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Contact Information
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6011 Hillsboro Pike
Nashville, TN 37215, US,
http://www.ijspt.org

IJSPT is a bimonthly publication, with release dates in February, April, June, August, October and December.

ISSN 2159-2896

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SCAN AND LEARN MORE AND APPLY TODAY
Disparities in research publications are common in the physiotherapy and rehabilitation fields. A small proportion of published research arises from low-income and middle-income countries (LMICs), home to 85% of the world's population. Systems-level, institutional-level, and individual-level factors contribute to these disparities. With urgent and unified actions, global health and the standard of physiotherapy research in LMICs can be improved and strengthened. In this editorial, we will discuss the challenges encountered by researchers from LMICs in conducting and publishing high-quality research and propose potential strategies to address these challenges.

**Background**

LMICs are defined as countries with a cumulative annual gross national income per capita of $13,205 USD or less (Table 1, next page). Many LMICs have a higher prevalence of injuries and long-term conditions requiring rehabilitation services compared to...
high-income countries. Despite the greater disability burden in LMICs, the quality and quantity of research conducted in these countries is underwhelming. For example, despite being ranked as the number one cause of disability, low back pain lacks primary data from many LMICs.

LMICs have different research priorities than high-income countries. Compared to high-income countries, LMICs often have underdeveloped and resource-limited health systems and different disease burdens, with research only starting to catch up. Because of between-country/culture differences in illness beliefs and coping strategies, research from high-income countries, where most evidence is generated, may not apply in LMICs. In other words, interventions developed using resources and clinical populations in high-income countries may not be culturally appropriate or feasible in LMICs.

For example, education, a commonly recommended intervention for chronic health conditions, is influenced by the patient’s socioeconomic and cultural characteristics. This warrants significant cultural adaptations of healthcare interventions when used in different health settings/systems. Given that there is limited local research on many clinical conditions, clinicians in LMICs are left to rely on research from high-income countries for patient care. Although the need for high-quality research to address local research gaps has been frequently highlighted, research publications from the LMICs remain limited.

### Barriers related to conducting high-quality research in LMICs

While LMICs may share some common barriers to conducting and publishing research with high-income countries, some challenges are unique to...
Many LMICs do not prioritise research, which results in a lack of research funding, no research culture, limited awareness of research, and no research workforce. LMICs rarely include research in their national budget. Awareness about research is lacking at all levels and therefore health professionals, academic staff, and the general public have little to no understanding of research. School and university curricula also lack a research focus.

Academic institutions do not offer adequate research support to their staff and students, who lack research training, ongoing mentorship, research resources and infrastructure, including but not limited to access to online databases, reliable internet access, secured computers, and statistical software. Unfair expectations are imposed on academic staff to generate research productivity without dedicated research hours and administrative support (e.g., research assistants). For example, publishing two to three original research papers (or more) is commonly expected in three years for academic promotion. In a survey of researchers from 27 African countries, lack of dedicated research-related roles was the most common barrier identified, reported by 48% of the respondents.

Barriers/threats to publishing research from LMICs

Barriers to publishing research are linked with the barriers to conducting research described above. One widely known barrier is the language barrier. Writing academic papers can be daunting, especially when writing in a non-native language. Researchers in LMICs who do not speak English as their first language find it especially challenging to write journal articles in English. They also lack local support to improve their writing skills.

The second barrier is related to, as alluded to earlier, the differences in research priorities in LMICs and high-income countries. Many international journals lack geographic diversity in their editorial boards. As a result, the manuscript handling editors (and reviewers) lack adequate understanding of the local research contexts and the need for studies in LMICs when looking from their own lenses of research priorities in high-income countries. Finding reviewers who understand local research contexts is also challenging, further complicating the editorial decision.

Third, researchers in LMICs are frequently the targets of predatory publishers. As a consequence, researchers from LMICs publish their work in “predatory” journals. The researchers see predatory journals as “low-hanging fruit,” despite costs associated with publication, because the publishing requirements are easier to meet while the publication process is often swift, as opposed to (international) peer-reviewed reputable journals.

Lastly, some editors/reviewers of international peer-reviewed journals deem research from LMICs to have local relevance and impact only, and therefore flag them as more appropriate for local journals. The major problem with this is that most local journals are not indexed and are therefore often undiscoverable through traditional databases (e.g., PubMed). Publishing in these non-indexed local journals contribute to duplicate research and therefore research waste. For example, 75% of research on clinical pain in Nepal was published in local journals with duplicate and redundant research. The international research community should facilitate research from LMICs so that this research can make both local and international impacts. The barriers to conducting high-quality research in LMICs and publishing them are summarised in Figure 1 (next page).

A Call to Action

Urgent actions can help address key barriers to conducting and publishing research in LMICs. The barriers to conducting and publishing high-quality research from LMICs with potential solutions are presented in Table 2.

What can researchers from LMICs do?

Early career researchers may initiate collaborations with experienced local and international researchers with shared interests. Experienced researchers may extend mentorship to junior researchers both locally and internationally, serve
on a journal editorial board, and volunteer to review papers.

**What can international journals do?**

International physiotherapy journals are in a strong position to support and promote physiotherapy research in LMICs, especially through the leadership of the International Society of Physiotherapy Journal Editors.

First, journals should consider equity, diversity, and inclusion within the editorial board—not only in terms of gender and race but also diversity based on national economies. Editors who understand local research contexts are better able to make informed editorial decisions. Where possible within the scope of the journal, editorial decisions should be made considering research priorities from the originating country and the impact of the research there. This will assist with providing strong research foundations for LMICs.

Second, editors should also prioritise recruitment of reviewers with research experience in LMICs, preferably from the same countries where the research was conducted. Editors may also request specific feedback regarding whether the study methods are appropriate for the local context.

Third, journals may provide additional support to authors from LMICs. This may include providing additional assistance in editing, proofreading, or responding to peer reviewers.

Journal websites may provide specific guidance to authors with limited publishing experience, such as links to resources for conducting and writing research. Journals may also offer current and prospective authors Massive Open Online Courses (MOOC) on research and academic writing, with the content targeted at authors from LMICs. Alternatively, paid workshops might be offered with a waiver for participants from LMICs.

A final strategy to consider is that publishers/journals may guide authors who need mentorship to a list of volunteer mentors. The journal manuscript submission platform could include a button to click if the author is looking for a mentor or willing to mentor. The extent of mentorship could vary from proofreading the current paper, to analysing data, assistance in writing a paper, to mentoring the development of a research question. The latter can especially be valuable for many, as journal editors frequently encounter research with poorly developed research questions and flawed research methods. With these problems, even the most supportive editors cannot help as it is too late to help. One initiative to support early career researchers is
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<th>Barriers</th>
<th>Proposed solutions</th>
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</thead>
<tbody>
<tr>
<td>Barriers to conducting research</td>
<td>Lack of research priority</td>
<td>• Government and academic institutions should prioritise research and develop a research priority agenda for common health conditions.</td>
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<td>• Funding should be allocated towards addressing these research priorities.</td>
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<td>Research awareness and education</td>
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<td>• Research should be introduced early in school and during undergraduate education.</td>
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<td>• The importance of research should be spread to the public.</td>
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<td>• But academic institutions and clinical settings (e.g., hospitals) should emphasise the importance of both conducting and using research for improving healthcare.</td>
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<tr>
<td>Research funding</td>
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<td>• Government and universities should allocate a defined proportion of their budgets into research.</td>
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<td>• Research scholarships should be awarded for postgraduate degree and postdoctoral fellowships.</td>
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<td>Lack of institutional support</td>
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<td>• Universities should support researchers.</td>
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<td>• Full-time and part-time research roles should be created so that researchers can commit their time and focus on conducting high-quality research.</td>
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<td>• Academic staff should be allocated research hours to allow dedicated research time.</td>
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<td>• Intuitions should also favorably appraise high-quality research over any research.</td>
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<tr>
<td>Lack of research workforce</td>
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<td>As above, both government and universities should support full-time and part-time research roles to develop research workforce and high-quality research skills.</td>
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<tr>
<td>Lack of research training</td>
<td></td>
<td>Government and universities should promote high-quality research training. They should also promote local and international research mentoring as well as collaborations across fields.</td>
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<tr>
<td>Barriers to publishing research</td>
<td>High editorial bar for international journals</td>
<td>• Journals could offer special editorial support to authors from LMICs.</td>
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<td>• International collaborations or mentorship could help with the publication process.</td>
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<td>• Appointing editors and reviewers who understand local research priorities and contexts are better able to make informed judgement about the need for the research and its potential impact.</td>
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<tr>
<td>Language barrier</td>
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<td>• Proofreading of the final manuscripts by Native English-speaking collaborators and journal editorial board members could address language barriers related to publishing in an international journal.</td>
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<td>• AuthorAID (<a href="https://www.authoraid.info/en/">https://www.authoraid.info/en/</a>) connects researchers from LMICs to the international community. Mentors and mentees can connect through the AuthorAID program.</td>
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Predatory publishing

- Frequent webinars around publishing in the right journals should be offered.
- Government, funding bodies (if present), and institutions should emphasise publishing in credible journals.
- Authors should think critically about the credibility of the journals they submit to, drawing on resources like Think, Check, and Submit (http://thinkchecksubmit.org).

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available through AuthorAID (https://www.authoraid.info/en/). Authors may choose to be listed as a mentor or a mentee and provide or receive mentorship at various stages of research including planning, analysis, writing, editing, and proofreading. Strategies to promote high-quality research in LMICs are summarised in Figure 1.

“Bright Spot”
Despite several significant challenges, research with wide-scale implications has started to arise from LMICs which addresses local health research priorities.8, 13-15 Some prominent journals in physiotherapy, pain, science, and medicine have already started to identify the importance of equity, diversity, and inclusion in health research which is likely to make a meaningful impact in promoting research from LMICs.16-20 Selected publishers also waive publication fees for authors from LMICs to assist in open-access publishing.

Conclusion
Local research in LMICs is necessary to advance science and improve patient care in these settings. However, researchers in LMICs face several unique challenges to conduct and publish their research internationally. The International Society of Physiotherapy Journal Editors and member journals support research from the LMICs in order to improve the health and lives of the 85% of the world's population that lives in LMICs.

References


18. Mccambridge AB, Elkins MR. If we can’t see race and ethnicity in research, how will we see racial inequality? *J Physio*. 2021;67(2):82-83.


Clinical Viewpoint

Ligament Healing After Anterior Cruciate Ligament Rupture: An Important New Patient Pathway?

Florian Forelli1,2,3, Jérôme Riera4, Jean Mazeas1,2, Claire Coulondre1,2, Sven Putnis5, Thomas Neri6,8, Alexandre Rambaud7,8,10

1 Orthosport Rehab Center, 2 Orthopedic Surgery Department, Ramsay Healthcare, Clinic of Domont, Education, Functional Exploration and Clinical Research unity, 3 SFMKS-Lab, Société Française des Masseurs-kinésithérapeutes du Sport, 4 University Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology, University Jean Monnet Saint-Etienne, 5 College of Health Sciences, University of Bordeaux, 6 Sports Orthopedics and Traumatology Center, 7 Avon Orthopaedic Centre, University of Bristol & Weston NHS Foundation Trust, 8 University Jean Monnet Saint-Etienne, Lyon 1, University Savoie Mont-Blanc, Inter-university Laboratory of Human Movement Biology, 9 Department of Orthopaedic Surgery, University Hospital of Saint Étienne, 10 Department of Clinical Physiology and Exercise Sports Medicine Unit

Keywords: anterior cruciate ligament, spontaneous healing, management, risk, return to sport

Recent studies have shown satisfactory functional results after spontaneous healing of a ruptured anterior cruciate ligament (ACL). However, current literature on this topic may exclude important parting selection, outcome measures, and long-term results. Rehabilitation protocols applied in those studies, as well as objective assessments appear far from the usual gold standard after ACL reconstruction. Ideally, outcomes measures should be based on the same testing procedures that are recommended to clear an athlete to return to sport following ACL reconstruction. There is still a lot to understand in how an injured ACL may heal, and therefore ACL injury management should be individualized to each patient and carefully discussed.

INTRODUCTION

In the last few years, non-operative management after anterior cruciate ligament (ACL) injury has gained a lot of popularity and surgery may not always be recommended. Specific criteria such as age, desired sport and work activities, intensity of sporting activities and associated lesions might be able to inform patients and practitioners on the possibility of non-operative management. A battery of functional tests and Patient Reported Outcomes Measures (PROM) have been shown to identify patients who might respond well to conservative treatment (copers) versus those who might not (non-copers).

In parallel to studies focusing on outcomes without ACL reconstruction, there is emerging evidence that the ACL may spontaneously heal offering similar perceived quality of life and sport participation than patients with reconstructed ACL in the long term. Within this context, a review of this new literature is necessary to best inform patients of the options available to them.

WHAT DETERMINES WHETHER AN ACL CAN HEAL?

It is well documented that the ACL attempts to heal, and a decrease and reduction in tibial translation may be observed in some patients. However, the process of healing is not considered optimal; the ACL may not heal onto the anatomical femoral attachment, and different patterns of scar formation may influence ligament length and subsequent knee stability. In a retrospective study, Costa Paz et al. demonstrated the possibility of ACL healing using magnetic resonance imaging (MRI). It should be noted that two patients over fourteen had a re-injury (and needed a reconstruction) and 50% had knee-related deficiencies on clinical examination (Lachman and pivot shift tests). These results are similar to Fujimoto et al. who showed that 26% of patients with a hypothetical ACL healing (MRI and KT-2000 arthrometer were performed) had to subsequently undergo reconstruction. Recently, a secondary analysis of the KANON trial showed that within the non-reconstructed group, those who were considered to have healed ACLs based on MRI findings, had better functional scores than the rest of the non-reconstructed group as well as the ACL reconstructed group at 2 years follow-up. These results may challenge current clinical practices and management of ACL injury. However, the term "healed" should not only
refers to ACL's fibers continuity observed on MRI but also to functional recovery. The "healed" ligament may have different mechanical properties than the original. This could explain why within the healed ACL group 25% had an abnormal pivot shift test, 56% had an abnormal Lachman's test and an increased tibial translation was observed in laximetry testing.

