms of cardiorespiratory activity that are lower impact and encourage more
### Table 1. Goals for Prenatal and Postnatal Performance 5,31,34

<table>
<thead>
<tr>
<th>Stage</th>
<th>Goals</th>
<th>Example Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Trimester</strong></td>
<td>Discuss musculoskeletal changes</td>
<td>Medical clearance for exercise</td>
</tr>
<tr>
<td></td>
<td>Discuss physiological changes associated with pregnancy</td>
<td>Independence in RPE ratings</td>
</tr>
<tr>
<td></td>
<td>Introduce transverse abdominis control in association with proper</td>
<td>Ability to appropriately contract and relax transverse abdominis without breath</td>
</tr>
<tr>
<td></td>
<td>diaphragmatic breathing</td>
<td>holding</td>
</tr>
<tr>
<td></td>
<td>Instruction in Rate of Perceived Exertion (RPE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Establish guidelines and develop exercise prescription</td>
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<td></td>
<td>Discuss warning signs and contraindications for exercise during pregnancy</td>
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</tr>
<tr>
<td><strong>Second Trimester</strong></td>
<td>Encourage safe exercise and mobility</td>
<td>Medical clearance for exercise</td>
</tr>
<tr>
<td></td>
<td>Develop postural strength and endurance</td>
<td>Awareness and independence of appropriate standing and sitting postures</td>
</tr>
<tr>
<td></td>
<td>Review warning signs and contraindications for exercise during pregnancy</td>
<td></td>
</tr>
<tr>
<td><strong>Third Trimester</strong></td>
<td>Improve coordination in relaxation of the pelvic floor musculature to</td>
<td>Medical clearance for exercise</td>
</tr>
<tr>
<td></td>
<td>allow for delivery while maintaining adequate facilitation for</td>
<td>Ability to contract and relax pelvic floor musculature without breath holding</td>
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<tr>
<td></td>
<td>continence</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continue focus on postural strength and endurance</td>
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<td></td>
<td>Education regarding potential birth positions as desired</td>
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</tr>
<tr>
<td><strong>Postpartum Weeks 0-2</strong></td>
<td>Encourage safe and appropriate movement to facilitate healing</td>
<td>Anterior/posterior pelvic tilting to assist with postural restoration</td>
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<td></td>
<td>Limit subjective pain levels associated with the expected decrease in</td>
<td>Appropriate performance of diaphragmatic breath to mimic walking</td>
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<tr>
<td></td>
<td>activity after delivery</td>
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<td></td>
<td>Instruct and incorporate proper body mechanics for handling of newborn</td>
<td></td>
</tr>
<tr>
<td><strong>Postpartum Weeks 3-4</strong></td>
<td>Slowly improve coordination with pelvic floor and transverse abdominis</td>
<td>Transversus abdominis sets - 20x5s holds in supine, side-lying, and quadruped</td>
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<td></td>
<td>musculature in association with proper diaphragmatic breathing</td>
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<td></td>
<td>Initiate a short duration (&lt;15 minutes) walking program with frequency</td>
<td>Bridges - double leg 30x5s</td>
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<td></td>
<td>increasing as desired with increasing frequency and duration as</td>
<td>10 minutes of asymptomatic walking</td>
</tr>
<tr>
<td></td>
<td>tolerated</td>
<td>Pelvic floor contract/relax – short holds (&lt;5s)</td>
</tr>
<tr>
<td><strong>Postpartum Weeks 5-6</strong></td>
<td>Increase walking program duration (&gt;30 minutes) to long as symptoms are</td>
<td>Muscular endurance tasks i.e. repetitions of 15-30 with weights &lt;10 lbs (baby can</td>
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<tr>
<td></td>
<td>not noted during or after performance</td>
<td>often be used as &quot;weight&quot; for functional performance)</td>
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<tr>
<td></td>
<td>Incorporate functional movements required of the athlete for activities</td>
<td>Pelvic floor contract/relax – long holds (10s)</td>
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<td></td>
<td>of daily living</td>
<td>Clamshells, reverse clamshells, standing march/hip abduction/hip extension,</td>
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<td></td>
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<td>quadruped fire hydrants/donkey kicks, sit to stand, double leg calf raises, 4-way</td>
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<td></td>
<td></td>
<td>straight leg raise</td>
</tr>
<tr>
<td><strong>Postpartum Weeks 7-12</strong></td>
<td>Discuss medical clearance and differences in medical and</td>
<td>Muscular strength tasks i.e. repetitions of 8-12 with weights as tolerated</td>
</tr>
<tr>
<td></td>
<td>musculoskeletal clearance for exercise</td>
<td>Squats, single leg sit to stand, mountain climbers (to table), single leg calf</td>
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<tr>
<td></td>
<td>Integrate strength, endurance, and power training to prepare for high</td>
<td>raise, step ups</td>
</tr>
<tr>
<td></td>
<td>impact exercise</td>
<td>30 minutes asymptomatic walking</td>
</tr>
<tr>
<td></td>
<td>Potentially include impact exercise (8-10 week mark)</td>
<td></td>
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<tr>
<td><strong>Postpartum Weeks 13+</strong></td>
<td>Return to full activity including running/sport</td>
<td>Exercises completed with a metronome consistent with desired athlete cadence</td>
</tr>
<tr>
<td></td>
<td>Running-specific medical interview to assist with prescription of</td>
<td>60s of symptom free performance - single leg calf raise, single leg hop down from</td>
</tr>
<tr>
<td></td>
<td>Individualized running plan</td>
<td>step, single leg hopping, jump in place, wall sit, plank hold</td>
</tr>
</tbody>
</table>
Table 2. Musculoskeletal Protocol for Pregnancy through Return to Sport\textsuperscript{,}7,31,34,36

<table>
<thead>
<tr>
<th>Stage</th>
<th>Focus</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Trimester</strong></td>
<td>Cardiovascular activity</td>
<td>a. Light-moderate activities kept at a conversational pace (RPE 1-4), occasional bursts of RPE range 5-7 (&lt;10 minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Modify interventions based on daily symptoms</td>
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<td>c. 150 minutes of moderate activity each week over a minimum of 3 days/week but preferred daily</td>
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<td></td>
<td>d. Variety of physical activities to include aerobic, strength training, and mobility work</td>
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<td></td>
<td></td>
<td>e. Awareness of appropriate warm up and cool down (5-10 minutes of gentle activity prior to and after completion of exercise routine)</td>
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<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Education on diastasis recti</td>
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<td></td>
<td></td>
<td>b. Eliminate and/or modify exercises creating coning</td>
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<td></td>
<td></td>
<td>c. Coordination of diaphragmatic breathing (exhale with pelvic floor contraction, inhale with pelvic floor relaxation)</td>
</tr>
<tr>
<td></td>
<td>Strength Training</td>
<td>a. At least 2 days of resistance training/week with selection of desired exercises by the individual patient and provider within surrounding limitations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Strength training should incorporate full body focus</td>
</tr>
<tr>
<td></td>
<td>Pelvic floor</td>
<td>a. Internal muscle exam typically deferred</td>
</tr>
<tr>
<td></td>
<td>Modifications for this phase</td>
<td>a. Work around varying symptoms including fatigue, nausea, and discomfort</td>
</tr>
<tr>
<td><strong>Second Trimester</strong></td>
<td>Cardiovascular activity</td>
<td>a. Light-moderate activities kept at a conversational pace (RPE 1-4), occasional bursts of RPE range 5-7 (&lt;10 minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Running may continue but athlete should consider more interval training to assist with musculoskeletal demand of the pelvic floor as baby grows</td>
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<td></td>
<td></td>
<td>c. Cross training (biking, swimming) should be encouraged</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Same as first trimester with continued focus on appropriate loading of transversus abdominis, linea alba</td>
</tr>
<tr>
<td></td>
<td>Pelvic Floor</td>
<td>a. If agreed upon with the athlete's medical providers, internal muscle exam may be performed if desired by patient to determine baseline pelvic floor function and address range of motion and strength/endurance deficits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. External muscle exam may also be performed to limit risk of infection associated with internal muscle examination</td>
</tr>
<tr>
<td></td>
<td>Strength Training</td>
<td>a. At least 2 days of resistance training/week with selection of desired exercises by the individual patient and provider within surrounding limitations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Strength training should incorporate full body focus</td>
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<tr>
<td></td>
<td>Modifications for this phase</td>
<td>a. Heavier focus on anti-core movements to encourage stability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Eliminate/modify tasks that require power movement of barbell over abdomen</td>
</tr>
<tr>
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<td></td>
<td>c. Limit/modify supine activity if patient is symptomatic</td>
</tr>
<tr>
<td><strong>Third Trimester</strong></td>
<td>Cardiovascular activity</td>
<td>a. Light-moderate activities kept at a conversational pace (RPE 1-4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Running may continue but athlete should consider more interval training and more frequent rest to assist with musculoskeletal demand of the pelvic floor as baby grows</td>
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<tr>
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<td></td>
<td>c. Heavier focus on cross training (biking, swimming) should be encouraged as opposed to running</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Increase focus on down-training techniques to assist with delivery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Increase focus on postural endurance as center of gravity shifts forward</td>
</tr>
<tr>
<td></td>
<td>Strength Training</td>
<td>a. At least 2 days of resistance training/week with selection of desired exercises by the individual patient and provider within surrounding limitations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Strength training should incorporate full body focus</td>
</tr>
<tr>
<td></td>
<td>Pelvic Floor</td>
<td>a. Perineal massage may be discussed to begin around 34 weeks gestation</td>
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<td></td>
<td></td>
<td>b. Discussion of appropriate birthing positions for pelvic mobility and opening of pelvic outlet</td>
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<td></td>
<td></td>
<td>c. Heavy focus on down-training/relaxation of pelvic floor musculature and breath techniques to assist with delivery</td>
</tr>
<tr>
<td></td>
<td>Modifications for this phase</td>
<td>a. All previous modifications maintained</td>
</tr>
<tr>
<td>Stage</td>
<td>Focus</td>
<td>Recommendations</td>
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</tr>
<tr>
<td>Postpartum Weeks 0-2</td>
<td>Cardiovascular activity</td>
<td>b. Impact work (jump/run) may be continued if asymptomatic for short bouts and increased rest time</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Minimize musculoskeletal stress to allow healing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Households ambulation in small bouts</td>
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<tr>
<td></td>
<td></td>
<td>c. Education related to nutrition (within scope of the provider) to ensure appropriate intake to accommodate for nursing and exercise</td>
</tr>
<tr>
<td></td>
<td>Pelvic Floor</td>
<td>a. Light transverse abdominis/pelvic floor contract/relax – defer if symptomatic</td>
</tr>
<tr>
<td>Postpartum Weeks 3-4</td>
<td>Cardiovascular activity</td>
<td>a. Walking program with shorter duration (&lt;10-15 minutes), frequency may increase as tolerated</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Increase focus on transversus abdominis coordination – supine, side-lying, and quarduped</td>
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<tr>
<td></td>
<td>Pelvic Floor</td>
<td>a. Pelvic floor contract/relax with focus on short holds (5 seconds)</td>
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<td></td>
<td>b. Continue to defer if symptomatic</td>
</tr>
<tr>
<td>Postpartum Weeks 5-6</td>
<td>Cardiovascular activity</td>
<td>a. Walking program may slowly increase in duration (&lt;20-30 minutes)</td>
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<td>b. Speed may gradually increase, but should be kept below jogging</td>
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<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Postural strength and endurance to include thoracic and cervical spine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Coordination of transversus abdominis in more functional movements such as sitting/standing</td>
</tr>
<tr>
<td></td>
<td>Pelvic Floor/Strength</td>
<td>a. Open kinetic chain hip strength in combination with appropriate pelvic floor contract/relax</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Pelvic floor contract/relax with focus on long holds (10 seconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c. Light functional movements (sit to stand, step ups)</td>
</tr>
<tr>
<td>Postpartum Weeks 7-12</td>
<td>Cardiovascular activity</td>
<td>a. Slow increase in duration of walking program with gradual speed increases</td>
</tr>
<tr>
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<td>b. Short &lt;60s bouts of jogging may be appropriate at the 8 week or beyond mark (dependent on response to impact readiness tasks)</td>
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<td>c. Recovery intervals should be 2x that of work phase in jogging (ie 60s jog:120s recovery)</td>
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<td></td>
<td></td>
<td>d. Work phases should be kept conversational with RPE &lt; 6</td>
</tr>
<tr>
<td></td>
<td>Neuromuscular activity</td>
<td>a. Awareness/improvement of postural changes that often persist postpartum</td>
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<td></td>
<td></td>
<td>b. Thoracic rotation/extension, improving excessive pelvic tilting (anterior or posterior) should be addressed</td>
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<td>c. Horizontal impact work (ie table plank position – mountain climbers) may be slowly progressed to begin force absorption focus until patient is ready to tolerate this in an upright position</td>
</tr>
<tr>
<td></td>
<td>Pelvic Floor</td>
<td>a. Internal muscle exam performed if desired by patient to determine baseline function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Focus should be both on appropriate contract/relax as well as strength/endurance to determine individual need for up vs. down-training</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td>a. Closed kinetic strength tasks beginning with slow performance and increasing speed of movement as tolerated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Progression from double to single leg weight bearing tasks</td>
</tr>
<tr>
<td>Impact-Specific Markers for Readiness for Progression</td>
<td></td>
<td>a. Double leg jump downs, heel raises with bounce, forward/lateral/reverse lunging performed rapidly, kettle bell swing variations to include the sagittal, transverse, and frontal planes</td>
</tr>
<tr>
<td>Functional Testing Options</td>
<td></td>
<td>a. Musculoskeletal pain or pelvic symptoms with loading and impact25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Run Readiness Scale36</td>
</tr>
<tr>
<td>Postpartum Weeks 13+</td>
<td>Cardiovascular activity</td>
<td>a. Slow increase in mileage and speed with walking/jogging/rest throughout run as needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. 2D running assessment may be performed to limit likelihood of injury</td>
</tr>
</tbody>
</table>
full body strength training and could potentially encourage a faster return to running and sport in the postnatal phase.