As highlighted in a recent systematic review, studies on this topic are of low quality and there results could not lead to a reliable and generalizable conclusion. This review also pointed out that healing capacity of the ACL may be dependent on the rupture's location and the conservation of the sheath of the ACL. Proximal ruptures having more chance to heal than distal ruptures. Another important factor observed by authors was that in many included studies rehabilitation protocols were not detailed. Rehabilitation protocols are different and have the potential to alter the outcomes between groups in studies. For example, Razi et al. recommended from the first week of injury to perform active range of motion out of brace, isometric quadriceps exercise, close kinetic chain exercise based on each individual's pain tolerance, and stationary biking from the third week. In patient with valgus knees, they delay weight bearing until 6 weeks. During the acute phase Fujimoto et al. allowed early range of motion and quadriceps muscle strengthening exercises with a brace that had a 20° initial range of motion restriction. Weight-bearing was also allowed, as tolerated, with crutches initially. Full weight-bearing without the use of crutches was generally achieved within 4 weeks after the trauma. According to Jacobi et al., full weight bearing was allowed from the start of the treatment. Range of movement to the extent possible in the brace was allowed, giving patients a range of flexion of about 0° to 100°. Removal of the brace was allowed in 90° of knee flexion (sitting position) without quadriceps contraction. With the knee in flexion it was also the recommended position to take a shower. After four months, the brace was removed and exercises and physiotherapy were started to aid the recovery of muscle strength and full mobility. Sporting activity, including cutting and pivoting, was allowed after six months.

According to Blanke et al. ACL healing happened in low-demand patients with femoral single bundle lesions without increased posterior tibial slope. In general, evidence is lacking regarding which criteria may indicate whether ACL healing is possible after an injury. The healing process of the ACL is still poorly understood, and it is difficult to know which patients are likely to have a healed ACL. It is also questionable whether some ACLs healing are not confused with ACLs scarring to the posterior cruciate ligament. This may happen in studies using MRI outcomes instead of an arthroscopic assessment which is the gold standard for ACL rupture.

FUNCTIONAL KNEE BRACE MANAGEMENT

To support ACL healing, some current protocols propose functional bracing management for periods of up to 12 weeks. Fujimoto et al. showed that functional bracing management can help ACL healing but in a population with low intensity of physical activity. Functional bracing management seems to reduce ACL strain, which may improve the healing process. More recently, a case series in which they immobilized patients at 90° ok knee flexion for four weeks after ACL injury was published. The purpose was to diminish the distance between the origin and the insertion of the ACL to favor the healing process. They obtained interesting result with 90% of patients showing signs of ACL healing at 5 months post injury (MRI and Lachman test). However, 50% were classified as grade 2-3 on the ACL Osteoarthritis Score which may be indicative of a non-functional ACL explaining significantly lower scores of this group on the ACL-Quality Of Life score.

It is to remember that current guidelines do not recommend functional bracing management after ACL injuries or ACL reconstruction. Strict bracing, as used in the case series study, can lead to knee joint disuse, which may alter muscle activation, spinal excitability and intrarticular inhibition. The role of functional bracing on postural control is not clear either. Birmingham et al. concluded that functional bracing may improve performance during simple tasks but not during more functional or daily living tasks. From a broader perspective, a systematic review looked at the effect of functional bracing on patient-reported outcome measures and functional outcomes. No difference was observed between patients who wore a knee brace after ACLR and those who did not.

Overall, there is very limited evidence that functional bracing influences ACL healing or is of any benefit for the patient and wearing a brace for a prolonged period may have undesirable effects.

RETURN TO SPORT AND SPONTANEOUS ACL HEALING

Filhay et al. presents the most advanced study in terms of objective results on spontaneous ACL healing with their secondary analysis of the KANON trial. Two-year outcomes were better in the healed ACL group (n=16) compared with the non-healed group (n=14) (mean difference 95% CI; KOOS-Sport/Rec: 25.1 (8.6-41.5); KOOS-QOL: 27.5 (13.2-41.8)). It is to notice that the battery of tests used in this study (KOOS-Sport/Rec, KOOS-QOL, KOOS pain, KOOS symptoms, Tegner Activity Score, KT-1000, Lachman and pivot shift tests, radiography) does not correspond to validated return to sports evaluations found in the current international literature, and KOOS subscales use as outcome measure in this study has been shown to be of poor responsiveness for patients with ACL injury. Objective data on muscle strength, functional tests and the psychological aspects of return to sport are lacking. Regarding the level of activity, authors recorded a mean pre-injury Tegner score of 8, which corresponds to high-intensity activity level. Unfortunately, they didn’t compare Tegner scores from the 2 and 5-year follow-up between healed and non-healed group. Similarly, the addition and comparison of a
pre- and post-Marx activity scale would have provided information on the homogeneity of the groups in terms of their involvement in pivoting sports, which are responsible for most ACL injuries. It should also be noted that professional athletes were excluded from this study. It is therefore impossible to extrapolate the results to this specific population.

Patients’ perceived function is very well represented in their study and it is a fundamental aspect of treatment’s success. However, the authors may not have chosen the most appropriate questionnaire to assess this aspect. Future research also needs to include more objective data on strength, function, and psychological aspects. This is especially true for populations involved in pivoting activities with a high level of intensity. To date, there is a lack of evidence regarding return to sport, especially at the elite level, after ACL ‘healing’ and too much uncertainty to recommend this type of protocol.

CONCLUSION

Different options to treat patients with an ACL rupture exist. Non-surgical options may not be suitable for every patient and should be taken with extreme caution and truthfully discuss with the patient and within the medical team. There is evidence that conservative treatment can be successful in the general population, with some people healing their ACL. This is not the case for elite athletes. The emerging evidence regarding the ability for the ACL to heal is intriguing and may change clinical practice in the future, but we urge clinicians to take these results with extreme caution as this may only be suitable for a very small percentage of the population. Much more research is needed before recommendations for this option can be generalized.
REFERENCES


Biomechanical Basis of Interval Throwing Programs for Baseball Pitchers: A Systematic Review

Travis Dias¹, Benjamin G. Lerch², Jonathan S. Slowik³, Kevin E. Wilk¹, James R. Andrews¹, E. Lyle Cain¹, Glenn S. Fleisig⁴

¹ University of South Carolina School of Medicine Greenville, ² Auburn University, ³ American Sports Medicine Institute, ⁴ Champion Sports Medicine

Keywords: elbow, pitching, shoulder, Tommy John Injury, varus torque

Background
Interval throwing programs are used in rehabilitation of throwing injuries, especially ulnar collateral ligament injuries. Athletes who are rehabilitating begin by throwing on flat ground progressing through increasing distances, number of throws, and intensity of throwing. If the athlete is a baseball pitcher, the flat-ground throwing phase is followed by pitching on a mound at progressively increased effort. The goal is to build back arm strength and capacity with an emphasis on proper mechanics.

Purpose
To determine whether interval throwing progressively builds joint kinetics (specifically, elbow varus torque) to the level required during full-effort baseball pitching. A secondary purpose was to examine the kinematics produced during interval throwing compared to those seen during baseball pitching.

Study Design
Systematic Review

Methods
Following PRISMA guidelines, PubMed, Embase, Web of Science, SPORTDiscus, and Google Scholar were systematically searched for biomechanical studies of flat-ground throwing and partial-effort pitching in baseball between 1987 and 2023. Studies that reported the biomechanics of either flat-ground throwing, or partial-effort pitching were included in this review. The AXIS tool was used to assess study quality.

Results
Thirteen articles met the inclusion criteria. Ten studies were determined to be of moderate quality, while three studies were deemed high quality. Elbow varus torque during partial-effort pitching was less than during full-effort pitching. Elbow varus torque for most flat-ground throws did not exceed full-effort pitching torque. While most studies showed increased elbow varus torque with increased flat-ground throwing distance, the distance at which elbow varus torque matched or exceeded full-effort pitching elbow varus torque was not consistent. As flat-ground throwing distance increased, shoulder external rotation angle and shoulder internal rotation velocity increased. Arm slot (forearm angle above horizontal) decreased as flat-ground throwing distance increased. For varied effort pitching, shoulder external rotation angle, shoulder internal rotation velocity, elbow extension velocity, and ball velocity increased as effort increased. While the front knee extended slightly from

References

¹ Corresponding Author:
Jonathan Slowik
American Sports Medicine Institute, Birmingham, AL, USA
jonls@asmi.org
foot contact to ball release in full-effort pitching, the front knee flexed slightly during partial-effort pitching.

Conclusions
An interval throwing program progressively builds elbow varus torque up to levels produced in full-effort baseball pitching. While differences exist between interval throwing kinematics and pitching kinematics, the patterns are similar in general.

Level of Evidence
2

INTRODUCTION
Baseball continues to grow in popularity throughout the United States and worldwide. In fact, nearly half a million athletes participate in baseball at the high school level alone.1 At the collegiate level, there was a 32% increase in participants between 2004 and 2019.2,3 With the growing number of participants, sport specialization, increased ball velocity during pitching, and the use of weighted balls during training, baseball throwing injuries and required surgeries have risen dramatically.3,4 Elbow surgeries, such as ulnar collateral ligament surgery ("Tommy John Surgery"), have seen a disproportionate rise with studies reporting two to sixfold increases in performed procedures.4,5,6

When a baseball player suffers a throwing-related injury, the subsequent rehabilitation process typically involves completing an interval throwing program to return to sport.10,12

Interval throwing programs are designed to systematically build strength, flexibility, and endurance to ensure a safe return to play while protecting post-surgical structures.10,11 The intensity of the throws and the quantity of throws are carefully monitored and gradually increased. An interval throwing program typically begins with an athlete throwing on flat ground (also known as "long-toss"), typically at a distance of 9 or 14 meters (30 or 45 ft), and incrementally progresses until the athlete can throw 37 m (120 ft) without pain.10,11,13 If the player is a position player, they continue the flat-ground throwing program until they reach 55 m (180 ft).13 If the player is a pitcher and can throw 37 m without pain, they transition to pitching from the mound at the standard pitching distance of 18.44 meters (60.5 feet). Pitchers begin pitching from the mound at 50% intensity, progress to 75% intensity, and eventually to 100% intensity, provided they do not experience any pain while doing so.10,15

There are instructions, assumptions, and implications about throwing biomechanics in the interval program relative to pitching biomechanics.10,11 Instructions for interval throwing programs emphasize proper throwing biomechanics utilizing coordinated movements of the legs, trunk, and arms.13,14 Improper biomechanics may decrease performance (i.e. fastball velocity) or increase risk of injury (i.e. joint kinetics).14,15 Elbow varus torque is a key kinetic parameter as it is related to risk of UCL injury.16,17 Theoretically, if an athlete attempts to throw at a longer distance or greater effort than for which he is ready, he may alter his kinematics, thereby increasing the kinetics and injury risk to his elbow and shoulder.

Several authors have reported the biomechanics of throws used in interval throwing programs, such as flat-ground throws and/or partial-effort pitching.12,18-27 However, there have been no systematic reviews examining the biomechanics that occur during interval throwing programs. The purpose of this review was to determine whether interval throwing progressively builds joint kinetics (specifically, elbow varus torque) to the level required during full-effort baseball pitching. A secondary purpose was to examine the kinematics produced during interval throwing compared to those seen during baseball pitching.

METHODS
This systematic review was completed according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) guidelines.28 An electronic, manual search of literature published between 1987 and 2023 was conducted by searching PubMed (which included Medline), Embase, Web of Science, and SPORTDiscus using search terms relating to upper extremity rehabilitation and interval throwing programs in baseball (Appendix A). The same search terms were used for all databases.

Two investigators (T.D. and B.L.) independently screened the resulting article titles and abstracts to identify records to be considered for full text review. In the case of disagreement, articles were discussed until a consensus was reached or the senior author (G.F.) was consulted for resolution. Next, the two investigators (T.D. and B.L.) independently screened the full text articles for inclusion in the systematic review; the senior author (G.F.) was once again consulted in case of disagreement. Eligible articles were included in this review if they were published in the prior 35 years, peer-reviewed, and included biomechanical data of baseball throws used in interval throwing programs, specifically flat-ground throwing and/or partial-effort pitching from the mound. Exclusion criteria were review articles, case reports, commentaries, technical notes, or studies that only evaluated subjects who were not baseball players. The references cited within the identified studies were also screened to discern additional articles that were not identified in the literature search. A supplementary search of “interval throwing program biomechanics” was performed on...
Google Scholar in which the first 100 search results were screened to identify any articles that may have been missed by the databases search. The entire search process in accordance with PRISMA guidelines. Additional data were requested and received via personal communication with the authors of one study.

QUALITY ASSESSMENT

Two authors (T.D. and B.L.) used the AXIS tool to assess the quality of each included study. The AXIS tool uses 20 Yes-No questions that assess the aims, methods, results, and conclusions reported in each study: A score greater than or equal to 75% is considered high quality. A score of 60% - 70% is considered moderate quality. A score below 60% is considered low quality.

RESULTS

The search of PubMed, Embase, Web of Science, and SPORTDiscus revealed 2985 articles (Figure 1). After removing duplicates, 1105 articles remained.

The supplementary search on Google Scholar revealed one additional journal article and one additional conference abstract that qualified for inclusion. After reviewing titles and abstracts, 85 articles remained for full-text review. Of the 85 articles, 75 were excluded, with 12 articles qualifying for inclusion. After reviewing the references of the 12 included articles, one additional record was identified that qualified for inclusion. In total, 11 journal articles and two conference abstracts qualified for inclusion in this review. Ten studies (77%) were determined to be of moderate quality, while three studies (23%) were deemed high quality (Table 1). No studies were scored as low quality. The mean AXIS score was 14±0.8 (70±4%) which indicates moderate quality for the 13 studies included. Table 2 provides details of all included studies.

Of the 13 studies, six,12,18,20,24,27,30 used optical motion capture while the other seven utilized inertial measurement unit (IMU) sensors.19,21-25,26,31 The majority of studies in this review investigated either high school pitchers, college pitchers, or a mix of both. Three studies investigated only high school pitchers;22,25,27; three studies investigated only college pitchers;12,18,25; five studies had a mix of high school and college pitchers;19,21,26,30,31; and one study had a mix of college and club (i.e., recreational), and one minor league pitcher.20; and the final study investigated professional pitchers.24 It should be noted that Leafblad et al.21 and Melugin et al.26 used the same group of subjects for their studies but investigated different aspects of interval throwing programs.

FLAT-GROUND THROWING KINEMATICS

Ten of the 13 studies investigated kinetics of flat-ground throwing. Nine of these investigated varying distances, while Melugin et al.26 looked at varied efforts at 37 meters. Fleisig et al.30 only evaluated the biomechanics of flat-ground throwing at 18 meters as part of an investigation into the biomechanics of weighted ball throwing. As shown in Figure 2, most included articles demonstrated that elbow varus torque increased as distance increased for most studies, while Slenker et al.20 and Wight et al.25 found different trends. Slenker et al.20 reported greater torque during 18m and 27m throws without a crown hop compared to their 57m and 55m throws with crow hop. Wight et al.25 found no differences in elbow varus torque across throws of 27, 37, 46, and 55 meters.

FLAT-GROUND THROWING KINETICS

Eight studies investigated the kinematics of flat-ground throws as commonly used in an interval throwing program,12,21-25,30,31 while Melugin et al.26 investigated kinetics of varied effort flat-ground throwing. Kinematics of flat-ground throwing and full-effort pitching from a mound are presented in Table 3. Stride length was consistently shorter during flat-ground throws in comparison to full-effort pitching.12,24,30 Values for foot position at foot contact were also lower during flat-ground throwing, suggesting that pitchers step more to the closed side when pitching than during flat-ground throwing.12,30 Additionally, upper trunk tilt was greater (more "uphill") in flat-ground throwing than in pitching.12,30

All seven studies that recorded maximum shoulder external rotation across multiple flat-ground throwing distances showed that maximum shoulder external rotation increased as flat-ground throwing distance increased.12,21-25,31 Similarly, all seven studies also found increasing shoulder internal rotation velocities (or "arm speed") for studies that used an IMU as flat-ground throwing distance increased.12,21-25,31 At ball release, shoulder abduction and lateral trunk tilt maintained consistent values around 90 degrees and 25 degrees, respectively, for flat-ground throws and pitching from the mound.12,30 Arm slot (i.e., the fore-arm and horizontal plane at the time of ball release) decreased as flat-ground throwing distance increased for each study that used an IMU sensor.21,23,31

PARTIAL-EFFORT PITCHING KINETICS

Four studies investigated kinetics of pitching at increasing effort.18-20,27 All four studies had pitchers pitch at varying perceived efforts, either throwing at 50%, 75%, and 100% intensity18,19 or 60%, 80%, and 100% intensity.20 Fiegen et al.,27 Fleisig et al.,18 Lizzio et al.,19 and Slenker et al.20 all found that elbow varus torque increased as pitching effort increased (Figure 3). Pitching at 50% and 60% effort produced less elbow varus torque than pitching at 75% and 80% effort, and all partial-effort pitching produced less elbow varus torque than full-effort pitching.18-20,27

PARTIAL-EFFORT PITCHING KINETICS

Fleisig et al. investigated the kinematics of pitching at increased effort.18 As shown in Table 4, they found no significant differences in stride length during partial-effort pitches. However, lead knee flexion at front foot contact was significantly less during 50% and 75% effort pitches.
Table 1. AXIS study assessment

| Study                | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  | 17  | 18  | 19  | 20  | Positive Responses | Score | Quality |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------------------|-------|---------|
| Carr et al.          | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y D | D D | D D | 14  | 70% | Moderate         |
| Cross et al.         | Y Y | N Y | Y Y | D N | Y Y | Y Y | D Y | D N | Y Y | Y Y | N D | Y D | Y D | 12  | 60% | Moderate         |
| Dowling et al.       | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | N Y | Y Y | Y Y | 14  | 70% | Moderate         |
| Fiegen et al.        | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y D | Y D | Y D | 14  | 70% | Moderate         |
| Fleisig et al., 1996 | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | N D | Y D | Y D | 13  | 65% | Moderate         |
| Fleisig et al., 2011 | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | N Y | Y Y | N Y | 15  | 75% | High            |
| Fleisig et al., 2017 | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | N Y | Y Y | N Y | 15  | 75% | High            |
| Leafblad et al.      | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | D Y | D Y | D Y | 14  | 70% | Moderate         |
| Lizzio et al., 2020  | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y D | Y D | Y D | 14  | 70% | Moderate         |
| Lizzio et al., 2021  | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y Y | Y Y | Y Y | 14  | 70% | Moderate         |
| Melugin et al.       | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y Y | Y Y | Y Y | 14  | 70% | Moderate         |
| Slenker et al.       | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | Y Y | Y Y | N Y | 15  | 75% | High            |
| Wight et al.         | Y Y | N Y | Y Y | D N | Y Y | Y Y | Y Y | D N | Y Y | Y Y | N N | Y N | N Y | 14  | 70% | Moderate         |

Y = yes, N = no, and D = do not know. For each question, 1 point is awarded depending on the answer. A yes is one point for all questions except 13 and 19. A no is one point only on questions 13 and 19. A do not know is 0 points. A score of 75% or greater is considered high quality. A score of 60% - 70% is considered moderate. A score below 60% is considered low quality.

AXIS questions:
1. Were the aims/objectives of the study clear?
2. Was the study design appropriate for the stated aims(s)?
3. Was the sample size justified?
4. Was the target/reference population clearly defined? (Is it clear who the research was about?)
5. Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?
6. Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?
7. Were measures undertaken to address and categorise non-responders?
8. Were the risk factor and outcome variables measured appropriate to the aims of the study?
9. Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialed, piloted or published previously?
10. Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., P values, CIs)
11. Were the methods (including statistical methods) sufficiently described to enable them to be repeated?
12. Were the basic data adequately described?
13. Does the response rate raise concerns about non-response bias?
14. If appropriate, was information about non-responders described?
15. Were the results internally consistent?
16. Were the results for the analyses described in the methods, presented?
17. Were the authors’ discussions and conclusions justified by the results?
18. Were the limitations of the study discussed?
19. Were there any funding sources or conflicts of interest that may affect the authors’ interpretation of the results?
20. Was ethical approval or consent of participants attained?
## Table 2. Description of Included Studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Subjects</th>
<th>Technology</th>
<th>Flat-Ground Throwing Distance (m)</th>
<th>Pitching from mound (18.44m)</th>
<th>Variables Reported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr et al., 2022(^{22})</td>
<td>7 high school pitchers</td>
<td>Inertial measurement unit</td>
<td>27m, 37m, 46m, 55m</td>
<td>Full-effort</td>
<td>Elbow varus torque, Arm speed</td>
</tr>
<tr>
<td>Cross et al., 2019(^{24})</td>
<td>19 professional pitchers</td>
<td>Optical marker tracking</td>
<td>18m, 37m, 55m, 73m, 91m</td>
<td>Full-effort</td>
<td>Full-body kinematics, Elbow and shoulder kinetics</td>
</tr>
<tr>
<td>Dowling et al., 2018(^{23})</td>
<td>95 high school pitchers</td>
<td>Inertial measurement unit</td>
<td>9m, 18m, 27m, 37m, 46m</td>
<td>N/A</td>
<td>Elbow varus torque, Arm slot, Arm speed, Maximum shoulder external rotation</td>
</tr>
<tr>
<td>Fiegen et al., 2023(^{27})</td>
<td>10 high school pitchers</td>
<td>Optical marker tracking</td>
<td>N/A</td>
<td>50% effort, 75% effort, &amp; full-effort</td>
<td>Elbow varus torque</td>
</tr>
<tr>
<td>Fleisig et al., 1996(^{18})</td>
<td>27 college pitchers</td>
<td>Optical marker tracking</td>
<td>N/A</td>
<td>50% effort, 75% effort, &amp; full-effort</td>
<td>Full-body kinematics, Elbow and shoulder kinetics</td>
</tr>
<tr>
<td>Fleisig et al., 2011(^{12})</td>
<td>17 collegiate pitchers</td>
<td>Optical marker tracking</td>
<td>37m, 55m, full-effort</td>
<td>Full-effort</td>
<td>Full-body kinematics, Elbow and shoulder kinetics</td>
</tr>
<tr>
<td>Fleisig et al., 2017(^{20})</td>
<td>18 high school pitchers and 7 college pitchers</td>
<td>Optical marker tracking</td>
<td>18.44m</td>
<td>Full-effort</td>
<td>Full-body kinematics, Elbow and shoulder kinetics</td>
</tr>
<tr>
<td>Leafblad et al., 2019(^{21})</td>
<td>28 high school and 32 collegiate pitchers</td>
<td>Inertial measurement unit</td>
<td>27m, 37m, 46m, 55m</td>
<td>Full-effort</td>
<td>Elbow varus torque, Arm slot, Arm speed, Maximum shoulder external rotation, Ball velocity</td>
</tr>
<tr>
<td>Lizzio et al., 2020(^{19})</td>
<td>26 high school and 11 collegiate pitchers</td>
<td>Inertial measurement unit</td>
<td>N/A</td>
<td>50% effort, 75% effort, &amp; full-effort</td>
<td>Elbow varus torque</td>
</tr>
<tr>
<td>Lizzio et al., 2021(^{31})</td>
<td>20 high school and collegiate pitchers (split not identified)</td>
<td>Inertial measurement unit</td>
<td>9m, 14m, 18m, 27m, 37m, 46m, 55m</td>
<td>N/A</td>
<td>Elbow varus torque, Arm slot, Arm speed, Shoulder rotation, Ball velocity</td>
</tr>
<tr>
<td>Melugin et al., 2019(^{26})</td>
<td>28 high school and 32 collegiate pitchers</td>
<td>Inertial measurement unit</td>
<td>37m</td>
<td>N/A</td>
<td>Elbow varus torque, Arm slot, Arm speed, Shoulder rotation, Ball velocity</td>
</tr>
<tr>
<td>Slenker et al., 2014(^{20})</td>
<td>25 collegiate, 3 club league, and 1 Minor League pitchers</td>
<td>Optical marker tracking</td>
<td>18m, 27m, 37m, 55m</td>
<td>60% effort, 80% effort, &amp; full-effort</td>
<td>Elbow and shoulder kinetics, Ball velocity</td>
</tr>
<tr>
<td>Wight et al., 2019(^{25})</td>
<td>19 college pitchers</td>
<td>Inertial measurement unit</td>
<td>27m, 37m, 46m, 55m</td>
<td>Full-effort</td>
<td>Elbow varus torque, Arm cocking angle</td>
</tr>
</tbody>
</table>
Table 3. Flat-ground throwing kinematic data. Full effort pitching kinematic data provided for comparison.

<table>
<thead>
<tr>
<th>Foot Contact</th>
<th>9m</th>
<th>14m</th>
<th>18m</th>
<th>27m</th>
<th>37m</th>
<th>46m</th>
<th>Pitch (18.44m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stride length (% subject’s height)</strong></td>
<td></td>
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<tr>
<td>Cross et al., 2019</td>
<td>59 ± 10</td>
<td></td>
<td>66 ± 9</td>
<td></td>
<td>76 ± 8</td>
<td></td>
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<tr>
<td>Fleisig et al., 2011</td>
<td>79 ± 6</td>
<td></td>
<td>80 ± 4</td>
<td></td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>80 ± 6</td>
<td></td>
<td>84 ± 6</td>
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<tr>
<td><strong>Foot position (cm to the “closed” side)</strong></td>
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<tr>
<td>Fleisig et al., 2011</td>
<td>16 ± 14</td>
<td></td>
<td>25 ± 12</td>
<td></td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>13 ± 13</td>
<td></td>
<td>21 ± 15</td>
<td></td>
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</tr>
<tr>
<td><strong>Upper trunk tilt</strong></td>
<td>13 ± 9</td>
<td>6 ± 7</td>
<td>7 ± 9</td>
<td></td>
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<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>10 ± 6</td>
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<tr>
<td><strong>Lead knee flexion</strong></td>
<td>46 ± 8</td>
<td>47 ± 9</td>
<td></td>
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<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>42 ± 9</td>
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</tr>
<tr>
<td><strong>Maximum Values</strong></td>
<td>148 ± 8</td>
<td>156 ± 8</td>
<td>160 ± 12</td>
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<tr>
<td><strong>Shoulder external rotation</strong></td>
<td></td>
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</tr>
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<td>Cross et al., 2019</td>
<td>147 ± 7</td>
<td>155 ± 5</td>
<td>161 ± 4</td>
<td>165 ± 4</td>
<td>167 ± 5</td>
<td></td>
<td></td>
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<tr>
<td>Dowling et al., 2018</td>
<td>174 ± 10</td>
<td>174 ± 10</td>
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<td>175 ± 11</td>
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</tr>
<tr>
<td>Leafblad et al., 2019</td>
<td>162 ± 10</td>
<td>167 ± 9</td>
<td>170 ± 9</td>
<td>161 ± 11</td>
<td></td>
<td></td>
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<tr>
<td>Lizzio et al., 2021</td>
<td>137</td>
<td>146</td>
<td>150</td>
<td>155</td>
<td>161</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>Lizzio et al., 2021a</td>
<td>159 ± 10</td>
<td>164 ± 9</td>
<td>167 ± 8</td>
<td>157 ± 11</td>
<td></td>
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</tr>
<tr>
<td>Wight et al., 2019</td>
<td></td>
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<tr>
<td><strong>Elbow flexion</strong></td>
<td>92 ± 8</td>
<td>93 ± 7</td>
<td>89 ± 5</td>
<td></td>
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<tr>
<td>Cross et al., 2019</td>
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<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>109 ± 12</td>
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<td><strong>Shoulder internal rotation velocity or Arm speed (deg/s)</strong></td>
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<tr>
<td>Foot Contact</td>
<td>Pitch (18.44m)</td>
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<tr>
<td>Carr et al., 2022&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9m 14m 18m 27m 37m 46m</td>
<td></td>
<td></td>
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<tr>
<td>Cross et al., 2019</td>
<td>3420 ± 416</td>
<td>3854 ± 460</td>
<td>4462 ± 439</td>
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<td></td>
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<tr>
<td>Dowling et al., 2018</td>
<td>2731 ± 563</td>
<td>4066 ± 480</td>
<td>4622 ± 328</td>
<td>4909 ± 332</td>
<td>5044 ± 416</td>
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<tr>
<td>Fleisig et al., 2011</td>
<td>3920 ± 1068&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4141 ± 757&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4482 ± 949&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4533 ± 864&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Fleisig et al., 2017</td>
<td>6705 ± 869</td>
<td>6594 ± 743</td>
<td></td>
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<td></td>
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<tr>
<td>Leafblad et al., 2019</td>
<td>5203 ± 736</td>
<td>5302 ± 633</td>
<td>5357 ± 510</td>
<td>5527 ± 554</td>
<td></td>
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<tr>
<td>Lizzio et al., 2021&lt;sup&gt;a&lt;/sup&gt;</td>
<td>346</td>
<td>527</td>
<td>661</td>
<td>753</td>
<td>796</td>
<td>839</td>
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</tr>
<tr>
<td>Wight et al., 2019</td>
<td>5461 ± 713</td>
<td>5483 ± 658</td>
<td>5490 ± 506</td>
<td>5589 ± 557</td>
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**Elbow extension velocity (deg/s)**

<table>
<thead>
<tr>
<th>Elbow extension velocity (deg/s)</th>
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</thead>
<tbody>
<tr>
<td>Cross et al., 2019</td>
</tr>
<tr>
<td>Fleisig et al., 2011</td>
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<td>Fleisig et al., 2017</td>
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**Ball Release**

**Forward trunk tilt**

<table>
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<tbody>
<tr>
<td>Fleisig et al., 2011</td>
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**Lateral trunk tilt**

<table>
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<tr>
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**Shoulder abduction**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Cross et al., 2019</td>
</tr>
<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
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</table>

**Arm slot**

<table>
<thead>
<tr>
<th>Arm slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowling et al., 2018</td>
</tr>
<tr>
<td>Leafblad et al., 2019</td>
</tr>
<tr>
<td>Lizzio et al., 2021</td>
</tr>
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</table>

**Lead knee flexion**

<table>
<thead>
<tr>
<th>Lead knee flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr et al., 2022&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cross et al., 2019</td>
</tr>
<tr>
<td>Dowling et al., 2018</td>
</tr>
<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
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<tr>
<td>Leafblad et al., 2019</td>
</tr>
<tr>
<td>Lizzio et al., 2021&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wight et al., 2019</td>
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<tr>
<td>Foot Contact</td>
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<tr>
<td>--------------</td>
</tr>
<tr>
<td>Fleisig et al., 2011</td>
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<tr>
<td>Fleisig et al., 2017</td>
</tr>
</tbody>
</table>

Data are presented in degrees as mean ± standard deviation and rounded to the nearest whole number unless otherwise noted. A bold value denotes that the study's flat-ground throwing value was statistically significantly different from the study's pitching value. Statistical significance was p < 0.05 unless otherwise noted.

a) Data are from throws with a crow hop. Data reported as least squares means.

b) Data received via personal communication with the study's authors.
These authors also found significantly less shoulder external rotation, internal rotation velocities, and elbow extension velocities during partial-effort pitching. At ball release, knee flexion was significantly greater compared to knee flexion during full-effort pitching, thus suggesting that pitchers do not achieve as much knee extension during partial-effort pitching. In fact, during partial-effort pitching, pitchers increased their knee flexion between foot contact and ball release.