The importance of transversus abdominis control should be established, and challenging this control in a variety of positions including supine, sitting, and standing is important for function. Coordinating this movement with diaphragmatic breathing is also important as encouraging patients to perform this movement as they exhale can assist with control and pelvic floor coordination. Awareness and modifications around activities that cause coning would indicate limited tension management through the linea alba and as such should be modified until the patient is able to perform appropriately to help load the affected tissue safely. If the athlete is unable to modify this movement without the presence of continuous or repetitive coning, the movement may need to be eliminated to decrease severity of potential diastasis recti (Figure 1). As pregnancy progresses, repeated lumbar flexion movements should be limited and instead focus on stability movements of the core/spine such as anti-rotation, anti-extension, and anti-rotation drills with modifications as needed to avoid and manage abnormal tension at the linea alba. In the final months of pregnancy, breath work and coordination of pelvic floor relaxation should be focused upon, in order to increase the ability to relax the pelvic floor musculature during both deep inhalation and exhalation to prepare for delivery. Increased focus should be placed on postural endurance and mobility as the center of gravity shifts forward to include thoracic extensors, thoracic rotators, transversus abdominis, internal/external obliques, and hip flexors and extensors.

Work that includes power movements of a barbell across the abdomen (i.e., snatches) should be modified as posture and bar path change. Movements such as this can be broken down into smaller multi- or single-joint exercises (deadlift, overhead press). Dumbbells may be substituted for bar exercises depending on the need and desires of the individual. Supine work may also be modified on an as needed basis dependent on symptoms such as pallor, increased heart rate, increased blood pressure, or generally feeling unwell. Such symptoms may indicate potential compression and can be quickly managed by moving the patient to at least a 30 degree reclined position. Positions that require stretching of the pelvic floor stretches such as deep squatting, child’s pose, and hip adductor stretching may be integrated to assist with muscular down-training techniques. Perineal massage techniques can be discussed around the 34-week mark for integration at home. Labor and delivery positions can be discussed in preparation for birth to include quadruped, deep squatting, or side-lying. Options should also be discussed for mothers who prefer to have epidurals as positioning may be more limited but may include side-lying with a peanut ball or rolling a towel around the tailbone/sacrum to allow opening at the pelvic outlet during the push phase.

Internal muscle exam is typically deferred in the first trimester due to the likelihood of miscarriage being highest in the first trimester. While an internal muscle exam is not correlated with any increase in this likelihood, potential association with miscarriage should be avoided if possible. It is also important to note that internal exam may not be necessary for assessment of the pelvic floor muscles as there are external techniques to determine pelvic floor muscle function, and that any addition of internal assessment does increase risk for potential infection. If desired by the athlete being treated by an individual trained in internal muscle examination, internal pelvic floor muscle exam may be completed in second or third trimester to assess baseline function of pelvic floor muscles and address associated deficits. It is important to ensure that this exam is performed in agreement with the athlete’s medical team in addition to ensuring appropriate informed consent to the athlete.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Focus</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength/Power</td>
<td></td>
<td>a. Impact work may be better tolerated from a pelvic floor perspective on an incline</td>
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<td></td>
<td></td>
<td>b. Incline may be slowly lowered until tolerating impact performance on flat surface</td>
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<tr>
<td></td>
<td></td>
<td>c. Full clearance for return to running/sport should be assessed weekly as training volume increases per ACSM guidelines (2-10%/week)</td>
</tr>
</tbody>
</table>

![Figure 1. Normal (A) vs. abnormal/coning (B) management of tension at linea alba with leg lifting in early pregnancy.](image-url)
POSTPARTUM (WEEKS 0–6)

Immediately postpartum, minimizing excessive musculoskeletal stress is important as healing begins. Household ambulation is encouraged in small bouts as tolerated but should not be an area of great concern. General intensity should remain in the RPE 0–2 ranges to allow for appropriate healing. As comfort increases, a walking program may be initiated with focus on shorter duration performance (<10–15 minutes) and increasing frequency as tolerated. Symptoms should be monitored over the 24–48 hours after completion of these bouts of walking to determine musculoskeletal response prior to increasing frequency as some indicators of pelvic floor dysfunction such as prolapse may be delayed. Incline walking and/or gradually increasing speed (below jogging) and duration (<20–30 minutes) is acceptable so long as symptoms are not noted during or after performance. If symptoms present, these should be discussed with a qualified provider to determine whether they are a normal response to new loading of affected tissue or if they are an indicator of dysfunction.

In the early postpartum period, initial focus should be on reconnecting with diaphragmatic breathing to restore thoracic and lumbar mobility as well as to increase on-demand neuromuscular connection of the pelvic floor musculature. Initiation of gentle transversus abdominis work may begin with tasks such as pelvic tilts. Gentle lumbar and thoracic mobility such as lumbar rotation (Figure 2, A, B) and the side-lying “open book” exercise (Figure 2, C, D) within pain-free range may be performed to limit stiffness and encourage safe range of motion.

Light pelvic floor contract/relax movements may be initiated but deferred if symptomatic. As recovery progresses, independence in diaphragmatic breathing and anterior/posterior pelvic tilting should occur. Transversus abdominis stability drills may be initiated, preferably with less reliance on pelvic tilting. This should be coordinated with breath work to include supine, side-lying, and quadruped positions (Figure 3). Pelvic floor contractions and relaxations can be incorporated in this timeframe but may be deferred until internal muscle examination if pain occurs with performance.

Exercises focused on postural strength and endurance are important, as this is an area many new mothers have difficulty with due to nursing and holding the baby. Coordination of the transversus abdominis in functional positions such as sitting, standing, and high plank positions may also be initiated at this point if asymptomatic. Gentle open kinetic chain (OKC) movements may be integrated to increase hip strength and begin improving function associated with pregnancy postural changes. Appropriate pelvic floor contract/relax should be integrated into these movements to include light functional movements such as sit to stand or steps.

POSTPARTUM (WEEKS 7–12)

A walking program may continue, increasing speed and duration as tolerated. As there is a wide amount of variation in readiness for impact at this phase, adding short <20 second jogging bouts may be appropriate at the eight-week postnatal mark for athletes dependent on labor duration, degree of tearing, and other biopsychosocial factors to in-
clude sleep, hormone changes, and nursing status. It is recommended that if jogging is added during this phase, initial work:recovery intervals should be 1:2 ratio of time. This interval impact training should begin with no more than 20 minutes total duration, followed by monitoring, to ensure no symptom increase in the 48 hours after completion. If no symptom increase is present, duration may be slowly increased both in length of the activity interval as well as length of total duration of training. Impact “readiness” should be indicated by implementation of impact drills and response to initiation of a running program.

A sample return to running program can also be found in Table 3 with the initial suggested 1:2 work:rest ratio. These guidelines are focused on duration as opposed to distance with the understanding that pace will vary significantly dependent on the individual athlete as well as type of birth and associated tissue injury. It is important to note that this is only a sample program, and work, rest, and total time parameters may each be adjusted up or down to meet the individual needs of each athlete. Based on a combination of guidelines with varying recommendations of return to run timeframes, this particular protocol suggests that running should begin no sooner than eight weeks postpartum, only after the athlete is able to walk a minimum of 30 minutes without symptoms, in addition to being able to tolerate the six tasks in the Run Readiness Scale (step ups, wall sits, single leg squats, double leg squats, and a plank hold – each lasting one minute) without symptoms.25,36,38

When initiating the return to running program, each portion should be completed twice with 48 hours of rest between completions to ensure that no delayed symptom onset occurs. In the absence of an increase in symptoms 48 hours after the completion of the second trial of each week, the athlete should progress to the next phase until continuous running of desired distances is achieved. Increased symptoms during or after running should be discussed with a pelvic health physical therapist and progression to the next phase should be restricted to allow for a more individualized assessment regarding the source of those symptoms. It is also important to note that running with a stroller will result in postural changes and increased energy expenditure. If running with a stroller, the two-handed method proposed by Goom et al is most commonly suggested as this resulted in the speed and stride length closest to the baseline of each athlete.25

Awareness and improvement of postural changes that have occurred during pregnancy and that often persist postpartum (limited thoracic rotation, improving degree of excessive anterior/posterior pelvic tilting) should all continue to be addressed as appropriate for each individual patient. An internal muscle exam should be performed if desired by patient to determine need for focused up-training vs. down-training at the pelvic floor once the individual is cleared for internal muscle examination by their OB/GYN. Pelvic floor muscle focus should be on achieving full range of motion, quick flicks (strength), and endurance holds without compensations to encourage carryover into the functional tasks mentioned below.