**DISCUSSION**

To determine if an interval throwing program progressively builds joint kinetics up to the level required during full-effort pitching, elbow varus torque values were normalized to the values produced in full-effort pitching (Figure 4). The distance at which flat-ground throwing elbow varus torque equals or exceeds maximum pitching torque varied between studies. Both Fleisig et al. found that 18-meter throws had greater elbow varus torque compared to full-effort pitching from the mound. Wight et al. found that throws of 27, 37, 46, and 55 meters all had greater elbow varus torque than pitching. Carr et al. and Leafblad et al. found that elbow varus torque during 55-meter throws was nearly equal to full-effort pitching elbow varus torque, while Fleisig et al. found that elbow varus torque during 55-meter throws was greater than elbow varus torque during full-effort pitching. Interestingly, Cross et al. found that elbow varus torque did not exceed full-effort pitching torque until 91-meter throws. Thus, while flat-ground throwing progressively builds elbow kinetic demands, it is unclear when flat-ground throwing kinetics surpass full-effort pitching kinetics. Caution should be exercised when performing these throws, especially when a pitcher reaches their final flat-ground throwing distance of 37 meters.
Elbow Varus Torque (Nm) vs Flat-Ground Throwing Distance (m)

Figure 2. Elbow varus torque (Nm) versus flat-ground throwing distance (m).

Note: both graphs have the same y-axis. On the y-axis, 100% represents full-effort pitching elbow varus torque. For reference, pitching distance is 18.44 meters.

Elbow varus torque during partial-effort pitching did not exceed the elbow varus torque of full-effort pitching in any study (Figure 4). While elbow varus torque systematically increases with effort, percent of elbow torque and percent of effort are not equal. Pitching with 50% effort produced about 75% of the elbow torque during full-effort pitching. Pitching with 75% to 80% effort produced 80% to 95% of the elbow torque during full-effort pitching.

A secondary purpose of this study was to determine if the kinematics produced during interval throwing programs are similar to baseball pitching kinematics. Despite limited kinematic data, it appears that kinematics of flat-ground throwing are similar to full-effort pitching, in general. However, some significant differences were reported. Compared to full-effort pitching, flat-ground throwing demonstrated a shorter stride, less distance landing to the closed side, and a more upright trunk position.12,24,30 As flat-ground throwing distance increases, both maximum shoulder external rotation and shoulder internal rotation velocities increase. The distance at which maximum shoulder external rotation exceeded shoulder external rotation during full-effort pitching varied between studies.12,21,24,25 Clinicians should be aware of these differences and ensure that proper pitching biomechanics are restored when the athlete returns to pitching on the mound.

At ball release, arm slot decreased as throwing distance increased.21,23,31 In these studies, the IMU sensor calculated arm slot as the angle created between the forearm and horizontal plane at ball release.32 It should be noted that arm slot for optical motion capture has been reported as the angle created by a vertical line and the vector connecting the shoulder joint center to the hand at ball release.33,34 Arm slot is affected by shoulder abduction, lateral trunk tilt, and elbow flexion.33,34 Interestingly, both shoulder abduction and lateral trunk tilt at ball release were similar in flat-ground throwing to full-effort pitching values. However, only three studies reported shoulder abduction12,24,30 and two reported lateral trunk tilt.12,30 so more research is needed on flat-ground throwing kinematics using optical motion capture in order to confirm the arm slot trends observed in the studies that used the IMU sensor.

Melugin et al.26 investigated partial-effort flat-ground throwing. In their study, the authors had subjects throw "on
a line" without a crow hop at 37 meters. The authors instructed subjects to throw at 50%, 75%, and 100% intensity. Similar to the trends observed in partial-effort pitching, the authors found that at 50% throwing intensity, players threw at 78% of maximum ball velocity and experienced 86% maximum elbow varus torque. When players threw at 75% intensity, ball velocity was 86% of maximum and elbow varus torque was 93% of maximum. Unlike the trend observed during partial-effort pitching, an unexpected finding was that shoulder external rotation remained constant regardless of flat-ground throwing intensity. However, both arm slot and arm speed increased as throwing intensity increased.

Unfortunately, only one study reported kinematics in partial-effort pitching. Fleisig et al. reported partial-effort kinematics at 50%, 75%, and 100% perceived effort. Shoulder external rotation, shoulder internal rotation velocities, and elbow extension velocities were all significantly decreased during partial-effort pitching. While stride length remained similar across effort levels, lead knee flexion was significantly lower during 50% and 75% effort pitches. Full-effort pitching requires coordinated movements of the legs, trunk, and arms, and the lack of knee extension observed during the 50%- and 75%-effort pitches results in less energy transferred up the kinetic chain and onto the ball. This kinetic chain concept has been supported by a recent study showing that high-velocity professional pitchers had greater lead knee extension and lead knee velocity than low-velocity professional pitchers. These results provide evidence that the partial-effort pitching phase of an interval throwing program does in fact systematically increase joint velocities as perceived effort increases, but partial-effort pitching does have kinematic differences from full-effort pitching.

Four studies reported ball velocity during partial-effort pitching. While ball velocity increases with effort as expected, the percent of ball velocity and percent of effort are not equal (Figure 5). Fleisig et al. and Fiegen et al. both found that at 50% effort, pitchers threw at 85% of maximum ball velocity. At 75% effort, pitchers threw at 90% of maximum ball velocity. Similarly, Lizzio et al. found that at 50% effort, pitchers threw with 79% of maximum ball velocity. At 75% effort, pitchers threw at 89% maximum ball velocity. Slenker et al. did a similar study by instruct-

![Image](image-url)
Table 4. Kinematics of partial-effort pitching from Fleisig et al., 1996.18

<table>
<thead>
<tr>
<th></th>
<th>50% effort</th>
<th>75% effort</th>
<th>100% effort</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foot Contact</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stride length (% of subject’s height) Fleisig et al., 1996</td>
<td>69 ± 4</td>
<td>70 ± 7</td>
<td>71 ± 4</td>
</tr>
<tr>
<td>Lead knee flexion Fleisig et al., 1996</td>
<td>40 ± 9</td>
<td>41 ± 10</td>
<td>47 ± 10</td>
</tr>
<tr>
<td><strong>Maximum Values</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Shoulder external rotation Fleisig et al., 1996</td>
<td>167 ± 11</td>
<td>169 ± 12</td>
<td>172 ± 12</td>
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<tr>
<td>Elbow flexion Fleisig et al., 1996</td>
<td>101 ± 11</td>
<td>102 ± 10</td>
<td>105 ± 10</td>
</tr>
<tr>
<td>Shoulder internal rotation velocity Fleisig et al., 1996</td>
<td>5820 ± 1110</td>
<td>6400 ± 1050</td>
<td>7290 ± 1090</td>
</tr>
<tr>
<td>Elbow extension velocity Fleisig et al., 1996</td>
<td>1940 ± 270</td>
<td>2130 ± 280</td>
<td>2350 ± 250</td>
</tr>
<tr>
<td><strong>Ball Release</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead knee flexion Fleisig et al., 1996</td>
<td>49 ± 10</td>
<td>44 ± 10</td>
<td>36 ± 12</td>
</tr>
<tr>
<td>Trunk angle above horizontal Fleisig et al., 1996</td>
<td>66 ± 9</td>
<td>64 ± 9</td>
<td>59 ± 8</td>
</tr>
</tbody>
</table>

Data are presented in degrees as mean ± standard deviation unless otherwise noted. Bold values denote a significant (p < 0.05) difference from full-effort pitching.

Figure 4. Percentage of maximum pitching elbow varus torque achieved in interval throwing program for pitchers. This includes (A) flat-ground throwing up to 45 m and (B) partial-effort pitching.

...ing pitchers to pitch at 60%, 80%, and 100% effort. Similar to the other studies, Slenker et al. found that at 60% effort, pitchers threw at 85% of maximum ball velocity. At 80% effort, pitchers threw at 91% of maximum ball velocity. These findings do not invalidate the use of partial-effort pitching in interval throwing programs, as no interval throwing pro-
Figure 5. Percentage of maximum velocity versus partial-effort pitching (percentage of full-effort) for four of the included studies. Note that both Fiegen et al. and Fleisig et al. found nearly identical values.

LIMITATIONS AND FUTURE RESEARCH

Like all studies, this systematic review had limitations. Although PRISMA guidelines were followed to search multiple databases, there is a possibility that articles with relevant data were missed by this search. Furthermore, two of the included studies were conference abstracts, however, the inclusion of abstracts in a systematic review is permissible when there is limited published articles on a topic. Additionally, the articles identified varied regarding which biomechanical parameters they measured. This review was focused on kinetic and kinematic parameters that were reported often and are considered relevant to injury risk and return to proper mechanics.

It also is important to note that the literature used two different technologies for collecting biomechanical data. Optical motion capture, which was used in six of the studies, is considered the "gold standard" of biomechanical data collection. The other seven studies used a wearable IMU. The wearable IMU in all seven studies was the MotusBASEBALL sensor, now called Driveline Pulse (Driveline Baseball, Kent, WA). Unfortunately, data from MotusBASEBALL sensors and optical motion capture are not directly comparable. Despite an initial pilot study that showed good to excellent correlations between the MotusBASEBALL sensor and optical motion capture values for elbow varus torque, arm rotation, arm slot, and arm speed, other studies have found only moderate correlations between IMU and optical motion data. Thus, the effect of throwing distance and pitching effort on elbow torque can be analyzed within IMU studies to analyze trends; however, the raw numbers from the IMU’s cannot be combined with optical motion data into a meta-analysis.

Another important difference between studies was the varying instructions surrounding flat-ground (long-toss) throwing technique. Some studies instructed participants to throw "hard, on a line" when performing their flat-ground throws. Others simply instructed their participants to throw either "on line" or "on a line". Carr et al. was a retrospective study and stated that participants threw at "full-effort" for all throws. Conversely, Lizzio et al. instructed their participants to throw "on an arc" when flat-ground throwing. In addition, throwing effort is not the only variable in flat-ground throwing. The crow hop, which is a sequence of steps of the front foot, back foot, and front foot, theoretically enhances lower extremity and core involvement to aid the throw.
literature, the authors noticed several different instructions regarding the use of a crow hop during flat-ground throws. Three studies\textsuperscript{25–27} gave no instructions or constraints involving the crow hop and two studies\textsuperscript{12,30} allowed players to use whatever crow hop technique they liked. Leafblad et al.\textsuperscript{21} discouraged the use of a crow hop but allowed it if it was needed for the participant to reach the desired throwing distance. Slenker et al.\textsuperscript{20} instructed participants to use a crow hop only during their longer (37 m and 55 m) throws and found decreased elbow varus torque during throws that used a crow hop. The investigators stated that the use of the crow hop with their long-distance throws was likely the reason elbow torque decreased. Lizzio et al.\textsuperscript{31} specifically studied the effects of the crow hop during flat-ground throwing. They found that when a crow hop was used, there was greater elbow varus torque and ball velocity compared to when a crow hop was not used. We believe that compared to a flat-ground throw with no run-up, a crow hop throw creates kinetic energy that is passed up the kinetic chain to the throwing arm, leading to greater joint torque and ball velocity. This lack of consensus defining flat-ground baseball throwing is not unique to biomechanical studies, as a survey of professional pitchers, pitching coaches, and certified athletic trainers found varying responses to what is the proper technique for long-toss.\textsuperscript{41}

Another limitation of this study was the relatively small sample sizes of participants used in some of the included studies, as five of the included studies had less than 20 subjects. Additionally, only one study, conducted over 25 years ago, investigated the kinematics of partial-effort pitching, which limits this study’s ability to confidently assess partial-effort pitching kinematics.\textsuperscript{18} Finally, most of the baseball players in the studies included in this review played at the high school or collegiate level. Further research including lower (i.e., youth) and higher (i.e., professional) level baseball players is needed.

Optimizing an interval throwing program is a combination of science and art. This systematic review of biomechanics revealed the stresses and mechanics used during interval throwing, but determining and monitoring the right progression was outside our scope. There has been much discussion on the future direction of interval throwing programs, with suggestions to adjust the throwing based on workloads. Some have suggested throwing programs should be performed with five-week blocks featuring a gradual increase in number of throws, effort, and distance for approximately four weeks followed by one week with reduced workload to allow the athlete to recover. Additional research is needed to determine the efficacy of this type of interval throwing program.

CONCLUSION

The results of this review indicate that elbow varus torque for most flat-ground throws does not exceed the torque produced during full-effort pitching. While most studies showed increased elbow varus torque with increased flat-ground throwing distance, the distance at which elbow varus torque matched or exceeded full-effort pitching elbow varus torque was not consistent. During the partial-effort pitching phase of an interval throwing program, elbow varus torque did not exceed the values observed during full-effort pitching.

As flat-ground throwing distance increased, shoulder external rotation angle and shoulder internal rotation velocity increased. Arm slot decreased as flat-ground throwing distance increased. Shoulder external rotation angle, shoulder internal rotation velocity, elbow extension velocity, and ball velocity increased as pitching effort increased. While the front knee extended from foot contact to ball release during full-effort pitching, the front knee flexed during partial-effort pitching.

Thus, the interval throwing program seems to be a reliable progression in building elbow varus torque up to the levels produced in full-effort pitching. Furthermore, while differences exist between interval throwing kinematics and pitching kinematics, the patterns are similar in general.

CONFLICT OF INTEREST

The authors report no conflicts of interest.

Submitted: June 14, 2023 CDT, Accepted: August 15, 2023 CDT
REFERENCES


SUPPLEMENTARY MATERIALS

Appendix A
Systematic Review/Meta-Analysis

The Effect of Ball Heading and Subclinical Concussion On the Neuromuscular Control Of The Lower Limb: A Systematic Review

Georgios Kakavas, PT, PhDd,e, Ioannis Giannakopoulos Sr., PhDc,b, Athanasios Tsiokanos, PhDf, Michael Potoupnis, MD, PhDf, Panagiotis V. Tsaklis, PhDf,a

1 Fysiotek Spine and Sports Lab Athens, Greece, 2 Department of Physical Education and Sport Science, University of Thessaly, ErgoMech-Lab, Greece, 3 Medical School, Aristotle University of Thessaloniki, Greece, 4 Department of Molecular Medicine and Surgery, Growth and Metabolism, Karolinska Institute, Sweden

Keywords: Lower limb, ball heading, neuromuscular control, concussion

https://doi.org/10.26603/001c.87922

International Journal of Sports Physical Therapy

Background

Soccer is unique among sports because it is the only sport that involves purposeful use of the head to control, pass, or shoot the ball. Over the previous five years, a relationship between lower extremity (LE) injury and sports related concussion (SRC) has been established in various sporting populations. Athletes at the high school, collegiate, and professional levels have demonstrated a greater risk for sustaining a LE injury post SRC. The purpose of this systematic review was to examine the relationship of the SRC with the incidence of LE injuries.

Methods

Ten databases were searched with the following keywords: Lower limb, ball heading, neuromuscular control, concussion, MEDLINE, Ovid MEDLINE(R) Daily, and Ovid MEDLINE(R), EMBASE, and Scopus. The search was limited to English-language and peer-reviewed publications, until 15/12/2022. The PEDro scale was used for the assessment of the risk of bias among the included studies. All included papers were qualitatively analyzed.

Results

A total of 834 studies were identified and 10 articles (four concussion-MSK biomechanics, six concussion-MSK injury) were included in the qualitative analyses. Included papers ranged from low to high quality. Due to the heterogeneous nature of the included study designs, quantitative meta-analysis was unable to be performed. All four of the included concussion-MSK biomechanics studies demonstrated, to some degree, that worse cognitive performance was associated with lower extremity MSK biomechanical patterns suggestive of greater risk for MSK injury. Among the six injury related studies, two investigations failed to determine group differences in cognitive performance between subsequently injured and non-injured athletes.

Conclusion

More research is needed to better understand the relationship of SRC and lower extremity injuries and the extent to which they are related to concussions and/or repetitive neurotrauma after ball heading sustained in soccer.

Level of Evidence

2

a Correspondence to:
Panagiotis V. Tsaklis, tsaklis@uth.gr https://orcid.org/0000-0002-6626-5795
INTRODUCTION

Soccer is unique among sports because it is the only sport that involves purposefully the use of the head to control, pass, or shoot the ball. The action of soccer heading has drawn considerable attention from policy makers, clinicians, researchers, parents, coaches, and athletes for its potential effects on the brain, particularly among younger players. The way soccer is played repeated impacts to the head (during headers) due to the high velocity at which the ball travels, reaching speeds up to 85 km/h (23.6 m/s). In fact, in response to a recent lawsuit and to minimize concussions that occur due to heading in youth soccer, U.S.A Soccer enacted guidelines restricting heading completely under the age of 11 and limiting it for players aged from 11 to 13 years. Many more institutions like the Football Association at UK follow similar guidelines for young footballers, males and females. Mild TBI is among the most common neurological conditions with an estimated annual incidence of 500/100,000 in the United States. One Canadian study examining both hospital-treated cases as well as those presenting to a family physician, calculated the incidence of mTBI in Ontario to lie between 493/100,000 and 653/100,000, depending on whether diagnosis was made by primary care physicians or a secondary reviewer.

Concussions account for 5.8 per cent to 8.6 per cent of total injuries sustained during games. Swainik et al. found that 62.7% of varsity soccer players had suffered symptoms of a concussion during their playing careers, yet only 19.2% realized it. Gilbert et al. found that 81.8 per cent of athletes who had suffered a concussion had experienced two or more and that players with a history of concussion had 3.15 times greater odds of sustaining an additional concussion than those who had never had a concussion. Concussion/mild TBI can be described as the acute neurophysiological event related to blunt impact or other mechanical energy applied to the head, neck or body (with transmitting forces to the brain), such as sudden acceleration, deceleration or rotational forces. Concussion can be sustained from a motor vehicle crash, sport or recreational injury, falls, workplace injury, assault or incident in the community.

Over the previous five years, a relationship between lower extremity (LE) injury and sports related concussion (SRC) has been established in various sporting populations. Athletes at the high school, collegiate, and professional levels have demonstrated a greater risk for sustaining a LE injury post-SRC. The majority of the studies consist of retrospective injury surveillance data that monitored LE injury rates in concussed and non-concussed athletes for a specified time period surrounding the initial SRC event (both prior to- and post-SRC). All athletes diagnosed with SRC in these investigations were clinically cleared to play sports by sports medicine staff (athletic trainer, doctor, physiotherapist) and monitored for LE injury rates at various time points after the initial SRC. Of note, it is unclear if the individuals responsible for clearing athletes strictly adhered to all components related to the latest SRC consensus.

A small number of studies examined the possible long-term effects of sub-concussive head impacts. While LE injury risk has been associated with SRC occurrence across multiple collegiate populations, previous investigations failed to control for LE injury history prior to an SRC, a potential confounding variable that may influence subsequent injury risk. Therefore, the purpose of this systematic review was to examine the relationship between SRC and LE musculoskeletal injuries.

MATERIALS AND METHODS

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines in the search strategy and reporting according to the PRISMA statement.

INFORMATION SOURCES AND SEARCH STRATEGY

Keywords were selected (Lower limb injury, ball heading, neuromuscular control, concussion) by agreement of all authors and then submitted to a librarian with expertise in systematic reviews who developed a draft MEDLINE search strategy. This was reviewed by a second expert health sciences librarian using the CADTH Peer Review Checklist for Search Strategies according to the PRESS 2015 Guideline Statement. The draft search strategy was revised based on suggestions from the PRESS review, and then tested to be sure known key studies were retrieved. The MEDLINE search was adapted and translated for all other databases. The following 10 databases were searched: MEDLINE (Epub Ahead of Print, In-Process & Other Non-Indexed Citations, Ovid MEDLINE(R) Daily and Ovid MEDLINE(R)), CINAHL Plus with Fulltext, EMBASE, PsycINFO, Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, Scopus, Web of Science, PsycARTICLES and SPORTDiscus. The search was limited to English-language and peer-reviewed publications with no date restriction. The search was conducted 12/11/2022.

RISK OF BIAS ASSESSMENT

The PEDro scale was used for the assessment of the risk of bias among the included studies. PEDro scale is a valid measure of methodological quality of clinical trials in rehabilitation. It consists of 11 items including external validity (item 1), internal validity (items 2–9), statistical reporting (items 10 and 11), and each one of them contributes one point to a total score of 10, except for one dichotomous item (yes/no). The PEDro scale is considered to meet interval level measurement, allowing score comparisons between studies. Scores of <4 are considered ‘poor’, 4–5 are considered ‘fair’, 6–8 are considered ‘good’, and 9–10 are considered ‘excellent’. Two reviewers assessed the risk of bias in each study independently and a third reviewer was recruited in case of any argument.
ELIGIBILITY CRITERIA AND DATA EXTRACTION

Studies were included if they (i) were original research; (ii) evaluated the incidence/prevalence, risk factors or causation related to neurodegenerative disease; (iii) included individuals who have suffered a sport-related concussion; (iv) evaluated athletes and/or retired athletes as the study subjects and (v) evaluated possible long-term sequelae defined as ≥10 years after sports-related injury. Studies were excluded from this review if they were published in a language other than English, studied animals, were review articles, case reports, book chapters, conference abstracts, editorials/commentaries/expert opinion, or theses or dissertations.

Citations were independently screened by pairs of authors. A third reviewer adjudicated disagreements between authors.

STUDY SELECTION PROCESS

After duplicates and irrelevant records were removed, several relevant reports were sought for retrieval and assessed for eligibility through full-text screening by the two reviewers, independently. Two researchers searched independently all titles and abstracts from each search were screened to identify relevant studies. Subsequently, they excluded any reports with reasons, before ending up with the final studies of the review. All studies were imported, screened, and assessed through the EndNote software. (Clarivate, Philadelphia, PA, USA).

DATA ITEMS AND COLLECTION PROCESS

The extracted data of the final studies included the characteristics of participants, the features of interventions, the outcome measures, and the main findings. The first reviewer sought and extracted these data, followed by the second reviewer checking the correctness of the data, and in case of disagreement, they were checked again. Reviewers worked independently during the process.

RESULTS

STUDY SELECTION

A total of 834 studies were identified from the databases and additional sources. Following the review of potential articles, 26 were full-text screened, of which 10 articles (four concussion-MSK biomechanics, six concussion-MSK injury) were included in the qualitative analyses. Due to the heterogeneous nature of the included study designs, this systematic review was unable to perform a quantitative meta-analysis for the present review. Therefore, our review presents a qualitative assessment of the available literature, as well as individual study characteristics and results. Included studies were prospective, retrospective, or cross-sectional designs, indicating that they were level 3 and 4 evidence studies. A comprehensive flowchart diagram of the study selection process is presented in Figure 1.

RISK OF BIAS IN STUDIES

Table 1 shows the results of the methodological assessment based on the PEDro criteria. Out of 10 studies, five were rated as ‘high’, three were rated as ‘moderate’ and two were rated as ‘low quality’. Blinding therapists was not feasible in all trials due to the nature of the interventions. Four out of 10 studies did not ensure the blinding of the participants. One study included the blinding of outcome assessors. There was a low to no drop-out rate among the trials. Results were extracted by one author and reviewed by a second author to ensure accuracy and completeness. (Table 1)

Table 2 presents data extracted from all included studies. All four of the included concussion-MSK biomechanics studies demonstrated, to some degree, that worse cognitive performance was associated with lower extremity MSK biomechanical patterns suggestive of greater risk for MSK injury. Among the six injury related studies, two investigations failed to determine group differences in cognitive performance between subsequently injured and non-injured athletes. The remaining four studies demonstrated that injured athletes significantly differed on baseline cognition measures versus matched controls, or that cognitive performance was a significant predictor for subsequent MSK injury.

Brooks et al14 found that the incidence of acute lower extremity musculoskeletal injury was higher among recently concussed athletes (15/87; 17%) compared with matched controls (17/182; 9%). The odds of sustaining an acute lower extremity musculoskeletal injury during the 90-day period after return to play were 2.48 times higher in concussed athletes than controls during the same 90-day period (odds ratio, 2.48; 95% CI, 1.04-5.91; p = 0.04). Also, Burman et al.15 stated that athletes with a concussion were more likely to sustain injuries compared with the control group, both before (OR 1.98, 95% CI 1.45 to 2.72) and after the concussion (OR 1.72. 95% CI 1.26 to 2.37). No increase in frequency of injury was found after a concussion compared with before. This was true for athletes in all four sports and for both sexes.

According to Cross et al.16 a total of 31,556 initial injuries were recorded soccer: 11,900; other sports: 19,656), which were followed by zero or one injury in the same season. Overall, first injury type was not a significant predictor of subsequent lower limb injury although certain contrasts yielded significant estimates. In soccer, the odds of sustaining a LE injury were higher after concussion than after upper extremity injury (UEMSKI; adjusted odds ratio [ORadj], 1.56; 95% CI, 1.06-2.31). In football, the odds of TL LEMSKI were lower after concussion than after UEMSKI (ORadj, 0.71; 95% CI, 0.51-0.99). No other significant effect estimates were observed for baseball or other sports.

Fino et al.17 found that concussion was associated with an increased instantaneous relative risk of LE injury when adjusting for LE injury history [hazard ratio (HR) = 1.67, 95% confidence interval (CI) = 1.11-2.53], agreeing with previous results. Among individuals who had a history of LE injuries before the concussion event, a nonsignificant yet moderate effect of concussion on the instantaneous rela-
Table 1. Methodological quality assessment using the PEDro scale.

<table>
<thead>
<tr>
<th>Study</th>
<th>Eligibility Criteria &amp; Source</th>
<th>Random Allocation</th>
<th>Concealed Allocation</th>
<th>Baseline comparability</th>
<th>Blinding of Participants</th>
<th>Blinding of Therapists</th>
<th>Adequate Follow Up (&gt;85%)</th>
<th>Intention to Treat Analysis</th>
<th>Between Group Statistical Comparisons</th>
<th>Reporting of point measures &amp; variability</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooks (2016)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>6/10</td>
<td></td>
</tr>
<tr>
<td>Burman (2016)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>7/10</td>
<td></td>
</tr>
<tr>
<td>Cross (2016)</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>4/10</td>
<td></td>
</tr>
<tr>
<td>Fino (2017)</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>5/10</td>
<td></td>
</tr>
<tr>
<td>Herman (2017)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>5/10</td>
<td></td>
</tr>
<tr>
<td>Lynall (2015)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>4/10</td>
<td></td>
</tr>
<tr>
<td>Lynall (2017)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>7/10</td>
<td></td>
</tr>
<tr>
<td>Makdissi (2009)</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>3/10</td>
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</tr>
<tr>
<td>Nordstrom (2014)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>7/10</td>
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<td>Nyberg (2015)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>8/10</td>
<td></td>
</tr>
</tbody>
</table>

1. Eligibility criteria were specified; 2. subjects were randomly allocated to groups (in a cross-over study, subjects were randomly allocated an order in which treatments were received); 3. allocation was concealed; 4. the groups were similar at baseline regarding the most important prognostic indicators; 5. there was blinding of all subjects; 6. there was blinding of all therapists who administered the therapy; 7. there was blinding of all assessors who measured at least one key outcome; 8. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; 9. all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome were analyzed by “intention to treat”; 10. the results of between-group statistical comparisons are reported for at least one key outcome; 11. the study provides both point measures and measures of variability for at least one key outcome; Note: The first item relates to external validity and the remaining 10 items are used to calculate the total score, which ranges from 0 to 10. + Yes - No.
### Table 2. Data extracted from studies