Closed kinetic chain (CKC) strength tasks such as squatting, lunging, heel raises, or step ups to mimic movements that would be required in running or sport may also be integrated at this point. As tolerated, movement should
Table 3. Sample Return to Running Program

<table>
<thead>
<tr>
<th>Week of Program</th>
<th>Work Phase (jog/run)</th>
<th>Rest Phase (walk)</th>
<th>Maximum Total Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 min</td>
<td>2 min</td>
<td>20 min</td>
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<td>2</td>
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</tr>
<tr>
<td>12*</td>
<td>10-15 min</td>
<td>2 min</td>
<td>45 min</td>
</tr>
</tbody>
</table>

*Beyond week 12, desired factors (i.e., intensity, duration) may increase or decrease dependent on athlete goals. If the client desires to increase shorter duration speed work, this program may be more heavily focused on the earlier components with increasing intensity of the work phase.

progress from single-leg to double-leg to improve tolerance to this position. In addition, towards the end of this phase the speed of these movements may increase (i.e., quick step ups or quick sit to stand) to prepare musculature for more power-based movement. Approaching end of this phase may also include more horizontal impact work such as mountain climbers or plank hop outs in preparation for more upright impact work in the next phase. While this horizontal impact work may require less strength and coordination of the pelvic floor muscles, it does require increased control of the core and thus the incline may be modified to meet the needs of the athlete as both areas are heavily affected during the postnatal recovery period.

Cadence in running should range between 160-180 bpm to limit excessive force through the lower extremities as even a 10% increase in cadence has been shown to decrease mechanical stress at the knee joint. Running gait should also be individually assessed to limit likelihood of injury. Factors such as peak hip and knee adduction and knee stiffness may demonstrate more notable compensations in the postpartum phase with a comprehensive guide to 2D running analysis provided by Souza and colleagues.

POSTPARTUM (WEEKS 13+)

Mileage may be increased gradually, increasing speed in short bouts while incorporating walking, jogging and rest into the run as needed. As cardiovascular output increases, cross training (weightlifting, complimentary cardiorespiratory modalities) should also increase to have an athletically balanced approach to increasing intensity and duration. Symptoms should be monitored during and post training to make the necessary adjustments in training variables.

Impact work can be slowly graded from horizontal to upright as tolerated without symptoms. Initial attempts at running may be performed on slight incline to assist the pelvic floor musculature from a postural perspective and slowly decreased to 0% as tolerated. This slight incline limits excessive anterior pelvic tilt that many new mothers note postpartum to assist with muscular function at the pelvic floor. As new mothers can better control these habitual postures acquired during pregnancy, incline can be decreased to promote flat road running. Full clearance for return to running and sport should be assessed weekly as training volume slowly increases per ACSM guidelines (2-10%/week).

ADDITIONAL CONSIDERATIONS

It is important to note that with this suggested timeline that there are common misconceptions surrounding regular pelvic floor contractions (Kegels) during pregnancy for pelvic floor strength. Many women are anecdotally instructed to focus on repeated pelvic floor contractions in order to strengthen the pelvic floor muscles for labor and delivery without being instructed on the need for relaxation of these muscles to encourage improved ease of delivery. Many athletes may suffer from the overactivity of their musculature both in pregnancy and postpartum, and symptoms can be made worse by performing repeated and regular muscle contractions at the pelvic floor when not indicated. The ability of a trained pelvic floor physical therapist to perform an internal muscle examination both during pregnancy and postpartum can ensure that the pelvic floor musculature is achieving appropriate range of motion and that contractions are being performed correctly. Any symptoms of pelvic floor dysfunction should serve as indicators for lack of readiness for progression to the next phase and may require additional visits to allow for safety in these progressions.

Other considerations as the athlete returns to running include timing of nursing with recommendations to empty the breasts just prior to running to limit discomfort and potential clogged ducts associated with full breasts. Athletes should be educated that exercise has not been shown to limit breastmilk production so long as appropriate hydration status and caloric intake is maintained. Sports bra fitting should provide appropriate support without being overly compressive and professional fitting of the bra is highly recommended, noting that previously worn breast support garments may no longer be adequate.

While highly variable among individuals, foot size and shape can also change during pregnancy because of increased laxity of the ligaments in the feet. As such, a postnatal footwear assessment should be performed to ensure that running shoes are providing adequate support in addition to the intrinsic foot strengthening suggested within this protocol and others. While there are theories that the relaxin hormone responsible for this laxity may increase likelihood for injury, there are no studies that currently support this.
CONCLUSION

Women in the pregnant and postpartum periods have lacked adequate guidance regarding appropriate exercise prescription. The proposed timeline of rehabilitation is proposed to facilitate improved quality of life, increased likelihood of full and safe return to sport, and less medical care requirements for postpartum symptoms. Understanding the intricacies of the female athlete during this time may assist clinicians and coaches with guidance to assist in safe return to sport. Without a slow and graded return to exercise which is commonplace for other musculoskeletal events, the current paradigm may unintentionally be overly conservative in some respects (during pregnancy) while not addressing dysfunction during the postpartum recovery.46,47

Despite evidence regarding the effectiveness of pelvic floor physical therapy,24,48,49 no specific rehabilitation guidelines currently exist to assist clinicians in determining appropriate frequency or progression of exercise for the pregnant and postpartum athlete. This commentary presents suggestions regarding graded activity during pregnancy and rehabilitation during post-partum recovery that may decrease the likelihood complications. The importance of this commentary lies not only in the outline of a preventive approach to postpartum care, but in the recommendation of continuous reassessment of the changing body throughout pregnancy and the early postpartum period as athletes perform and return to activities of daily living, work, exercise activity, and sport participation. As musculoskeletal health has been largely unstudied in this population, this protocol may provide guidelines for the prevention of common musculoskeletal dysfunction in the pregnant and postpartum athlete and spark future research.

COI STATEMENT

The authors of this study report no conflicts of interest with regard to this manuscript or its contents.

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Hamstring injuries (HSIs) are common in female athletes and are associated with a lengthy recovery period and a high rate of reinjury. Currently, the majority of existing literature investigating HSI rehabilitation has been conducted using male participants. However, female athletes display intrinsic anatomical and biomechanical differences compared to males that influence the way this population experiences HSIs and HSI rehabilitation. HSI rehabilitation and injury prevention guidelines for female athletes must take these differences into account. Female athletes display anatomical differences such as increased anterior pelvic tilting, gluteus maximus weakness, an increased pelvic width-to-femoral length ratio, and an increased degree of femoral anteversion, all of which can predispose females to HSIs. Maneuvers designed to strengthen the gluteal musculature and transverse abdominis can overcome these risk factors. Females show increased joint laxity and a greater range of motion of hip flexion and internal rotation compared to males. Females have lower passive hamstring stiffness than males, therefore hamstring flexibility exercises may not be as necessary during rehabilitation for females as in the male athlete population. Female athletes may instead benefit from trunk stabilization exercises and agility training due to neuromuscular control deficits that arise from the maturation and growth of the female pelvis. Existing literature on hamstring injury prevention shows consistent use of the Nordic Hamstring Exercise and balance exercises may reduce the risk of sustaining an HSI in both males and females, though more studies are needed to ascertain the optimal regimen for injury prevention in the female athlete population specifically. The goal of this clinical commentary is to discuss sex-specific anatomic and biomechanical differences of the lumbar, pelvic, and hip regions with the aim of providing guidelines for rehabilitation and injury prevention of HSIs in female athletes.

Level of Evidence
5

INTRODUCTION

Hamstring injuries consistently rank as one of the most frequent injuries sustained by female athletes and can result in lengthy amounts of time off from sport.1–4 Women are underrepresented in many sports and exercise medicine studies, including those focused on hamstring injury rehabilitation and prevention.5 Male-only research studies may not translate effectively due to sex-based differences in biomechanical properties, hormones, and sporting environments.6 O’Sullivan et al. have emphasized the importance of recognizing intrinsic differences between males and females in the risk factors that lead to hamstring injury.7 Female athletes demonstrate increased hamstring flexibility, lower hamstring musculotendinous stiffness, and increased resistance to skeletal muscle fatigue compared to male athletes.7 These differences, along with the high incidence and burden of hamstring injuries in this population, demonstrate the need for implementation of effective female-specific rehabilitation and injury prevention programs.
Proper prevention and rehabilitation are especially crucial for HSIs because the rate of re-injury is so high. Approximately 1/3rd of all HSIs result in reoccurrence and athletes are 4.8 times more likely to sustain an HSI if an HSI had occurred within the previous season. Additionally, athletes often experience significant and persistent deficits in the injured hamstring after sustaining an HSI. No studies directly compare the extent of injured limb deficits in male athletes versus female athletes and how that may impact rehabilitation. Therefore, the purpose of this clinical commentary is to discuss sex-specific anatomic and biomechanical differences of the lumbar, pelvic, and hip regions with the goal of providing guidelines for rehabilitation and injury prevention of HSIs in female athletes.

**HAMSTRING INJURY REHABILITATION**

A strong rehabilitation program should focus on restoring an athlete’s pre-injury functionality and performance as well as correct for any deficits that may have led to the injury. Eccentrically strengthening the injured hamstring muscle has been shown to reduce the time to return to play in both men and women, as well as decreasing the risk of reinjury. Strengthening during HSI rehabilitation and prevention includes facilitation of muscle hypertrophy in the hamstring musculature as well as addressing functional requirements of the hamstrings through eccentric loading and stretch/shorten cycle exercises. Of equal importance is identifying impairments that may contribute to increased provocative load on the hamstrings. Increasing flexibility and neuromuscular control of the lumbopelvic region has also been shown to be beneficial for HSI rehabilitation. Consideration of the sex-specific anatomical and biomechanical features in the lumbopelvic and hip region are necessary when building effective HSI rehabilitation and prevention programs for female athletes.

**ANTERIOR PELVIC TILT**

The acetabulum exhibits sexual dimorphism. Acetabular anteverision is significantly greater in females, ranging from 21-23 degrees compared to 17-18 degrees in males. A greater degree of acetabular anteverision is thought to be compensated for by increasing the degree of anterior pelvic tilt. In fact, females are found to have increased anterior pelvic tilting compared to men, both while standing and during the gait cycle. The increased degree of anterior pelvic tilt in the female pelvis has been linked to HSI. Due to the proximal attachment of the hamstrings to the ischial tuberosities of the pelvis, an increased anterior pelvic tilt places the hamstrings in a relatively lengthened position. This will also lengthen the gluteus maximus (GMax) and gluteus medius (GMed) muscles due to their distal attachments to the femur and posterior orientation on the innominate.

Restricted hip flexor muscle length can be associated with a more pronounced anterior pelvic tilt in the female pelvis. Shortened hip flexors will limit hip extension, decrease primary hip extensor recruitment and increase reliance on the secondary hip extensors. In the presence of GMax weakness, there is an increased dependency on the hamstrings to work. This is referred to as “synergistic dominance” and places greater stress on the hamstring tissue resulting in higher risk of HSI. Identifying and addressing shortened hip flexors will facilitate GMax recruitment and strengthening in order to reduce provocative load on the hamstrings.

The abdominal drawing-in maneuver combined with hip strengthening exercises has been found to increase activation of the gluteal musculature. Activating the TrA can help to stabilize against compensatory movements in the lumbar spine and pelvis including lumbar hyperextension and excessive anterior pelvic tilt, minimize lengthening of the GMax, GMed and hamstrings and maximize recruitment of the GMax and GMed. TrA activation through the abdominal drawing-in maneuver is an essential modification to hip strengthening in female-specific HSI rehabilitation and prevention programs.

GMax strengthening is initially addressed through isometrics and initiated in early HSI rehabilitation. Glute sets in prone with a pillow under the pelvis (Figure 1) to reduce an anterior pelvic tilt promotes TrA activation and facilitates GMax activation. Once GMax activation is properly established, dynamic strengthening is initiated. As the hip is abduced to 15-30 degrees, GMax activation increases and hamstring activation decreases. Hamstring activation is the greatest with the hip in neutral alignment. The bridge exercise, which has high levels of EMG activity in the GMax, is performed in 15-30 degrees of hip abduction to encourage GMax activation and discourage hamstring recruitment. This can be facilitated in the female athlete by placing a band just proximal to the knees to promote hip abduction (Figure 2).

**HIP ABDUCTOR STRENGTH**

Compared to the adult male pelvis, the adult female pelvis is broader with a wider pelvic outlet and a wider and more circular pelvic inlet. The larger pelvic width-to-femoral length ratio in the female anatomy is in part a reason why females tend to have weaker hip abductors compared to their male counterparts. Greater degrees of
femoral anteverision in females have been associated with decreased utilization of the gluteus medius muscles.\textsuperscript{17–19,40} Weakness in the GMed has been associated with HSI suggesting that an increase in hip adduction and difficulty controlling contralateral pelvic drop places additional strain on the hamstrings. Female athletes with stronger hip abductors and external rotators have been shown to be less likely to experience lower extremity injury.\textsuperscript{41}

In the female athlete, activation of the TrA to stabilize the pelvis and lumbar spine and minimize anterior pelvic tilting has been shown to maximize GMed strengthening.\textsuperscript{31} Side stepping with a resistance band in a squat position (Figure 3) has been shown to increase GMed recruitment and decrease hip flexor activity which can be an effective modification during HSI rehabilitation and prevention for female athletes with hip flexor length deficits.\textsuperscript{42}

HAMSTRING STRENGTH

Guidelines for hamstring strengthening during rehabilitation and injury prevention programs are similar for females and males; however basic modifications to exercises are given to correct for any proximal alignment and trunk control needs specific to the female anatomy and biomechanics. Females are at higher risk for lower extremity injury when there is a knee flexor/knee extensor ratio of less than 0.75. Knapik et al studied 158 female collegiate athletes, 40% of whom experienced one or more lower extremity injuries.\textsuperscript{43} This imbalance between knee extensors and flexors highlights how relative posterior kinetic chain weakness contributes to lower extremity injury and the importance of fully rehabilitating the injured hamstring in order to reduce risk of injury prior to return to sport in the female athlete.\textsuperscript{39}

The Nordic hamstring exercise (NHE) (Figure 4) is the most popular eccentric loading exercise for both HSI rehabilitation and prevention. When performed with good trunk control, this exercise produces the highest activation levels in all three of the hamstring muscles when compared with other common hamstring eccentric exercises like the deadlift and ball leg curl.\textsuperscript{44} With an increase in anterior pelvic tilt, a higher degree of femoral and acetabular anteverision and higher likelihood of joint hypermobility, there needs to be more emphasis on establishing adequate trunk control in order for the female athlete to effectively perform the NHE.

The 45-degree hip extension exercise (Figure 5) is another commonly prescribed eccentric hamstring loading exercise. Messer et al. evaluated hamstring muscle activation during the NHE and the 45-degree hip extension exercise in women. While they found that both the 45-degree hip extension exercise and the NHE produced activation of all three hamstring muscles, the NHE elicited higher activation in the semitendinosus with the 45-degree hip extension exercise eliciting a higher biceps femoris long head to semitendinosus activation ratio.\textsuperscript{45} The long head of the biceps femoris has been shown to be more active at the hip, and when strained, is associated with persistent deficits in muscle activation.\textsuperscript{46,47} Furthermore, it has been proposed that the semitendinosus may play a more significant role than the other hamstrings in unloading the ACL,\textsuperscript{24} due to its role in preventing excessive anterior tibial translation and knee valgus which are movement patterns associated with non-contact ACL injury.\textsuperscript{48} Both the NHE and 45-degree hip extension exercise should be considered in HSI rehabilitation and prevention programs for female athletes. When prescribing these two exercises, another consideration is to place a band just proximal to the knees to promote hip abduction further reducing the tendency to collapse into hip adduction and femoral internal rotation.

HYPERMOBILITY

Hypermobility and differences in laxity of surrounding soft tissue structures in the hip have been described in the female athlete. Females tend to show greater range of motion in hip flexion and hip internal rotation at 90 degrees of flexion than males.\textsuperscript{18} This can place additional demand on the muscles of the posterior kinetic chain to control excessive hip internal rotation including the biceps femoris. Though not as well understood in regard to hip injury and dysfunction in the female athlete, females are also more likely to
Figure 3. Side stepping with a resistance band in a squat position. Place a band around the feet standing in a mini squat position. Take steps laterally maintaining stability through the lumbopelvic region and maintaining resistance on the band without dragging the feet.

Figure 4. Nordic hamstring exercise. Begin in a tall kneeling position with a band proximal to the knees and hips abducted isometrically against the band. Using a partner to stabilize the feet and ankles, lower the trunk with control maintaining neutral lumbopelvic and hip alignment using the arms to break the “fall”.

have generalized joint laxity, lower passive hamstring stiffness, and higher tolerance to stretch.49–52 Furthermore, instability and laxity of the sacroiliac joint may contribute to hamstring muscle pathology and injury.53–55 Knee and hip range of motion along with hamstring flexibility are commonly addressed during HSI rehabilitation; however, feelings of hamstring “tightness” is a common report in the female athlete when the hamstrings are repetitively overloaded.56 In the presence of joint hypermobility, lower passive hamstring stiffness and normal hamstring length, the tendency to incorporate flexibility exercises for the hamstrings should be avoided with female athletes.

BIOMECHANICAL/NEUROMUSCULAR CONTROL

The neuromuscular control differences between females and males have been well documented with a focus on how these differences impact non-contact knee injuries, but the relationship to hip and hamstring injuries have not been commonly described. Deficits in neuromuscular control have been shown to be correlated to the specific anatomical changes that occur through puberty as the female pelvis matures.38 During a single leg task, females can demonstrate the improper movement pattern of decreased trunk flexion, in-
creased hip adduction, increased femoral internal rotation, increased knee abduction and trunk lean towards the weight bearing limb. Female athletes have weaker hip abductors and decreased hip extensor moments associated with this faulty movement pattern related to an increase in femoral internal rotation and adduction. This can be exacerbated in the setting of increased anterior pelvic tilt and larger pelvic width-to-femoral length ratio. Decreases in proximal strength measures suggest that females may have a less stable foundation upon which to develop or resist force in the lower extremities. Biomechanical studies indicate that hip muscle activation significantly affects the ability of the hamstrings to generate force or resist forces experienced by the entire leg during a single leg task. This tendency for core instability has been suggested to predispose females to lower extremity injury.

Trunk stabilization and agility training have an added benefit to HSI rehabilitation and prevention. Sherry and Best demonstrated that a rehabilitation program consisting of progressive strength and trunk stabilization exercises was more effective in promoting return to sport and preventing re-injury than isolated hamstring stretching and strengthening in males and females after sustaining an acute hamstring strain.

HAMSTRING INJURY PREVENTION

Neuromuscular training programs have been shown to be effective in the prevention of non-contact ACL injuries in female athletes. These programs incorporate lower extremity strengthening, eccentric hamstring loading, trunk stabilization and agility training. This highlights the importance of posterior kinetic chain strength, HS eccentric strength and trunk stability and its role in reducing lower extremity injury in female athletes. The Prevent Injury and Enhance Performance (PEP) program specifically utilizes the NHE as their primary exercise for hamstring eccentric strengthening.

Petersen et al. followed 942 male soccer players for 10 weeks; the players were either allocated to a control group and performed their usual training program or allocated to an intervention group and performed an additional 27 sessions of the NHE during the 10-week period. The NHE program reduced the rate of new HSI injuries in the intervention group athletes by over 60%, from 8.1 injuries per 100 player-seasons in the control group to 3.1 in the intervention group. It was also highly effective at reducing the rate of recurrent HSIs, which was 45.8 per 100 player-seasons in the control group compared to 7.1 in the NHE intervention group (an approximate 85% reduction). While Petersen et al. all performed this study with only male subjects, their results emphasize the effectiveness of the NHE.

Soligard et al., studied 1,892 female adolescent soccer players who were divided into intervention and control groups and followed for eight months. The intervention group performed a comprehensive warm-up program before every training session which included running, strength, and balance exercises, one of which was the NHE. While there were fewer HSIs recorded in the control group (eight versus five), these results were not significant. However, the authors did find there was a significantly lower risk of injuries overall, overuse injuries, and severe injuries in the intervention group. A randomized controlled trial consisting of 45 professional women soccer players tested the effect of a 21-week eccentric strength training program which consisted of the Nordic Hamstring
exercise and eccentric band exercises. Five players who did not undergo the training program later sustained an HSI, compared to only one player in the intervention group; the training program therefore reduced the risk of HSI by 81%. However, the results did not reach significance due to the small number of participants in the study.64 As sex-specific differences exist in HSI risk factors and rehabilitation, future studies are needed to identify the optimal preventative training program to reduce hamstring injuries in female athletes.

CONCLUSION

Effective hamstring injury rehabilitation and prevention programs are crucial considering the significant burden HSI can place on a female athlete.1–4 Existing literature regarding hamstring rehabilitation demonstrates that eccentric hamstring strengthening, flexibility training, and agility and trunk stabilization exercises may reduce return-to-play time and rates of re-injury and that use of the Nordic Hamstring Exercise in HSI prevention programs successfully reduces the rate of HSIs.12,13,16,62–66 Sex-specific hamstring injury rehabilitation guidelines that acknowledge and address anatomical differences such as increased anterior pelvic tilt, greater degree of both femoral and acetabular anteverision and greater pelvic width to femoral length ratio should be considered, as should biomechanical differences such as decreased utilization of the hip abductor muscles, decreased neuromuscular control, and hypermobility. Future comparative studies on the efficacy of sex-specific rehabilitation protocols can help optimize the management and prevention of HSI in female athletes.

CONFLICTS OF INTEREST

Lucy R. O’Sullivan: None

Jamie A. Preszler: None

Miho J. Tanaka: Grants from Arthroscopy Association of North America and Fuji Film; Consultant Medical Reviewer at Verywell Fit; Editorial Board of ASJM and Arthroscopy Journal; Associate Editor CME Panel at JBJS; Editor at Journal of Women’s Sports Medicine; Committee member at AOSSM, AANA, AAOS, ISAKOS

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**Background:** Physical therapy (PT) following shoulder surgery has traditionally occurred via in-office supervised visits. Recently digital health tools with remote patient monitoring (RPM) have emerged as an option to enhance the ability to both monitor and encourage engagement of home PT. The appeal of such tools has been accelerated by the impact of COVID-19 on the healthcare system.

**Purpose:** The primary purpose of this study was to compare patient-reported outcomes (PROs) following shoulder surgery of patients who completed at-home PT with a digital rehab application to patients who completed in-office supervised PT. The secondary purpose was to assess engagement among patients who used digital PT.

**Study Design:** Retrospective Review.

**Methods:** A retrospective matched comparative evaluation was performed of patients who underwent arthroscopic shoulder surgery or shoulder arthroplasty at a single institution between April 2020 and May 2021. Patients who underwent home-based physical therapy with a digital remote monitoring platform (PT Genie; Orland, FL) were identified and age and procedure matched (arthroscopy or arthroplasty) to a cohort of patients that underwent in-office physical therapy. The digital platform provided remote monitoring capabilities with measurement of range of motion. PROs measured preoperatively and at 1 year postoperative included visual analogue scale pain score (VAS), American Shoulder Elbow Surgeons Score (ASES), and Single Assessment Numeric Evaluation (SANE). Engagement measured as the number of sessions recorded was analyzed in the digital PT based on 6 age groups (≤40, 41-50, 51-60, 61-70, 71-80 and 81+). Statistical analysis using the student t-test to compare means was performed using SPSS version 17 (SPSS Inc., Chicago).