<table>
<thead>
<tr>
<th>Lead Author (Year)</th>
<th>Athletes With Concussion, No. and Level of Participation</th>
<th>Sports</th>
<th>Control Athletes</th>
<th>Quality Checklist Score</th>
<th>Time from concussion to Return to Sport</th>
<th>Injuries Tracked</th>
<th>Injury Tracking Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooks (2016)</td>
<td>75 (58 male, 17 female) college Football, soccer, hockey, basketball, volleyball, softball</td>
<td>Non concussed, matched players</td>
<td>8</td>
<td>21 days</td>
<td>Acute, non-contact lower extremity injuries</td>
<td>90 days</td>
<td></td>
</tr>
<tr>
<td>Burman (2016)</td>
<td>281 (206 M, 75 F) Hockey, soccer, handball</td>
<td>Athletes with an ankle sprain, same 3 sports non concussed players</td>
<td>7</td>
<td>Not reported</td>
<td>Not defined</td>
<td>24 months</td>
<td></td>
</tr>
<tr>
<td>Cross (2016)</td>
<td>135 (135 M, 0 F) professional Rugby</td>
<td>Non concussed players</td>
<td>9</td>
<td>11 days</td>
<td>Any injury</td>
<td>2 seasons</td>
<td></td>
</tr>
<tr>
<td>Fino (2017)</td>
<td>110 (76 M, 34 F) college Baseball, basketball, lacrosse, football, tennis, volleyball</td>
<td>Non concussed matched players</td>
<td>9</td>
<td>18±40 days</td>
<td>Acute lower extremity injuries</td>
<td>12 months</td>
<td></td>
</tr>
<tr>
<td>Herman (2017)</td>
<td>73 (52 M, 21 F) college Football, basketball, lacrosse, soccer</td>
<td>Non concussed matched players</td>
<td>9</td>
<td>9±7 days</td>
<td>Acute lower extremity injuries</td>
<td>90 days</td>
<td></td>
</tr>
<tr>
<td>Lynall (2015)</td>
<td>44 (28 M, 16 F) college Hockey, football, lacrosse, soccer, basketball, tennis</td>
<td>Non concussed matched athletes</td>
<td>11</td>
<td>Not reported</td>
<td>Acute lower extremity injuries</td>
<td>12 months</td>
<td></td>
</tr>
<tr>
<td>Lynall (2017)</td>
<td>2004 high school Baseball, basketball, lacrosse, soccer, softball, tennis</td>
<td>Not applicable</td>
<td>6</td>
<td>Not reported</td>
<td>Acute and chronic lower extremity injuries</td>
<td>Undefined</td>
<td></td>
</tr>
<tr>
<td>Makdissi (2009)</td>
<td>117 [117M, 0 F] professional Australian football</td>
<td>Non concussed matched players from same team</td>
<td>10</td>
<td>Not reported</td>
<td>Any injury</td>
<td>Undefined</td>
<td></td>
</tr>
<tr>
<td>Nordstrom (2014)</td>
<td>66 (66 M, 0 F) professional Soccer</td>
<td>Non concussed injured player</td>
<td>9</td>
<td>Not reported</td>
<td>Any injury</td>
<td>12 months</td>
<td></td>
</tr>
<tr>
<td>Nyberg (2015)</td>
<td>81 (81 M, 0 F) professional Hockey</td>
<td>Athletes with Knee injury</td>
<td>9</td>
<td>Not reported</td>
<td>New knee injuries</td>
<td>42 days</td>
<td></td>
</tr>
</tbody>
</table>
The effect of ball heading and subclinical concussion on the neuromuscular control of the lower limb: A systematic review

Figure 1. Flowchart diagram of the study selection process

The risk of ipsilateral injuries was found after adjusting for the competing risk of contralateral injuries and censored values (HR = 1.85, 95% CI = 0.76-4.46). Similarly, Herman et al. found that lower extremity musculoskeletal injuries occurred at a higher rate in the concussed athletes (45/90 or 50%) than in the non-concussed athletes (30/148 or 20%; p < 0.01). The odds of sustaining a lower limb musculoskeletal injury were 3.39 times higher in the concussed athletes (95% confidence interval 1.90-6.05; p < 0.01). Overall, the number of days lost because of injury was similar between concussed and non-concussed athletes (median 9 versus 15; p = 0.41).

Lynall et al. also found that lower extremity injuries accounted for most injuries (56.3%), and concussions for 4.5% of total injuries. For every previous concussion, the odds of sustaining a subsequent time-loss lower extremity injury increased 34% (odds ratio [OR] = 1.34; 95% confidence interval [CI] = 1.13, 1.60). The number of previous concussions had no effect on the odds of sustaining any subsequent lower extremity injury (OR = 0.97; 95% CI = 0.89, 1.05) or a non-time-loss injury (OR = 1.01; 95% CI = 0.92, 1.10).

Makdissi et al. concluded that 199 concussive injuries were observed in 158 players. Sixty-one concussive injuries were excluded from analysis because of incomplete data (45 players) or presence of concurrent injury (16 players). Of the 158 concussive injuries assessed, 127 players returned to play without missing a game (92%). The remainder of
Concussed players returned to play after missing a single game (8%). Overall, there was no significant decline in concussed players on return to competition.

In soccer, Nordstrom et al.\textsuperscript{21} found during the follow-up period, 66 players sustained concussions and 1599 players sustained other injuries. Compared with the risk following other injuries, concussion was associated with a progressively increased risk of a subsequent LE injury in the first year (0 to <3 months, HR=1.56, 95% CI 1.09 to 2.23; 3 to <6 months, HR=2.78, 95% CI 1.58 to 4.89; 6–12 months, HR=4.07, 95% CI 2.14 to 7.76). In the second model, after adjustment for the number of injuries in the year preceding the concussion, this injury remained significantly associated with the risk of subsequent injury in the first year (HR=1.47, 95% CI 1.05 to 2.05). Finally, Nyberg et al.\textsuperscript{22} found that players who sustained a concussion did not have an increased risk for subsequent injuries compared with players who experienced a knee injury; however, concussed athletes experienced significantly more serious subsequent LE injuries (absence >28 days) within 21 days after return to play.

When accounting for previous LE injury, Fino et al.\textsuperscript{23} found college athletes post-SRC to be at a 67% greater risk for subsequent LE injury when matched to those of the same team. While the exact location of LE injury following SRC was unclear in the studies, determined significant associations between SRC (reported, unreported, and unrecognized) and lateral ankle sprain, knee injury, and LE muscle strain. This investigation consisted of 335 athletes (61% female) who completed a questionnaire pertaining to their injury history following the completion of their collegiate career. Although limitations exist due to self-reporting and an inability to determine order of injury occurrence, athletes with a stated SRC history were 1.6–2.9 times more likely to report a LE injury, findings similar to related retrospective data.\textsuperscript{24}

Various authors have also suggested that collegiate athletes are at greater risk for LE injury at 90 days,\textsuperscript{25} 180 days,\textsuperscript{26} and 365 days\textsuperscript{27} post-SRC. collegiate male and female athletes across seven sports were 2.5 times more likely to sustain a LE musculoskeletal injury compared to matched counterparts 90 days after sustaining an SRC.\textsuperscript{28} It was determined that 17% of post-SRC athletes sustained a non-contact LE injury, while the incidence of similar injury was less (9%) in the matched control group.\textsuperscript{29} In a related study of collegiate basketball, soccer, and lacrosse athletes, LE musculoskeletal injury risk was 3.4 times greater in athletes who were previously concussed when matched to those of comparable athletic status during a 90 day follow-up period.\textsuperscript{30} Male soccer athletes with prior SRC were 3.7 times more likely to injure the LE, while female sport participants demonstrated a 2.8 times greater risk for LE injury after SRC.\textsuperscript{31} These findings at 90 days post-SRC have not been observed in other collegiate cohorts,\textsuperscript{32} and it is presently unclear why these findings are equivocal. While Lynall et al. did not observe differences at 90 days, athletes were significantly more likely to sustain a LE injury at 180 days (2.02 times), and 365 days (1.97 times) post-SRC compared to pre-concussive injury rates.\textsuperscript{33} In addition to youth and collegiate athletes, professional athletes have demonstrated greater injury risk and frequencies following SRC.

**DISCUSSION**

This systematic review and meta-analysis revealed that individuals appear to be at greater risk of sustaining a lower extremity musculoskeletal injury following a concussion compared to individuals without a history of concussion.\textsuperscript{34} Of the 10 included studies, some were of low quality which affects the strength of the conclusions of this systematic review.

Concussions can involve multiple and varied regions of the brain, including those associated with orienting and executive components of visuospatial attention and stimuli. When one suffers a concussion, these parts may become injured or impaired, which compromises the ability to process stimuli in terms of disengagement, movement, and re-engagement. Even after concussion symptoms resolve, there is a possibility that muscle strength and neuromuscular impairments are still present.\textsuperscript{35}

There is ongoing research that has revealed that individuals continue to experience neuromuscular, neurocognitive, sensory processing, and balance deficits related to concussion well after RTP. While LE injury risk has been associated with SRC occurrence across multiple collegiate populations, previous investigations have failed to control for LE injury history prior to an SRC, a potential confounding variable that may influence subsequent injury risk.\textsuperscript{36} For example, athletes returning from ACL reconstruction are 15 times more likely to reinjure the ACL on the contralateral or ipsilateral\textsuperscript{37} addition to youth and collegiate athletes, professional athletes have demonstrated greater injury risk and frequencies following SRC.\textsuperscript{37} Elite male European soccer athletes were at greater risk for subsequent injury (combined lower and upper extremity) following SRC occurrence across three time periods (0–3 months, 3–6 months, and 6–12 months post-SRC with injury risk being greatest at 6–12 months after an SRC.\textsuperscript{38} Following 28 seasons of injury data in professional ice hockey players, researchers concluded that, in comparison to a knee injury, athletes post-SRC were more likely to sustain a subsequent severe LE injury (>28 days recovery) within 21 days of returning to sport.\textsuperscript{39} However, no differences were reported at the seven and 42 day follow-up and the reported injury after the SRC or knee injury was not classified by location.\textsuperscript{40} Furthermore, no differences were observed in the frequency of subsequent injury between athletes who sustained an SRC or knee injury.\textsuperscript{41} Mounting evidence along with this systematic review suggests that athletes with a prior SRC history across all sporting populations are at greater risk for LE injury, although the mechanism for this relationship is presently unclear. Multiple theories have been postulated, such as impaired motor planning and coordination,\textsuperscript{42} reductions in cortical excitability,\textsuperscript{43} and neuromuscular alterations that persist far beyond resolution of traditional post-SRC measures It has been demonstrated through numerous studies that following a concussive event, the majority of athletes are able to return to baseline.
values relating to symptom reporting, performance, and balance/sway within a relatively short time period. However, subtle cognitive and physical deficiencies may persist, only to be revealed during a dynamic sporting environment that tasks performers with completing highly complex maneuvers.

Recent evidence suggests that cognitive deficits related to dual tasking (which is very crucial in soccer), a hallmark of SRC, play a serious role in LE injury risk during sport. Examinations between musculoskeletal injury and cognition determined that collegiate athletes currently injured in the upper or lower extremity performed worse on matching tasks than healthy controls, and no statistical differences were found between athletes with a musculoskeletal injury or SRC on any neurocognitive metrics. Young adults classified as "low performers" on a NP test battery displayed biomechanical patterns suggesting a greater risk for ACL injury when performing dual-task drop landings. Compared to "high performing" individuals, those with a lower score completed landings with greater vertical ground reaction forces, anterior shear forces, knee abduction moment/angle, along with decreased trunk flexion angle. An athlete with deficiencies in processing environmental stimuli and task constraints (such as an athlete post-SRC), may have difficulty preplanning correct movement sequences, may not be able to produce protective muscular forces, which may lead to high impact loads on musculoskeletal components that result in injury.

LIMITATIONS AND FUTURE RESEARCH

The results of the present systematic review should be interpreted carefully in light of its’ limitations. First, restricting the inclusion criteria to only English-language publications may have increased the risk of missing critical information published in other languages. Second, there were only a small number of well-designed studies included, however they may have been underpowered. Third, some of the included studies were of low quality.

FUTURE DIRECTIONS

Rehabilitation professionals should be aware that collegiate athletes may be at increased risk for lower extremity musculoskeletal injury following a sports related concussion, even after being cleared for return to play (RTP). Many of the RTP concussion protocol tests are important, but some are subjective, such as the symptom checklist and assessments. Research has suggested that current concussion testing methods may not possess sufficient sensitivity to detect any lingering concussion-related abnormalities that persist after symptom resolution which may in turn affect motor performance. Future research should attempt to identify new methods to evaluate athletes during the RTP concussion protocol to ensure that they are fully prepared to return to their sport and are not experiencing subtle or lingering deficits when returning to participation.

CONCLUSION

Mounting evidence indicates that athletes with a prior SRC history across all sporting populations may be at greater risk for LE injury, based on moderate to low quality evidence. The reasons for this relationship is presently unclear and needs more research to discern the underlying mechanisms.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

Submitted: May 16, 2023 CDT, Accepted: August 19, 2023 CDT
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High Compliance with the 11+ Injury Prevention Program Results in Better Win-Loss Records

Holly Silvers-Granelli1,2, Mario Bizzini3, Bert Mandelbaum4, Amelia Arundale5, Ryan Pohlig6, Lynn Snyder-Mackler7

1 Research, Major League Soccer, 2 Research, Velocity Physical Therapy, 3 Research, Schulthess-Klinik, 4 Orthopaedic Surgery, Cedars-Sinai Kerlan-Jobe Institute - Santa Monica, 5 Red Bull’s Athlete Performance Center, 6 Biostatistics, University of Delaware, 7 Department of Physical Therapy, University of Delaware

Keywords: injury prevention, soccer, 11+, compliance, performance

International Journal of Sports Physical Therapy

Background
The 11+ injury prevention program (IPP) has been shown to decrease injury rates. However, few studies have investigated compliance and its overall relationship to team performance.

Hypothesis/Purpose
To examine if level of compliance while implementing the 11+ would impact team performance outcomes (wins, losses, and ties). The authors hypothesized that higher team compliance to the IPP would be consistent with improved overall team performance (more wins and fewer losses).

Study Design
Prospective, cluster randomized controlled trial

Methods
This study was conducted in NCAA men’s soccer teams for one season and examined the efficacy of the 11+ IPP. The outcome variables examined were levels of compliance and team performance record: wins, losses, and ties. Twenty-seven teams (n=675 players) served as the intervention group (IG) and used the 11+ program while 54 teams (n=850 players) served as the control group (CG). Compliance and team performance were recorded. There were three compliance categories that were defined prospectively, low (LC, <1 dose/week), moderate (MC, >1 and <2 doses/week), and high (HC, >2 doses/week). Descriptive and inferential tests were used to compare the CG, the IG, and compliance to team performance. Three independent t-tests were used to analyze outcome to group (IG vs. CG). A one-way MANOVA test was used to analyze compliance to win/loss/tie record, followed up by one-way ANOVA tests to analyze how compliance impacted wins, losses and ties, independently. Partial η2 measures were calculated to determine the effect size of level of compliance on outcome. A Tukey post-hoc analysis was used to analyze specific differences between levels of compliance and specific outcome measures.

Results
There were significantly more wins (IG: 10.67±2.65 versus CG: 8.15±3.83, CI, 7.95 – 9.69, p = 0.005) and fewer losses (IG: 5.66±1.97 versus CG: 8.12±3.59, CI, 5.66 to 7.43, p = 0.002) recorded for the teams using the 11+ program. There was a statistically significant difference between levels of compliance (high, moderate or low) on the dependent

a Corresponding Author:
Holly Silvers-Granelli, PhD, PT
2716 Ocean Park Blvd, Suite 1065, Santa Monica, CA 90405 USA
Email: hollysilverspt@gmail.com
(310) 871-2823

https://doi.org/10.26603/001c.87502
variables (wins, losses, and ties), F(3, 22) = 3.780, p =0.004; Wilks’ Λ = .435; partial η² = .340.

Conclusion
The 11+ has the capacity to improve overall team performance in male collegiate soccer teams. The higher the compliance, the more favorable the team performance. This research may be a vital addition when attempting to persuade coaching staffs to adopt an IPP into their training regimen.

Level of Evidence
Level I

INTRODUCTION
Compliance and adherence to injury prevention programs (IPP) during the coaching implementation phase has been a significant obstacle, from a public health perspective.1,2 Universally, implementation rates for scientifically vetted IPPs have been historically low, and even if a successful implementation occurs, the compliance to such programs tends to decrease over time.3-5 Low compliance to an IPP has been linked to increased injury rates over the course of a competitive season.6-8 Establishing a dose-response relationship between neuromuscular training programs and injury incidence rates would, ostensibly, serve as a positive incentive for coaches and athletes to regularly utilize these prevention programs during training.2 Compliance to training programs has been historically low and inconsistent.1,9,10 Despite efforts to increase coaching awareness and exposure to existing neuromuscular training program efficacy, high levels of program implementation are not achieved, despite effectively impacting coaching attitudes and intent to implement.11 Demonstrating improvements in overall team performance (i.e. improved win-loss records) may help convince the coaching and athletic community to include IPPs into their training regimens.

Injury to an athlete has obvious negative consequences to both the individual athlete, and their team, respectively.12 Coaches are often pressured to make strategic decisions when their preferred starting athlete(s) is unavailable for selection due to injury. Efforts to educate coaches to injury risk and restrictions for athletes returning to play after sustaining an injury have been shown to be successful.13 The percentages of coaches that adopt these procedural methodologies consistently are limited, even at the professional levels of competition.1,14 Coaches’ perceptions of IPPs often are subject to negative associations; such as excessive time consumption, lack of sport specificity, and lack of player commitment.10,15 Despite overwhelming research that suggests that the benefits of utilizing IPP methodology may far outweigh any cost, real or perceived, that might be associated with the internal and external factors that disrupt compliance.16,17

The purpose of this study was to determine if level of compliance while implementing the 11+ would impact team performance outcomes (wins, losses and ties). Furthermore, this study sought to determine if high adherence and compliance to the 11+ IPP would improve overall team performance for male collegiate Division I and II soccer players. The authors hypothesized that higher team compliance to the IPP would be consistent with improved overall team performance (more wins and fewer losses).

METHODS
The parent study was a prospective cluster randomized controlled trial, which was conducted in Men’s Division I and II soccer teams competing in the National Collegiate Athletic Association (NCAA).18 Every Division I and II Men’s soccer program was contacted via email, mail, and telephone for participation in the study. Human ethics internal review board approval and informed consent was obtained through Quorum Internal Review Board (IRB #26182/1) (Seattle, Washington, USA).

Individual player consent was obtained, and a documentation of coaching understanding was signed by each institution to ensure that there was a thorough understanding of the expectations of study participation. Sixty-five institutions were randomly assigned using a computerized random number generator and completed the intervention study during one full competitive collegiate soccer season (August – December): 34 control institutions (N=850 athletes) and 31 intervention institutions (N=775 athletes) with athletes between the ages of 18-25 participated. Four Division II intervention teams discontinued the intervention (N=100 athletes) due to “time and personnel constraints”, while all Division I intervention teams completed the study. For the current study, only the intervention teams that completed the study were used for analysis (27 teams, N = 675 athletes). The competitive season lasted from August through early December. (Figure 1) All sixty-one teams were monitored for team performance (i.e., wins, losses, ties). The 27 intervention teams were also monitored daily for 11+ program compliance by the certified Athletic Trainer (ATC) at each respective institution.

INTERVENTION
The 11+ is an injury prevention program designed as a dynamic warm-up program to address lower extremity injury incurred in the sport of soccer for athletes over the age of 14. It is a twenty-minute field-based program that consists of 15 exercises divided into three separate components: running exercises (8 minutes) that encompass cutting, change of direction, decelerating and proper landing techniques, strength, plyometric and balance exercises (10
minutes) that focus on core strength, eccentric control and proprioception, and running exercises (2 minutes) to conclude the warm-up and prepare the athlete for athletic participation. There are three progressions (level 1, level 2, level 3) that increase the difficulty for each respective exercise. This allows for both individual and team progression throughout the course of the competitive season. In this specific study, the 11+ program served as the intervention program over the course of one competitive collegiate soccer season. The warm-up was implemented under the guidance of the ATC at each institution.

DATA COLLECTION
COMPLIANCE DATA

An internet-based injury surveillance data collection system was used (HeatheAthlete<sup>TM</sup>, Overland Park, Kansas, USA) by every enrolled institution in the study. Utilization of the 11+ program and compliance data were entered weekly by the team’s ATC and verified by the research staff. Upon completion of the competitive soccer season, compliance data entry was confirmed by each ATC and verified with their individual institutions’ data collection system for accuracy and thoroughness. Compliance levels were defined prior to the commencement of the study (low <1 dose per week, moderate 1 to < 2 dose per week and high = 2 or more

Figure 1. Description of NCAA Team Randomization and Study Flow
doses per week). At the completion of the season, compliance was analyzed by implementation consistency. At the culmination of the NCAA season, the performance record for each individual intervention and control team was ascertained by the head researcher (HSG), using an online query.

STATISTICAL ANALYSIS

This manuscript is based on an exploratory post hoc analysis of the data collected from the 11+ Intervention group that was engaged in a larger randomized controlled trial.18 All statistical analyses were conducted utilizing IBM SPSS for Windows version 24 (Armonk, NY). Descriptive data for compliance, exposures and performance are presented as means (M) with standard errors (SE) and 95% confidence intervals (CI). P values of 0.05 or less were considered significant. The outcome variables examined were utilization of the intervention (yes or no), levels of compliance (high, moderate, low), and team performance record (wins, losses and ties). Compliance was defined prospectively as follows: low (LC) ranged between 1-19 doses/season (<1 dose per week), moderate compliance (MC) ranged between 20-59 doses/season (1 to < 2 doses per week), and high (HC) was defined as utilization >40 doses per season (2 or more doses per week). Descriptive and inferential tests were used to compare the Control and Intervention groups, the tertiles of compliance (high, medium, low), to team performance. Three independent t-tests were used to analyze outcome (wins, losses and ties) to group (IG vs. CG). A one-way MANOVA test was used to analyze tertiles of compliance to win/loss/tie record. This was followed up by one-way ANOVA tests to analyze how compliance impacted wins, losses and ties, independently. Partial η2 measures were calculated to determine the effect size of level of compliance on the outcome measures. A Tukey post-hoc analysis was used to analyze specific differences between levels of compliance and specific outcome measures.

RESULTS

Wins, losses and ties were compared between Intervention and the Control groups. For the Intervention group, there were significantly more wins (Intervention: 10.7±3 versus Control: 8.2±4, CI, 8.0 – 9.7, p = 0.005) and fewer losses (Intervention: 5.6±2 versus Control: 8.1±3.6, CI, 5.7 to 7.4, p = 0.002) over the course of the competitive season. There was no significant difference in ties (Intervention: 2.4 ±1.6 versus Control: 2.3 ±1.6, CI, 1.5 to 2.3, p=0.856). (Table 1)

There was a statistically significant difference between among levels of compliance on the outcomes, Wilks’ Λ = .455; F(3,22)=5.78; p =0.004; partial η2 = .340. There was a statistically significant main effect for wins and losses among compliance groups (F(2, 24) = 12.38, p < .001; partial η2 = .508; and F(2, 24) = 4.663, p=0.019; partial η2 = .280, respectively. There was no significant effect of compliance on the number of ties (F(2, 24) = 1.609, p=0.221; partial η2 = .118. Tukey post-hoc tests showed that, highly compliant teams had more wins than moderate (p=0.002) or low compliance teams (p=0.001). Highly compliant teams had significantly fewer losses than moderately compliant teams (p=0.019), but not low compliance teams (p=0.122). No significance differences were found between groups for ties. (Table 3)

Overall, level of compliance was statistically different than the control group with respect to performance. Each compliance group (low, moderate and high) had more wins (p=0.005) and fewer losses (p=0.002). There was no statistical difference for ties (p=0.856). (Figure 2)

DISCUSSION

This study analyzed how the implementation of the 11+ IPP impacted overall team performance during a competitive season. In addition, this study analyzed how differences in compliance within the intervention group impacted the win/loss record of the Intervention teams. The results from this study support each of the hypotheses. Implementation of the 11+ demonstrated a positive relationship with overall team performance. The teams that implemented the program recorded more wins and fewer losses throughout the competitive season compared to the Control teams that were using their own warm-up protocols. Furthermore, the teams that were highly compliant utilizers of the 11+ recorded more wins and fewer losses compared to the teams with moderate and low compliance.

This study is the first of its kind to analyze how team win/loss record may be positively impacted by virtue of using the 11+ warm-up program. Prior studies have analyzed how the individual user might be impacted by virtue of using the program.19,20 Implementation of the 11+ IPP has led to significant changes in vertical jump height, improvements in knee biomechanics, increased lower extremity strength, improvement in sprint speed, improvement in proprioceptive balance testing and total body stability.21-27

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Table 1. Comparison of Wins, Losses and Ties in the CG versus IG with Standard Error, 95% Confidence Intervals (CI) and p-values

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Intervention</th>
<th>Standard Error</th>
<th>95% Confidence Interval</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wins</td>
<td>8.15 ± 3.83</td>
<td>10.67 ± 2.63</td>
<td>0.44</td>
<td>7.95 to 9.69</td>
<td>0.005</td>
</tr>
<tr>
<td>Losses</td>
<td>8.12 ± 3.59</td>
<td>5.56 ± 1.97</td>
<td>0.44</td>
<td>5.66 to 7.43</td>
<td>0.002</td>
</tr>
<tr>
<td>Ties</td>
<td>2.29 ± 1.61</td>
<td>2.37 ± 1.64</td>
<td>0.21</td>
<td>1.46 to 2.31</td>
<td>0.856</td>
</tr>
</tbody>
</table>
Positron emission tomography musculature activation analysis of athletes using the 11+ demonstrated increased uptake in the cells of the gluteus minimus, gluteus medius, and rectus abdominis muscles compared to controls. These specific muscles have been hypothesized to have a protective benefit with respect to knee and hip injuries incurred in the sport of soccer. Youth and collegiate soccer players using the 11+ program demonstrated decreases in peak knee abduction during a drop jump, improved peak ankle eversion moment during both preplanned and unanticipated cutting and double leg jump, and increased knee flexion during a drop jump, respectively. These biomechanical changes have demonstrated a protective benefit in reducing lower extremity injury in the soccer athlete, particularly with respect to ACL injury risk. In addition, the 11+ has been shown to be as effective as other traditional warm-up programs in increasing individual oxygen uptake, core temperature and systemic lactate levels. This is an important aspect of the program when medical personnel delineate the value of using the 11+ to directly replace a team's traditional warm-up program.

There have been numerous studies that have demonstrated the merits of the 11+ program with respect to implementation in youth, upper and lower injury rates reduction, decreases in time loss and improved biomechanics. However, the implementation of this program, and others like it, continues to suffer with respect to widespread adoption and implementation in the soccer com-

Table 2. Level of compliance, number of teams (N), N=number of wins represented as Mean ± Standard Deviation (SD), Standard Error, and 95% Confidence Interval limits for tertiles of compliance and team performance.

<table>
<thead>
<tr>
<th>Compliance</th>
<th>Team N</th>
<th>Games Mean ± SD</th>
<th>Std. Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wins</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>8.0±1.63</td>
<td>0.96</td>
<td>6.02 to 9.98</td>
</tr>
<tr>
<td>Moderate</td>
<td>14</td>
<td>9.86±1.46</td>
<td>0.51</td>
<td>8.80 to 10.92</td>
</tr>
<tr>
<td>High</td>
<td>9</td>
<td>13.11±2.57</td>
<td>0.64</td>
<td>11.79 to 14.43</td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>6.25±1.89</td>
<td>0.87</td>
<td>4.46 to 8.04</td>
</tr>
<tr>
<td>Moderate</td>
<td>14</td>
<td>6.29±1.9</td>
<td>0.47</td>
<td>5.33 to 7.24</td>
</tr>
<tr>
<td>High</td>
<td>9</td>
<td>4.11±1.36</td>
<td>0.58</td>
<td>2.92 to 5.31</td>
</tr>
<tr>
<td>Ties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>3.5±2.38</td>
<td>0.80</td>
<td>1.84 to 5.16</td>
</tr>
<tr>
<td>Moderate</td>
<td>14</td>
<td>2.43±1.79</td>
<td>0.43</td>
<td>1.54 to 3.32</td>
</tr>
<tr>
<td>High</td>
<td>9</td>
<td>1.78±0.67</td>
<td>0.54</td>
<td>0.67 to 2.88</td>
</tr>
</tbody>
</table>

Table 3. Comparison of Outcome (wins, loss or tie) to compliance (low, moderate or high)