**Results:** A total of 862 patients were identified, included 393 arthroscopic surgeries (198 in each PT group) and 466 in the arthroplasty group (233 patients in each PT group). The groups were similar at baseline other than a higher preoperative ASES score in the digital PT arthroplasty group. The ASES score for the PTG-arthroplasty group was 44.5 and for the non-PTG group it was 59.0 (p=0.002). There was no significant difference in any PROs between the two groups at 1 year follow up. The highest engagement in digital PT group was observed in the arthroplasty group and over the age of 50.

**Discussion/Conclusion:** In conclusion, there appears to be no difference in PROs following shoulder surgery whether physical therapy is performed in-office or at home via a digital platform with remote patient monitoring capabilities. Interestingly, engagement with digital PT was highest in older patients, suggesting that the technology is not a large barrier. Although further study is needed to confirm these findings, benefits of digital PT with remote monitoring may include: 1) Decreased cost for the healthcare system, 2) Decreased travel time for the patient, and 3) Scheduling efficiency and improved access to the PT for the patient.

**Presenting Author:** yousef@clevelandshoulder.com
ABSTRACTS

RESEARCH SYMPOSIUM AT THE 2022 ORTHOPEDIC SUMMIT

ENCORE BOSTON
FRIDAY, SEPTEMBER 23
5:30 PM to 6:30 PM
The International Journal of Sports Physical Therapy is pleased to publish abstracts from the 12th Orthopaedic Summit (OSET) taking place in Boston, September 21-24, 2022. The IJSPT hosted the 2nd annual research forum and reception at OSET, sponsored by ATI Physical Therapy and Hyperice.

The abstracts presented in the following pages were selected by the OSET Research Committee and editorial staff of the International Journal of Sports Physical Therapy. After careful review, a total of 17 research abstracts were accepted and presented at OSET 2022. Awards for outstanding abstracts were presented on September 23rd.

The 2022 abstracts include contemporary orthopaedic and rehabilitation topics across various research designs. Each abstract presents only a brief summary of a research project / presentation and does not permit full assessment of the scientific rigor with which the work was conducted. While the abstracts offer only preliminary results that may require further refinement and future validation, they do serve an important role in sharing new research ideas and rehabilitation advancements. This sharing of ideas helps to encourage dialogue among researchers, clinicians, and educators that will ultimately contribute to the orthopaedic and rehabilitation body of knowledge. We strongly encourage authors to continue pursuing the publication of their research as a full manuscript.

Thank you to all submitting abstracts for consideration. We look forward to another outstanding season of submissions for OSET 2023.

Phil Page PhD, PT, ATC
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OSET Research Committee Co-Chairs
A MUSCULOSKELETAL APPROACH FOR PRE- AND POSTNATAL REHABILITATION TO PROMOTE RETURN TO SPORT: A CASE SERIES

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**Background:** Recent changes to exercise guidelines have expanded to include pregnant athletes. More women are transitioning into motherhood at the height of their athletic careers and there is limited guidance on appropriate musculoskeletal rehabilitation from pregnancy through return to sport. Lack of education and awareness of a standardized musculoskeletal approach in this population may lead to increased postpartum symptoms and delay of treatment, ultimately hindering athletic performance.

**Purpose:** The purpose of this case series is to assess the athletes' musculoskeletal response through a new pre- and postnatal rehabilitation protocol.

**Study Design:** Case Series

**Methods:** Six women were referred to physical therapy during pregnancy to participate in this protocol. The women completed a time and criterion based pregnancy and postpartum rehabilitation plan. Subjective and objective data was collected for each participant from the first trimester up to 16 weeks postpartum over the course of approximately 18 months.

**Results:** Pain, urinary dysfunction, and pelvic floor muscle strength were assessed at 6 weeks postpartum and at discharge. Meaningful improvement was noted in pain, urinary dysfunction, and muscle strength by the time of discharge both within participants and as compared to general population statistics.

**Conclusion:** These changes suggest that a musculoskeletal protocol monitored by a licensed and specialized physical therapist should be considered as part of the standard of care in pregnancy and postpartum due to high musculoskeletal demands in pregnancy, postpartum, and sport. Improving understanding of training in these athletes can minimize musculoskeletal and urinary symptoms while decreasing this population's exposure to scrutiny and judgement as they excel in both motherhood and sport.

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**3D-PRINTED SHORT ARM CASTS: A PILOT CASE STUDY OF RELIABILITY, VALIDITY, AND FEASIBILITY COMPARED TO CONVENTIONAL WATERPROOF FIBERGLASS CASTS**

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**Background:** Short arm casting (SAC) is a common treatment of various sports injuries including wrist fractures. Currently, fiberglass and waterproof lining reflect a standard of practice for SAC; however, evolving techniques involving three-dimensional (3D) print fabrication show early promise in optimizing the mechanical properties of orthopedic immobilization techniques, and advantages such as comfort, customization, breathability, waterproofing, lifestyle, and social effects have been reported. However, limited studies have been performed to examine the reliability of 3D printed cast application and the validity and feasibility of the fitting compared to the conventional fiberglass approach.

**Purpose:** To evaluate the reliability, validity, and feasibility of 3D printed short arm casts versus conventional casts.

**Study Design:** Case Study.

**Methods:** Three raters of varying experience were instructed on the application of both the conventional and 3D printed (ActivArmor) SAC. Each rater applied two conventional and two 3D printed casts to a participant's dominant wrist to evaluate reliability. Each cast was worn for 24 hours and removed the following day after data collection. Data collection included measures of clinical effectiveness, patient satisfaction, patient rated wrist evaluation, and the upper extremity functional index.

**Results:** ICCs demonstrated ‘excellent’ intra-rater reliability for clinical effectiveness (0.997, 0.766, 0.997) and patient satisfaction (0.789, 0.892, 0.877). ICCs demonstrated ‘excellent’ inter-rater reliability for both clinical effectiveness and patient satisfaction metrics (ICC: 0.857, 0.767, respectively). There were no significant differences between fiberglass and 3D printed SACs in terms of average scores of clinical effectiveness (11.50 vs. 11.17, P = 0.342), patient satisfaction (11.50 vs. 12.50, P = 0.307), or the patient rated wrist evaluation (10.92 vs. 10.14, P = 0.865), respectively. The 3D printed SAC group had significantly higher wrist function compared to the fiberglass SAC group as reported in the upper extremity functional index (65.83 vs. 64.00, P < .001, respectively).

**Discussion:** This pilot case study demonstrates that 3D printed short arm casts may be a valid immobilization technique of the wrist compared to conventional waterproof fiberglass casting. Equivalence in clinical effectiveness and patient rated wrist and upper extremity function was reported between the two types of casting. Participants were slightly more satisfied with the 3D printed casts, which also proved to be more waterproof. The psychomotor skills of both casting techniques were learned by Athletic Trainers, who were then able to reliably apply, retain, and repeat the technical work.

**Conclusion:** The most common fracture in humans before the age of 75 is a wrist fracture. Furthermore, wrist fracture is the second most common specific injury that brings a person to the emergency room, and many wrist fractures are treated with short arm casting (especially in children). As evolving techniques such as 3D printing in medicine emerge, reliability, validity, and feasibility studies are paramount to further investigations on clinical effectiveness with randomized controlled trials. This study illustrates this specifically with short arm casting techniques. This study sets the foundation for further investigations of 3D printed casting techniques for orthopedic conditions by demonstrating specific reliability, validity, and feasibility for short arm casting. Further studies should investigate similar qualities of lower extremity casts (short leg casts) and pursue randomized controlled trials involving patients requiring definitive immobilization treatment of fractures.

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2022 IFSPT Orthopedic Summit Research Abstracts
SCREENING ASSESSMENT, PERCEIVED TRAINING LOAD AND INJURY INCIDENCE IN A YOUNG AND PRESELECTED VOLLEYBALL POPULATION: RESULTS FROM A 3-MONTH OBSERVATION PERIOD USING A RETROSPECTIVE DESIGN

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Background: The value of screening for the prediction of injury risk in team sports has been questioned. The relation between screening and injury incidence has to a lesser extent been studied in youth volleyball athletes, while the relationship between perceived training load and injury incidence is unexamined in this population.

Purpose: This study investigates the relationship between a group of physical screening parameters, perceived training load and observed injuries during a 12-week follow-up period. We hypothesize a higher incidence of injuries for: 1) players with inferior outcomes on physical screening parameters and/or 2) players with a higher perceived training load.

Study Design: Level 3: Non-randomized controlled cohort/follow-up study.

Methods: This retrospective study analyses the information from a routine, standardized screening assessment in 46 youth elite athletes between 12-16 years. This screening included various mobility, strength and stability tests. Injuries, training participation and perceived training load using Borg scores were administered by the medical team during a 12-week follow-up period. The group with chronic overuse injuries was compared to a group without chronic overuse injuries using a Mann-Whitney U test. Effect size was reported using rank-biserial correlation (rpb).

Results: Sixteen athletes (34.8%) reported a chronic injury. Only the Biering-Sørensen test (rpb = 0.392) and the relative strength for hip abduction of the right leg (rpb = 0.381) were significantly lower for the injured group. Small to moderate effect sizes were found for all other screening parameters, but no significant differences. Both groups showed no significant difference regarding perceived training load.

Discussion/Conclusion: Our results confirm results in adult athletes, that screening information at group level cannot be linked with future injuries. In addition, perceived training load does not indicate injury susceptibility. Based on these results, other approaches should be explored. The use of multivariate analysis methods or personalized approaches can help in unraveling the complex, dynamic nature of injuries.

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A SCOPING REVIEW OF REAL-TIME PERFORMANCE DATA TRACKING IN PROFESSIONAL RUGBY ATHLETES

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Background: Athletes and coaches are under stress to maximize performances and outcomes. Every advantage can matter in the world of athletics; technology can be one of those advantages as a tool that can be utilized by coaches, athletes, and medical professionals. The data recorded by global positioning systems (GPS) and accelerometers can provide a valid and reliable means of objectively measuring and assessing physical performance parameters in athletics.

Purpose: The purpose of this scoping review was to provide an overview of the existing literature on real-time data tracking technology in the performance of professional rugby athletes.

Study Design: Scoping Review.

Methods: One reviewer searched SportDiscus, CINAHL, Academic Search Complete, and MEDLINE databases using PRISMA guidelines between June and November 2020. The inclusion criteria were articles evaluating professional rugby athletes that were published after 2004 in peer-reviewed journals. Data were extracted for study title, year, study design, tracker technology used, the technology company, athletic variables tracked in the study, notable findings, any changes implemented or suggested, and further research needed.

Results: Eleven included studies were identified as descriptive observational studies quantified and reported on performance variables during rugby matches and practices, including total distance, average speed, max speed, number of sprints, low, medium, and high accelerations, max heart rate, mean heart rate, and time in heart rate percentages. Five synthesis studies suggested these devices have different capabilities to accurately measure some movements. Four validation studies identified a lack of clear consensus on the validity of the tracking technology used in professional rugby. Five associative designed studies indicated data collected from these tracking devices can provide sports medicine teams with insight into game trends and workloads of athletes that can then be used to create more appropriate and specific training protocols. The comparative study found that teams may perform better with longer recovery periods, potentially playing a role in team schedule planning.

Discussion/Conclusion: The extensive number of variables available from performance tracking devices may provide an overwhelming number of options to consider in capturing, interpreting, and applying the data. GPS and accelerometer units provide valuable data that give insight into the athletes’ performance, training load, and health; however various factors such as the brand of tracking device used, and proprietary outcome algorithms limit an analysis of the validity of performance tracking. These data and devices would be best used in combination with other player measurement and assessment methods to provide a comprehensive assessment of the athlete.

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**Does Blood Flow Restriction Change Forearm Muscle Activation Amplitude in the Upper Extremity?**

Seal L, 1 Page P

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**Background:** Blood flow restriction (BFR) training involves the use of a band or inflatable cuff to partially restrict blood flow during exercise. Blood flow restriction is thought to create a metabolic environment resulting in muscle hypertrophy and strength. Several researchers have observed increases in muscle activation during and/or following BFR combined with resistance exercises; however, none have investigated acute changes in forearm musculature. Understanding the changes in forearm muscle activation after upper extremity BFR exercise may aid clinicians treating upper extremity tendinopathies such as lateral epicondylitis.

**Purpose:** The purpose of this study was to evaluate the feasibility of a study to evaluate acute changes in surface electromyography (sEMG) activation levels of forearm muscles after strengthening exercise with and without BFR.

**Study Design:** A randomized crossover observational pilot study using a convenience sample of healthy university students was IRB-approved and conducted at Franciscan Missionaries of Our Lady University.

**Methods:** Six subjects completed pretest measurements of maximal grip strength using a Jamar® hand dynamometer while sEMG was assessed in the wrist flexors and extensors. Subjects then performed wrist strengthening exercise with or without BFR using the TheraBand® Flexbar (the "Tyler Twist" exercise) followed by post-test measures of grip strength and sEMG immediately afterward. Subjects were randomly assigned to perform the strengthening exercise with or without BFR first followed by a 60-minute wash-out. Due to the small sample size, non-parametric statistical analysis was performed.

**Results:** Wilcoxin Signed Rank Test for matched pairs demonstrated no significant differences in the activation of flexors (p = .463) or activation of extensors (p = .753) between BFR and non-BFR after exercise. There were no adverse events reported.

**Discussion:** This protocol was feasible. There were several limitations of this study. As a pilot study, the statistics were underpowered to detect a true difference. The convenience sample consisted of young, healthy individuals and only 1 female, also limiting the generalizability of the results.

**Conclusion:** This pilot study demonstrated no significant difference in forearm muscle activation after strengthening exercises with or without BFR. The protocol should be performed in larger samples among upper extremity patient populations.

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DIAGNOSIS OF DEEP VEIN THROMBOSIS IN OUT-PATIENTS WITH MUSCULOSKELETAL DISORDERS: A SURVEY OF ORTHOPEDIC AND SPORTS ACADEMIES

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Background: Venous thromboembolism can present as either a deep vein thrombosis (DVT) or dislodge and become a pulmonary embolism. Physical therapists routinely examine patients with musculoskeletal conditions that may have serious associated disorders like a DVT.

Purpose: The purpose of this study was to determine if there was a difference in physical therapists’ estimation of the probability of a patient having a DVT in patient vignettes as compared to the actual Modified Wells criteria prediction.

Study Design: Exploratory Survey.

Methods: Following a university Institutional Review Board approval, members of the American Academy of Orthopedics (AOPT) and American Academy of Sports Physical Therapy (AASPT) were asked to complete a survey of patient vignettes. Descriptive statistics were calculated, and Sign Tests were performed to assess differences between responses of presence of DVT (likely or unlikely), and whether the respondent would refer the patient. Nonresponse bias was assessed via Chi square or Fisher's Exact Tests.

Results: Six hundred and seventy members consented and 521 completed the full survey out of 24,028 academy members. 7.2% of full survey respondents reported not considering themselves as competent to screen for DVT. However, this number may be as high as 19.8% due to 75 consent individuals exiting the survey as they declined to answer the competence to screen question. Frequency analysis revealed substantial difficulty in respondents determining whether a DVT was likely or unlikely in 4 of the 5 vignettes, as compared to the Modified Wells criteria, with only vignette 2 having 92.9% of respondents correctly answering as DVT being unlikely. In all vignettes there were statistically significant differences between determination of DVT being likely or unlikely and decision to refer, with respondents consistently choosing to refer despite providing a determination of DVT being unlikely (p<.001 for vignettes 1,3-5. p=.038 for vignette 2). There were no differences in any vignette based on residency or fellowship status, specialist certification, or practicing direct access. There was no evidence of response bias.

Discussion: It appears that members of the AOPT and AASPT have difficulty in determination of DVT presence or absence in clinical vignettes. Despite this difficulty, more respondents were likely to refer, possibly indicating their understanding that the ultimate decision to rule out presence of a DVT is beyond the scope of physical therapist practice.

Conclusion: Efforts to educate members should be considered to improve the understanding of DVT assessment.

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THE EFFECT OF ADDING A FOAM SURFACE CONDITION TO THE HEAD SHAKE SENSORY ORGANIZATION TEST IN HEALTH AND CONCUSSED ADULTS

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Background: Visual-motor disruptions occur in 65% to 90% of concussed patients that impair balance and can be measured by posturography. The Head Shake-Sensory Organization Test (HS-SOT) is a computerized postural test that increases complexity by including dynamic head motions while maintaining balance.

Purpose: The purpose of this study is to compare equilibrium scores while standing on stable and foam cushion surfaces between the SOT and HS-SOT in healthy adults and those concussed.

Study Design: Cohort Study.

Methods: Twenty-five participants completed outcome measures and 3 trials of testing. Sixteen individuals (21.50 ± 4.52 years) were healthy and nine (20.33 ± 3.35 years) were concussed. Participants completed the Dizziness Handicap Inventory, Activities of Balance Confidence Scale, SOT, HS-SOT, and Foam cushion HS-SOT in one session.

Results: The groups did not show significant differences on gender, age, DHI, or ABC. The LMM (3 Tasks x 2 SOT conditions x 2 groups) showed that there was a significant effect of task, F (2, 100.584) = 55.372, p < 0.001, a significant effect of SOT condition, F (1, 98.930) = 179.653, p < 0.001, and a significant effect of group, F (1, 28.367) = 14.701, p < 0.001. No significant 2- or 3-way interactions were found (p > 0.05). A post hoc analysis of task effect with Sidak adjustment showed that the average equilibrium scores (average of SOT2 and SOT5) in both groups significantly decreased with more complex tasks. Furthermore, the concussion group had significantly worse equilibrium score than the control group during HS-SOT (p = 0.007) and Foam HS-SOT (p = 0.002) tasks but not during the standard SOT.

Conclusions: The HS-SOT may assess and quantify subtle balance deficits in concussed individuals that are not losing balance during simple balance testing such as the BESS. The addition of a foam cushion could be considered to increase complexity of balance performance.

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THE ASSOCIATION OF JOINT POWER KINETIC VARIABLES WITH RUNNING INJURIES: A CASE CONTROL STUDY

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Background: There is conflicting data on which kinetic variables are important to consider with runners. Furthermore, less is understood regarding differences in these variables when controlling demographics. Our primary question is what joint power variables are different between healthy and injured runners.

Purpose: The purpose of this study is to identify if there are differences in joint power variables of healthy runners and injured runners.

Study Design: Case Control Study.

Methods: Joint power kinetic variables from the hip, knee, and ankle were collected from 122 runners (26 healthy and 96 injured) over three years with a Bertec force plated treadmill and Qualisys 3D motion capture. The injured runners performed gait analysis in conjunction with physical therapy care, and the healthy runners independently obtained gait analysis for injury prevention and performance goals. Further variables include age, sex, height, weight, BMI, foot strike, and speed.

A two sample T-test was used to compare means of joint power between healthy and injured runners. A logistic regression was used to create a model with the binary dependent variable being injury status of the runner. All alphas were set at .05. Normality of the joint power variables were assessed with Shapiro-Wilk, Kolmogorov-Smirnov, Histograms, and Q-Q Plots.

The predictive value of the logistic regression was assessed with the likelihood ratio of the global null hypothesis. Hosmer and Lemeshow Good-of-Fit test was referenced for fit statistics. Area under the ROC curve was given preference during model building, with R-Square adjusted used to compare models and R-Square values referenced for the final model to report total variation in injury status.

Results: There were no significant differences in the means of the peak joint power data between the injured and healthy runners when using a two-sample t-test. However, lower hip power absorbed was found to be associated with injuries (odds ratio, .16; 95% CI .025-.88) when considering demographics using a logistic regression model including categorical age, gender, BMI categories, speed, and power absorbed from the hip, knee, and ankle and power generated from the hip and knees. Ankle power generated was omitted secondary to multicollinearity. The area under the ROC curve was .74, which is considered acceptable discrimination. The R-Square was 9%, suggesting the model is only responsible for 9% of the total variation in the injury status versus a model with no variables. The only significant predictor of the variables included was hip power absorbed ($\alpha = .04$).

Discussion/Conclusion: When simply comparing the mean values of healthy and injured groups included in this study, there was no difference in joint power. When controlling for age, sex, BMI, foot strike, and speed with logistic regression analysis; lower hip power absorbed was found to be associated with the runners within the injured group of this study. This could be due to the hip muscles’ unique role in absorbing force during early stance phase and may warrant consideration in the context of running injuries.

The findings confirmed much of the previous understandings about running injuries, as they are multimodal with a proportion of the risk being associated with biomechanics. This study further identifies hip power absorbed as being associated with the runners within the injured group, possibly warranting a closer look. These results do not suggest that improving runners’ ability to absorb hip power would decrease their injury risk, it simply shows there may be an association.

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VALIDATION OF DIGITSOLE® PRO SMART INSOLES FOR TEMPORAL GAIT ANALYSIS
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**Background:** Inertial motion units (IMUs) are used to quantify biomechanical variables by capturing movement data relative to body segments. Physical therapists (PTs) are educated on performing gait analyses to identify specific patient gait deviations and devise intervention plans to improve function. While gait analysis is an important part of a physical therapist's initial examination, it may not be feasible to perform due to time and technology constraints, and the physical limitations of the patient. Smart insoles containing IMUs may be an alternative tool for PTs to measure gait parameters and identify potential gait deviations. Despite this seemingly convenient technology, previous validity studies are limited in sample size and data collection; therefore, further validation is necessary to support the clinical use of IMU insoles.

**Purpose:** The purpose of this pilot study was to compare the temporal gait parameters collected by IMU insoles (Digitsole Pro®, France) to the gold standard Noraxon® Ulti-tium Motion IMU (Noraxon, Scottsdale, AZ) biomechanical analysis system.

**Study Design:** Descriptive Pilot Study.

**Methods:** This study was approved by the FranU IRB. Temporal gait data were collected from 10 healthy individuals (mean 25 years old) during a 2-minute bout of over-ground walking at their self-selected speed using the IMU insoles and biomechanical sensors. Temporal data were processed using the respective technology software. Independent t-tests using a priori p < .05 were conducted to compare parameters simultaneously measured using the Digitsole and Noraxon IMUs.

**Results:** There was no significant difference between temporal parameters of cadence, stride, and swing duration on the right and left sides. A significant difference was observed during the specific phases of the stance portion of gait on both extremities (loading, foot flat, and propulsion phases).

**Conclusion:** In this small pilot sample, overall temporal variables were similar between the Digitsole and Noraxon IMU measurements; however, specific phases of the stance phase were not similar. Because the significant differences were consistent on each side, it is likely the timing of different phases of stance may not be calculated in the same way. Future research should include larger sample sizes, patient populations, and comparison of spatial parameters.

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KINEMATIC SEQUENCING OF THE FOOTBALL PASS USING INERTIAL MOTION ANALYSIS

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Background: The biomechanics of the overhead throw has been heavily researched in baseball players; however, little research exists on the biomechanics of quarterback passing in football.

Purpose. The purpose of this pilot study was to identify the kinematic sequencing of football quarterbacks using wireless inertial motion technology.

Study Design. Descriptive Study.

Methods. Eight healthy, right-handed, painfree quarterbacks (four high school and four collegiate) performed three dropback passes each at three increasing distances (nine total passes at 10, 20 and 30 yards) while wearing wireless IMUs (Noraxon, Scottsdale AZ) as part of their pre-season assessment. Each pass was synchronized to video; kinematic data in each pass were identified and marked with four points of interest: foot contact, maximal external rotation (ER), ball release, and maximal internal rotation. Data were analyzed with Noraxon MyoMotion 3.18.98 using a customized kinematic sequence algorithm to provide mean angles over 9 throws of each quarterback.

Results. Kinematic sequencing of the extremities revealed shoulder abduction and ER peaked respectively at 112 degrees and 134 degrees during acceleration, and decreased during follow-through. Elbow flexion ranged from 100 degrees to 17°, decreasing after the cocking phase. Knee flexion remained relatively consistent, ranging from 29 degrees to 46 degrees. The trunk remained relatively upright, generally leaning away from the throwing arm by two to nine degrees; however, quarterbacks experienced an average of 23 degrees of lumbar extension at maximal shoulder ER. The trunk initiated rotation with an average of 40 degrees to the right at foot contact, which reversed during the acceleration phase to a maximum of 21 degrees to the left. The pelvis followed a similar sequence, although the rotation of the pelvis toward the target began earlier in the cocking phase and generally faced the target for the remainder of the throw (2-6 degrees of left rotation). This sequence was seen in the hip-shoulder separation, which remained about 20 degrees, initially favoring right trunk rotation in cocking phase, but quickly reversed to 20 degrees favoring left trunk rotation in the follow-through. Minimal hip-shoulder separation (11 degrees) occurred at ball release.

Conclusion: This pilot study provided kinematic sequencing similar to previous video analysis studies and added insight into the hip-shoulder kinematic sequencing in football quarterbacks.

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DEEP GLUTEAL PAIN: WHEN MIXED NOCICEPTIVE AND NEUROPATHIC PAIN DRIVERS MASQUERADE AS PROXIMAL HAMSTRING STRAIN

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Introduction: Deep gluteal pain (DGP) is a common occurrence in outpatient physical therapy settings. Etiologies may include ischiofemoral impingement, piriformis syndrome, hamstring tendinopathy, hamstring syndrome, and lumbosacral radiculopathy. This case study uses the Pain and Disability Drivers Model (PDDM) to differentially diagnose and inform intervention.

Case Description: A 32-year-old female diagnosed with right hamstring strain, was referred to outpatient physical therapy. PMH included obesity with a BMI of 30, anxiety, depression, partial thyroidectomy. Her Global Health was 54%. PHQ-2 score was 0/6 and GAD-7 score was 1/21. No prior pertinent imaging was available.

Outcome: During the initial virtual examination, the patient stated her low back pain started four weeks prior with no known cause. The back pain had since resolved but she was now reporting pain localized to the right buttck, exacerbated by rolling in bed or transitioning from a seated to supine position. Symptoms were alleviated with standing or walking. Pain radiated down the posterior thigh terminating proximal to the knee. Initial NPRS reflected a pain score ranging from 1/10 to 8/10. She was taking 600 mg ibuprofen BID with minimal effect. Initial LEFS score was 69/80 (86%). Observation showed bilateral genu recurvatum and pes planus with a FPI-6 score of +4. Lumbar flexion was limited to 70% secondary to hamstring tightness. Lumbar extension was full and painless while return to standing elicited gluteal pain. Right lateral lumbar flexion generated mild discomfort in the right hamstring. Seated rotation caused mild discomfort in lumbosacral region. Quadruped position, backward and forward rocking elicited pain in the hamstring region. Hip ROM was WNL and painless. Mild weakness in the hamstrings was noted during supine bridging. Active SLR without a belt was 60 degrees on the R, limited by concordant pain, and 90 deg on the L. Physical exam revealed absent right ankle jerk reflex. Positive confirmatory tests: Seated Slump, Single Limb Chair Bridge, Puranen–Orava, Long-Stride Walking. Negative special test: Seated Piriformis Stretch Test. The differential diagnoses of hamstring tendinopathy and hamstring syndrome were considered. A plan of care was established to address impairments. HEP included eccentric hamstring strengthening and seated sciatic nerve glide.

Discussion: Initial PT treatment focused on hamstring tendinopathy, however due to limited improvement with conservative therapy, a request to the treating physiatrist was made for dedicated imaging after 4 visits. MRI results revealed a L5-S1 disc extrusion, a labral tear, mild tendinopathy in the gluteus medius and proximal hamstring muscles. A bony lesion of unknown clinical significance was identified in the posterior acetabulum, later characterized by an orthopedic oncologist as an enchondroma without cortical erosion, periosteal reaction, or soft tissue involvement. The patient was prescribed 100 mg Gabapentin at bedtime and topical lidocaine patches were recommended. She received a steroid injection into the right gluteus medius and hamstring muscles while continuing her physical therapy for a total of 19 visits over eight months. Final NPRS was 0/10, LEFS was 95%, and HOOS score was 100%.

Conclusion: Using PDDM, we constructed a radar plot to determine the primary drivers of pain and disability. Asymmetrical areflexia supported a neuropathic etiology while pain elicited with applied pressure supported a nociceptive determinant. Cognitive, emotional, and social factors played a minimal role in this patient's presentation; therefore, disability drivers were not investigated further.
Clinical impression: Red flag symptoms are divided into different classes. While some findings require immediate medical attention, others allow examination and initiation of care while dedicated physical therapy is continued. This case study demonstrates the importance of an interdisciplinary approach with effective communication and informed investigation. It underscores the importance of astute clinical reasoning as precautionary intervention measures are implemented.

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**EVALUATION OF QUARTERBACK THROWING MECHANICS: A SCOPING REVIEW**

**Foret W, Page P**

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**Background:** The biomechanics of a football quarterback's full-body throwing motion are understudied in comparison to baseball pitching mechanics. Although less common, quarterbacks can suffer from similar stress injuries as baseball pitchers. Understanding the throwing mechanics of quarterbacks may help guide prevention, performance, and rehabilitation programs.

**Purpose:** The purpose of this scoping review was to identify studies that analyzed and quantified the biomechanics (kinematics, kinetics, and electromyography (EMG)) of the throwing motion in football quarterbacks.

**Study Design:** Scoping Review.

**Methods:** A systematic literature search was performed in May of 2022 in the following databases: CINAHL, Medline, and SPORTDiscus. Boolean searches and terms included: "quarterback," "throwing," "football," and "biomechanics." The article inclusion criteria were studies that measured kinematics, kinetics, and/or EMG of football throwing mechanics. Exclusion criteria were (1) abstracts without full text; (2) literature reviews or Level 5 studies; (3) studies that did not include football quarterbacks. The selection and data extraction processes were performed by a single researcher following the PRISMA-ScR guidelines.

**Results/Discussion:** Six studies were included (four Level 3 observational studies and two Level 4 case studies). A total of 94 quarterbacks were analyzed within all selected studies; there were 23 high school, 36 college, 20 aspiring professionals, and 15 recreational male quarterbacks. The age range of the subjects was 15 to 32. Most cited biomechanical research on football throwing was from 3 studies completed between 1995 and 2002.3-5 Maximum angular velocity of elbow extension was reported to be between 1,280°/s and 1,760°/s while internal rotation was reported to be between 2,990°/s and 4,950°/s.1,5 Researchers2-6 have described between 3 to 6 phases to quantify the throwing motion amongst quarterbacks. One researcher analyzed ground reaction forces (GRFs) through the lower extremities during various drop-back steps ranging from 1024N to 1510N. All studies collected data using high-speed cameras and data acquisition systems (60 to 1000 Hz) both inside labs and outdoors using various drop-back steps and a range of throwing distances (4 to 30 yards), while one study completed two throws for max distance.

**Conclusion:** This review suggests that technological advances in biomechanical data collection and the progression of coaching and training necessitate an updated evaluation of quarterback biomechanics during throwing across multiple age groups, drop-back steps, receiver patterns and throwing distances. New technology such as wireless EMG and inertial motion units may provide updated biomechanical data in more realistic environments for football quarterbacks.

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INCORPORATING BOTH MODIFIABLE AND NON-MODIFIABLE FACTORS IMPROVE PROFESSIONAL BASEBALL PITCH INJURY NET BENEFIT COMPARED TO CURRENT BEST EVIDENCE-BASED PRACTICE

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Background: The best available evidence to guide pitching injury reduction has focused on evaluating each specific physical factor in isolation. Clinical prediction models have demonstrated the ability to account for the multi-factorial nature of injuries that can aid in clinical decision making. Clinical accuracy is an important step in developing improved clinical examination; however, these current analytical methods do not assess the true impact of clinical decisions on patient/team health outcomes. Net benefit can assess clinical impact of clinical decisions. Net benefit methodology can be used to assess an action by calculating the potential value and harm of the action on the same scale, allowing for a direct comparison. While calculating the net benefit of one particular injury threshold is important, within sport, injuries vary between different teams, competition levels, and individual pitchers. As a result, the net benefit of a prediction model must be analyzed over a range of thresholds through decision curves, allowing to evaluate the clinical decision impact at the organizational level.

Purpose: To determine if a clinical prediction model improves clinical decisions compared to current best evidence-based practice in minor league (MiLB) pitchers.

Design: Prospective cohort in MiLB.

Methods: A 10-year prospective injury risk study was conducted with MiLB pitchers. Pitchers were evaluated during preseason and pitches and arm injuries were documented prospectively. Preseason measures included shoulder internal, external, and horizontal adduction range of motion and humeral torsion using validated methods. Body mass index, arm injury history, professional experience, and arm dominance were also assessed. Pitches and arm injuries were documented throughout the season. A priori it was determined that 400 pitchers were needed to develop a multivariable prediction model. A logistic regression incorporating non-linear transformations was developed and internal validation was performed with elastic net and 10-fold cross-validation. Clinical decision analysis curves, which calculate net benefit, were performed with an a priori risk threshold of 15-30 percent based on published baseball injury rates and stakeholder involvement. Net benefit is calculated by (sensitivity - (1 - specificity)) * sample injury rate. Net benefit is interpreted on an additive scale, such that one point increase in net benefit is equivocal to properly identifying one more patient with the outcome without falsely misidentifying other patients that will not have the outcome as sustaining the outcome. The clinical net benefit was determined by comparing clinical decision curves between groups that treat all as high risk ("treat all"), all are at low risk ("treat none"), and 'risk profile' (TROM > 10 degree difference and HA < 0 degree).
**Results:** 407 MiLB pitchers (Age: 23.2 (2.4); BMI: 25.1 (2.3); Right-Handed: 83%; 141 arm injuries) participated. Arm injury incidence was 0.27 arm injuries per 1000 pitches. The prediction model demonstrated greater net benefit. At 20% risk, ‘treat all’ demonstrated 0.06, TROM 0.13, HA -0.01, and prediction model net benefit was 0.21. At 25% risk, ‘treat all’ demonstrated -0.25, TROM 0.04, HA 0.00, and prediction model net benefit was 0.07.

**Conclusions:** The multivariable prediction model demonstrated greater clinical net benefit compared to ‘treat all’ and ROM risk profiling for pitchers between 15-30% arm injury risk. Out of 100 pitchers, at 25% arm injury risk, the prediction model would improve injury identification by 3 pitchers compared to TROM risk profiling, and compared to ‘treat all’ that would intervene on all 100. While only modifiable factors can be intervened upon, these findings suggest including both modifiable and non-modifiable factors can improve injury risk assessment and clinical resource allocation compared to current evidence which assesses each risk factor in isolation.

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COMPARISON OF ADOLESCENT PITCHING ARM INJURIES OUTCOMES BETWEEN GROWTH PLATE AND SOFT TISSUE INJURIES

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Background: Non operative management led by supervised rehabilitation is the first line treatment advocated for adolescent arm injuries. However, there is very little evidence to guide a treatment approach including patient reported outcome (PRO) measures at the time of return to sport. While many patients are given region specific PRO, they not overly sport-specific and have demonstrated a ceiling effect in athletic populations. Sport specific scales such as the Functional Arm Scale for Throwers (FAST) is specific, but lengthy. In other populations the Single Assessment of Numeric Evaluation (SANE) has shown acceptable measurement properties, however it has not been evaluated in the throwing athlete.

Design: Retrospective Cohort.

Purpose: To compare region specific PROs, FAST and SANE scores at time of RTS for non-operative baseball pitchers following arm injury.

Design and Setting: Retrospective review of non-operative adolescent baseball players at time of RTS from a large outpatient orthopedic physical therapy clinic.

Participants: Adolescent baseball pitchers (15.0 + 1.9yo; 36 R handers; 175 ± 11.3 cm, 69 ± 14.3 kg), who completed non operative rehabilitation for either soft tissue (ST) or growth plate (GP) injuries were included for analysis.

Methods: Pitchers completed a region-specific PRO, either Quick Dash (DASH) for elbow or Pennsylvania Shoulder Scale (PENN) for shoulder injuries at the beginning and end of care. Additionally, at the time of RTS pitchers completed the FAST and SANE at the time of return to sport. A one-way ANOVA comparing age, visits, and outcome measures between injury types and body regions was performed (α ≤ 0.05). Pearson correlation coefficients were also assessed between region specific PRO, FAST and SANE scores at time of RTS.

Results: When comparing the 29 ST to the 11 GP injuries, pitchers with ST injuries tended to be older (15.3 ± 4 v 14.2 ± 5 years; P=0.10), taller (177 ± 11 v 169 ± 14 cm P=0.07), and heavier (72 ± 9 v 62 ± 10 kg P=0.05) than patients with a GP injury. Average visits 17.8 ± 7.9, PENN = 97% ± 10, DASH = 96% ± 14, SANE = 94 ± 8 and FAST 9% ± 9 scores were not different between groups (P>0.05). There was a moderate correlation between FAST and SANE scores (-0.53), but not region-specific PROs (0.20).

Conclusion: Adolescent pitchers who complete rehabilitation and return to sport require around 18 visits over 8-12 weeks to achieve normalized patient outcome measures. Interestingly, adolescents with GP injuries have greater disability at onset and experience lower region PROs at time of RTS even though their sport specific PRO and SANE are normalized. The SANE appears to provide a simple, reasonable approximation of pitcher function at the time of RTS in adolescent pitchers and is not influenced by arm injury location or type.

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ORGANIZATIONAL RISK PROFILING AND EDUCATION ASSOCIATED WITH REDUCTION IN PROFESSIONAL PITCHING ARM INJURIES: A NATURAL EXPERIMENT

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Background: Baseball has a high injury incidence, and these injuries continue to increase. The greatest injury incidence is to the shoulder and elbow, with pitchers having a higher injury incidence and prevalence than position players. One method to assess injury risk is through risk profiling. Risk profiling is defined as the ability to screen individuals and subsequently identify individuals at high risk for the outcome (i.e., injury). Within baseball, risk profiling has been performed, with shoulder range of motion used as the risk profile gold standard. However, despite the integration of injury risk profiling, education, and individualized interventions for high injury risk athletes, it is currently unclear how these strategies affect injuries in professional baseball pitchers.

Purpose: To evaluate the influence of risk profiling and education on arm injury incidence in minor league (MiLB) pitchers and to stratify by injury severity.

Study Design: Prospective natural experiment in MiLB.

Methods: A prospective natural experiment study was conducted from 2013-2019 on MiLB pitchers. Shoulder external (ER) and internal (IR), total range of motion (TROM), horizontal adduction (HA), and humeral torsion (HT) were measured in preseason and prospectively followed throughout the season for pitch count, pitching appearances, and injuries. Organizational risk profiling and education was implemented in 2015 based on preseason assessments. Shoulder IR ROM risk was defined as <= -15 degrees, shoulder ER ROM risk was defined as >= 15 degrees, shoulder TROM risk was defined as <= -10 degrees, and dominant shoulder HA risk as < 0 degrees. χ² were performed to investigate potential differences between shoulder ROM risk categories between the 2013-2014 (Pre) and 2015-2019 (Post) seasons. Interrupted time series analyses with quasi-poisson distributions were performed to assess the effect organizational risk profiling and education on arm injury in MiLB pitchers and repeated for 7 and 28 day injury severity. Sensitivity analyses were performed separately for elbow and shoulder injury, time to injury, and combined trunk and lower extremity injury.

Results: 297 pitchers (Age: 23.0 (2.2) years, Left Handed = 21%) were included (Pre: 119, Post: 178). Pitchers in the 2013-2014 seasons demonstrated less preseason shoulder injury risk for IR (P = 0.003) and ER (P = 0.007), while the 2015-2019 seasons demonstrated less HA risk (P = 0.04). There were no differences between seasons for TROM risk (P = 0.76). There was a significant adjusted time loss arm injury reduction for the 2015-2019 seasons (0.68 (95% CI: 0.47, 0.99)). Similar relationships were observed for 7 days (0.62 (95% CI: 0.42, 0.93)), but not for 28 days (0.71 (95% CI: 0.47, 1.06)). There was a significant decrease in elbow injuries for the 2015-2019 seasons (0.53 (95% CI: 0.30, 0.95), p = 0.034). There was no reduction in shoulder injuries for the 2015-2019 seasons (0.89 (95% CI: 0.53, 1.56), p = 0.690). There was no relationship between arm injuries time occurrence within the baseball season (1.07 (95% CI: 0.74, 1.56), p = 0.723). There was no reduction in

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combined trunk and lower extremity injuries for the 2015-2019 seasons (1.55 (95% CI: 0.79, 3.01), p = 0.204).

**Conclusion:** Organizational risk profiling and education appear to reduce professional pitching overall and 7 day arm injury risk by 33%-38% but not for 28 day injury risk due to the wide confidence intervals. These findings suggest that while injury risk increased over time, organizational risk profiling mitigated the expected increase in arm injury rates. Risk profiling and education can be used as a clinical screening and intervention tool to help decrease arm injuries in professional baseball populations.

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FORWARD FLEXION CAN RELIABLY BE MEASURED WITH A FRONT-FACING CAMERA USED FOR AT-HOME PHYSICAL THERAPY

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Background: Accurate assessment of shoulder range of motion (ROM) is important for both initial evaluation and evaluating the rehabilitation progress. Recently, digital platforms have been developed which assess ROM with the use of a front-facing camera available on smart phones. Such tools allow ROM to be objectively assessed and monitored remotely but require validation.

Purpose: The purpose of this study was to compare forward flexion (FF) measured with a digital health platform (PT Genie, Orlando, Fl) to in-office measurements with a hand-held laser-powered digital goniometer (Halo Medical Devices, Australia).

Study Design: Prospective Evaluation.

Method: Consecutive patients were evaluated in a single shoulder specialist’s practice. All participants completed 3 consecutive FF efforts measured first with a digital goniometer, followed by 3 consecutive FF efforts measured with the front-facing camera of a mobile device. All digital goniometer measurements were recorded by the same examiner. All measurements using the front-facing camera were obtained with an iPhone 11 running iOS 15.4.1, and the PT Genie platform. The mean from the 3 measurements was calculated and the mean differences between the two measurement options were then compared using the simple Student t-test. Analysis was completed using SPSS version 17 (SPSS Inc., Chicago).

Results: Thirty-two patients, including 16 males and 16 females, aged 58.5 ± 17.4 years (range 24-80) participated in the study. For both the digital goniometer and front-facing camera groups there were no significant differences within the 3 measurements. Mean FF measured with the digital goniometer was 120.1° ± 24.7° (range 71.7° - 164.7°) compared to 123.5° ± 26.0° (range 74.7° – 173.0°) with the front-facing camera, for a difference of 3.4° between groups (p<0.001).

Discussion/Conclusion: The findings from our study suggest that measurement of shoulder Forward Flexion is comparable between a handheld digital goniometer and a digital application front-facing camera. While small differences were seen between the methods, the differences are not likely clinically relevant, and more importantly the findings were internally consistent. These preliminary findings help in establishing the use of such an application for remote physical therapy. Further study is needed to assess other planes of range of motion and obtain data in a larger cohort.

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AT-HOME PHYSICAL THERAPY WITH A REMOTE MONITORING DIGITAL HEALTH PLATFORM LEADS TO SIMILAR PATIENT REPORTED OUTCOMES COMPARED TO TRADITIONAL IN-OFFICE PHYSICAL THERAPY FOLLOWING SHOULDER SURGERY

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Background: Physical therapy (PT) following shoulder surgery has traditionally occurred via in-office supervised visits. Recently digital health tools with remote patient monitoring (RPM) have emerged as an option to enhance the ability to both monitor and encourage engagement of home PT. The appeal of such tools has been accelerated by the impact of COVID-19 on the healthcare system.

Purpose: The primary purpose of this study was to compare patient-reported outcomes (PROs) following shoulder surgery of patients who completed at-home PT with a digital rehab application to patients who completed in-office supervised PT. The secondary purpose was to assess engagement among patients who used digital PT.

Study Design: Retrospective Review.

Methods: A retrospective matched comparative evaluation was performed of patients who underwent arthroscopic shoulder surgery or shoulder arthroplasty at a single institution between April 2020 and May 2021. Patients who underwent home-based physical therapy with a digital remote monitoring platform (PT Genie; Orland, FL) were identified and age and procedure matched (arthroscopy or arthroplasty) to a cohort of patients that underwent in-office physical therapy. The digital platform provided remote monitoring capabilities with measurement of range of motion. PROs measured preoperatively and at 1 year postoperative included visual analogue scale pain score (VAS), American Shoulder Elbow Surgeons Score (ASES), and Single Assessment Numeric Evaluation (SANE). Engagement measured as the number of sessions recorded was analyzed in the digital PT based on 6 age groups (≤40, 41-50, 51-60, 61-70, 71-80 and 81+). Statistical analysis using the student t-test to compare means was performed using SPSS version 17 (SPSS Inc., Chicago).

Results: A total of 862 patients were identified, included 396 arthroscopic surgeries (198 in each PT group) and 466 in the arthroplasty group (233 patients in each PT group). The groups were similar at baseline other than a higher preoperative ASES score in the digital PT arthroplasty group. The ASES score for the PTG-arthroplasty group was 44.5 and for the non-PTG group it was 39.0 (p=0.002). There was no significant difference in any PROs between the two groups at 1 year follow up. The highest engagement in digital PT group was observed in the arthroplasty group and over the age of 50.

Discussion/Conclusion: In conclusion, there appears to be no difference in PROs following shoulder surgery whether physical therapy is performed in-office or at home via a digital platform with remote patient monitoring capabilities. Interestingly, engagement with digital PT was highest in older patients, suggesting that the technology is not a large barrier. Although further study is needed to confirm these findings, benefits of digital PT with remote monitoring may include: 1) Decreased cost for the healthcare system, 2) Decreased travel time for the patient, and 3) Scheduling efficiency and improved access to the PT for the patient.

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<td>With InternalBrace (in weeks)</td>
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