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Compliance comparison</th>
<th>Mean Difference</th>
<th>Standard Error</th>
<th>p-value</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
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<tr>
<td>Wins</td>
<td>Low vs. Moderate</td>
<td>-1.86</td>
<td>1.09</td>
<td>0.224</td>
<td>-4.58 to 0.86</td>
</tr>
<tr>
<td></td>
<td>Low vs. High</td>
<td>-5.1111*</td>
<td>1.15</td>
<td>0.001</td>
<td>-7.99 to -2.23</td>
</tr>
<tr>
<td>Low vs. Moderate</td>
<td></td>
<td>1.86</td>
<td>1.09</td>
<td>0.224</td>
<td>0.63 to 3.08</td>
</tr>
<tr>
<td></td>
<td>Low vs. High</td>
<td>-3.2540*</td>
<td>0.82</td>
<td>0.002</td>
<td>-5.30 to -1.20</td>
</tr>
<tr>
<td>Low vs. High</td>
<td></td>
<td>5.1111*</td>
<td>1.15</td>
<td>0.001</td>
<td>2.23 to 7.99</td>
</tr>
<tr>
<td></td>
<td>Low vs. Moderate</td>
<td>3.2540*</td>
<td>0.82</td>
<td>0.002</td>
<td>1.20 to 5.30</td>
</tr>
<tr>
<td>Loss</td>
<td>Low vs. Moderate</td>
<td>-0.04</td>
<td>0.99</td>
<td>0.999</td>
<td>-2.50 to 2.43</td>
</tr>
<tr>
<td></td>
<td>Low vs. High</td>
<td>2.14</td>
<td>0.99</td>
<td>0.122</td>
<td>-0.47 to 4.75</td>
</tr>
<tr>
<td>Moderate</td>
<td>Low vs. High</td>
<td>0.04</td>
<td>0.99</td>
<td>0.999</td>
<td>-2.43 to 2.50</td>
</tr>
<tr>
<td></td>
<td>Low vs. Moderate</td>
<td>2.1746*</td>
<td>0.74</td>
<td>0.019</td>
<td>0.32 to 4.03</td>
</tr>
<tr>
<td>High</td>
<td>Low vs. High</td>
<td>-2.14</td>
<td>1.04</td>
<td>0.122</td>
<td>-4.75 to 0.47</td>
</tr>
<tr>
<td></td>
<td>Low vs. Moderate</td>
<td>-2.1746*</td>
<td>0.74</td>
<td>0.019</td>
<td>-4.03 to -0.32</td>
</tr>
<tr>
<td>Tie</td>
<td>Low vs. Moderate</td>
<td>1.07</td>
<td>0.91</td>
<td>0.479</td>
<td>-1.20 to 3.35</td>
</tr>
<tr>
<td></td>
<td>Low vs. High</td>
<td>1.72</td>
<td>0.97</td>
<td>0.196</td>
<td>-0.69 to 4.13</td>
</tr>
<tr>
<td>Moderate</td>
<td>Low vs. High</td>
<td>-1.07</td>
<td>0.91</td>
<td>0.479</td>
<td>-3.35 to 1.20</td>
</tr>
<tr>
<td></td>
<td>Low vs. Moderate</td>
<td>0.65</td>
<td>0.69</td>
<td>0.616</td>
<td>-1.06 to 2.37</td>
</tr>
<tr>
<td>High</td>
<td>Low vs. Moderate</td>
<td>-1.72</td>
<td>0.97</td>
<td>0.196</td>
<td>-4.13 to 0.69</td>
</tr>
<tr>
<td></td>
<td>Low vs. High</td>
<td>-0.65</td>
<td>0.69</td>
<td>0.616</td>
<td>-2.37 to 1.06</td>
</tr>
</tbody>
</table>
The reasons that coaches provide for refusing to implement IPPs include; time constraints, economic cost, complexity, lacking the personnel to conduct the program, boredom with using a consistent warm-up, lack of sport specificity and lack of player commitment or belief in the program. In the German amateur level soccer clubs, more than half of the surveyed participants were not aware of the 11+ IPP. Among the coaches who were familiar with the IPP, however, 75% reported utilizing it regularly (at least once per week). Variables that were associated with increased utilization of the 11+ IPP included holding a coaching license, high competitive level, and coaching a youth team. A study compared the implementation of the 11+ IPP among Australian and Saudi Arabian soccer coaches. In Australia 75% implemented the 11+ IPP, but only 51% implemented the program as it is recommended. In Saudi Arabia, only 40% used the 11+, but 70% of those coaches reported using all the 11+ exercises as recommended. In the United States, the 11+ was used an an IPP in high school aged athletes with no reduction in lower extremity injury rate. However, only 32% of coaches reported that the 11+ was implemented at least twice a week. Without proper implementation fidelity and compliance, the researchers cannot expect these programs to demonstrate the intended benefit of injury mitigation.

The results of the current study suggest that in addition to improving overall compliance, program fidelity must also be considered. To improve the rate of IPP implementation fidelity, education should directly address relative advantage, compatibility, and complexity. In order to facilitate optimal implementation of an IPP, it is important to emphasize our results which demonstrated improved winning percentage. Relaying the relative advantage and performance benefit of IPPs may increase the likelihood of coaches, managers and players to adopt programs with more consistency, and with adequate adherence and program fidelity. This is a critically important message that may optimally impact adoption rates and overall injury mitigation.

Prior research has demonstrated that team performance (games won) is often negatively correlated to injury rate. In addition, increased injury rates that impact the highest ranked players are detrimental to team success. Player availability, particularly in late season and post-season play, is very important to a coaching staff. The premise that an IPP may improve player availability should also be emphasized when attempting to facilitate consistent program implementation. The researchers have previously shown in this cohort that in the Intervention teams, the 11+ significantly decreased time loss to injury by 28.6%. Player availability may partially explain why the Intervention teams in our study won more games than the control team. While using a neuromuscular training program, such as the 11+, the programs were not designed to improve overall athleticism or increase a player’s level of skill. However, the notion of improved overall player durability and mitigation of injury risk gives a player an advantage and an opportunity to be available to play more consistently throughout the season. This improvement in overall player availability may assist a coaching and managerial staff in strategizing for in-season and post-season play more consistently.

LIMITATIONS

The limitations of this study include the fact that this study was only included male Division I and Division II collegiate soccer players and did not include women or lower divisions within the NCAA collegiate system. The study was only conducted for one competitive season, and performance was only tracked for that season. Also, individual compliance was not tracked for each player. Compliance was tracked as a team, thus individual variances in compliance were not captured in this study.
CONCLUSIONS

The findings of this current study indicate that implementing the 11+ has the capacity to improve overall team performance in comparison to an age and skill matched control group. The higher the compliance to the 11+ program, the more favorable the team performance was, with respect to more wins and fewer losses. This research may be persuasive in encouraging coaching staffs to implement an injury prevention intervention in training. This data may assist in shifting the paradigm to enhance overall IPP program adoption, improve team performance and decrease overall injury rates.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

Submitted: June 20, 2023 CDT, Accepted: August 09, 2023 CDT
REFERENCES


Hop to It! The Relationship Between Hop Tests and The Anterior Cruciate Ligament – Return to Sport Index After Anterior Cruciate Ligament Reconstruction in NCAA Division 1 Collegiate Athletes

Michael Zarro1,2, Madelyn Dickman1, Timothy Hulett1, Robert Rowland1,2, Derrick Larkins1, Jeffrey Taylor1, Christa Nelson4

1 Physical Therapy and Rehabilitation Science, University of Maryland, Baltimore, 2 Orthopaedics, University of Maryland, Baltimore, 3 Physical Therapy, High Point University, 4 Physical Therapy, Northwestern University

Keywords: Anterior Cruciate Ligament, ACL reconstruction, hop testing, rehabilitation, return to sport, ACL-RSI, psychological status, physical therapy, athletic training, sports medicine, orthopedics

https://doi.org/10.26603/001c.86130

Background
Outcomes after anterior cruciate ligament reconstruction (ACLR) may not be optimal, with poor physical and psychological function potentially affecting return to sport (RTS) ability. Understanding the relationship between commonly used hop tests and the Anterior Cruciate Ligament – Return to Sport Index (ACL-RSI) may improve rehabilitation strategies and optimize patient outcomes.

Hypothesis/Purpose
The purpose of this study was to examine the relationship between ACL-RSI scores and limb symmetry index (LSI) for the single hop for distance (SHD), triple hop for distance (THD), crossover hop for distance (CHD), timed 6-meter hop (T6H), and single leg vertical hop (SLVH) in a cohort of National Collegiate Athletic Association (NCAA) Division 1 collegiate athletes after ACLR. The hypothesis was that SLVH LSI would be more highly correlated with ACL-RSI score than all horizontal hop tests.

Study design
Cross-Sectional Study

Methods
Twenty-one National Collegiate Athletic Association (NCAA) Division 1 collegiate athletes (7 males, 14 females) at 6.62 ± 1.69 months after ACLR were included in this retrospective study. Primary outcomes were ACL-RSI score and LSI for SHD, THD, CHD, T6H, and SLVH. The relationship between ACL-RSI scores and performance on hop tests (LSIs) was evaluated using correlation analysis and step-wise linear regression (p ≤ 0.05).

Results
There were significant correlations found when comparing ACL-RSI and the LSI for SHD (r = 0.704, p < 0.001), THD (r = 0.617, p = 0.003), CHD (r = 0.580, p = 0.006), and SLVH (r = 0.582, p = 0.006). The CHD explained 66% (R² value of 0.660) of the variance in the ACL-RSI, while the other hop tests did not add to the predictive model.

a Corresponding author:
Michael Zarro
100 Penn St
Allied Health Building, Room 240I
Baltimore, MD 21201
(410) 706-3449 (phone)
(410) 706-6387 (fax)
Michael.zarro@som.umaryland.edu
Conclusions
Physical function has the capacity to influence psychological status after ACLR. Clinicians should recognize that SLVH, SHD, THD, and CHD are correlated with ACL-RSI and improvements in physical function during rehabilitation may improve psychological status and optimize RTS after ACLR.

Level of evidence
Level 3

INTRODUCTION
There are over 120,000 anterior cruciate ligament (ACL) tears per year in the United States.1 In athletes, the majority of these tears are addressed with ACL reconstruction (ACLR) surgery.2 Post-surgical rehabilitation attempts to restore knee function and promote return to activities of daily living (ADLs) and sport. However, despite surgery and rehabilitation, outcomes after ACLR may not be optimal. A systematic review of prospective studies found that 5.8% of patients sustained an ipsilateral ACLR autograft failure and 11.8% of patients had an ACL tear in the contralateral limb within the first five years after surgery.3 Arden et al. reported that while 74% to 87% of patients returned to sports, only 59% to 72% of patients returned to their pre-injury sport, and only 46% to 63% of patients returned to competitive sports.4 Furthermore, fear of re-injury may contribute to the inability to return to sport. Kvist et al. found in a survey of patients after ACLR, of the 47% that had not returned to their pre-injury activity, with 24% of those patients reporting fear of re-injury as the reason.5

To optimize outcomes, sports medicine and rehabilitation professionals should attempt to restore patients to their prior level of function, including pre-injury physical and psychological performance. Clinicians may use return to sport (RTS) testing batteries to measure these outcomes and guide rehabilitation and return to sport after ACLR.6-10 A common return to sport test battery may include a series of horizontal and vertical hops.6,11-16 These tests are proposed to evaluate lower extremity status in a manner that is relevant to athletic ability by assessing dynamic movement in multiple planes.6,11,15 Patient reported outcome measures (PROMs) such as the Anterior Cruciate Ligament – Return to Sport Index (ACLR-RTS) may also be included in RTS testing batteries after ACLR to quantify subjective information regarding patients’ psychological status, an area of paramount importance that may influence return to play ability and fear of re-injury.17-22

Many other RTS tests have been described to assess various physical, neurocognitive, and psychosocial outcomes however it is difficult to design the optimal RTS battery as the evidence is emerging (and is mixed) regarding the association between RTS testing, successful return to play, and future injury risk.23 Sports medicine and rehabilitation professionals must balance the challenges of clinical practice with a detailed understanding of RTS testing options in order to provide optimal care to patients after ACLR.23-30

Despite the challenges of RTS testing, hop testing and collection of PROMs are simple, low cost, and easy to perform in the clinic. They have demonstrated appropriate reliability and validity to evaluate outcomes after ACLR.18,31 The purpose of this study was to examine the relationship between patient-reported ACL-RSI scores and limb symmetry indices (LSIs) for single hop for distance (SHD), triple hop for distance (THD), crossover hop for distance (CHD), timed 6-meter hop (T6H), and single leg vertical hop (SLVH) in a cohort of National Collegiate Athletic Association (NCAA) Division 1 collegiate athletes after ACLR. Further research into the intersection between psychological status and functional performance may provide valuable insight into drivers of optimal outcomes after ACLR. The hypothesis was that SLVH LSI would be more highly correlated with ACL-RSI score than all other hop tests after ACLR as its vertical component may better reflect perceived knee function and influence self-reported psychological status.

METHODS
PARTICIPANTS
A retrospective review was conducted to examine a consecutive series of patients between August 2018-May 2022 who met the inclusion criteria of 1) being an NCAA Division 1 collegiate athlete referred one of two Sports Medicine practices and 2) having undergone unilateral ACLR. Patients were excluded from the study for 1) a history of prior ACLR to either knee or 2) any other lower extremity musculoskeletal surgery within the previous two years. Based on previous studies, an a priori power analysis was conducted to determine that a sample size of 14 was required to detect an effect size of 0.8 for the primary outcome measure, ACL-RSI, with α ≤ 0.05 and a power (1 - β) = 0.80.11,14 The Institutional Review Board at the University of Maryland determined this study to be exempt.

PROCEDURES
Demographic and outcomes data were extracted and de-identified from subjects’ electronic medical records. Demographic data is included in Tables 1 and 2. Outcomes included LSI for SHD, THD, CHD, T6H, and SLVH and ACL-RSI score and are reported in Table 3. Data were collected as part of usual clinical practice by two physical therapists who are board-certified in either sports or orthopedic physical therapy and each have over nine years of experience working with patients with ACL injuries.

Testing procedures for hop tests included standardized instructions, warmup, and two practice trials followed by two test trials. Test trials were averaged and included in statistical analysis.6 The testing order began with the SHD, THD, and CHD which were performed over ground and
measured with a tape measure. The T6H followed and was performed over ground and measured with the stopwatch function on a smart phone. The SLVH was last and was performed using the Just Jump System (JJS, Probotics Inc, Huntsville, AL, USA), a commercially available jump mat that calculates jump height and is valid when compared to three-camera motion analysis.32

For all hop tests, LSIs were calculated by dividing the result on the involved limb by the result on the uninvolved limb and multiplying by 100 to produce a percentage, except for the T6H, when the numerator and denominator were reversed as a lower time indicates better performance. For all hop tests, an LSI less than 100% indicates a worse performance on the surgical limb compared to the non-surgical limb while a value greater than 100% indicated better performance on the surgical limb compared to the non-surgical limb.

The ACL-RSI is a twelve-item PROM that evaluates emotions, confidence in performance and risk appraisal and has been validated for use after ACLR.18 It was administered electronically using a smart phone application after all completion of all hop tests with the final score expressed as a percentage out of 100% (Felipe Andai Ignacio, Orthosoft ©).18 A higher percentage on the ACL-RSI indicates greater psychological function in the context of return to sporting activity.

STATISTICAL ANALYSIS

Descriptive statistics (means and standard deviations) were calculated for demographic data and all dependent variables (hop test LSI and ACL-RSI score). Normality of the primary outcome measures was assessed using Shapiro-Wilk test. Due to a significant Shapiro-Wilk test for five of the six variables (indicating non-normal nature of the data), a non-parametric Spearman’s Rho correlation coefficient was used to determine if a significant relationship exists between LSI for each hop test and ACL-RSI. Significance level was determined a priori as p ≤ 0.05. Correlations were qualified as very strong (r = 0.90-1.00), strong (r = 0.70-0.89), moderate (r = 0.40-0.69), weak (r = 0.10-0.39) or negligible (r = 0.00-0.10).33

Finally, LSI variables determined to have a significant correlation with RSI were then utilized in a step-wise linear regression model to determine which hop tests (independent variables) best predicted the ACL-RSI (dependent variable). All statistical analyses were performed using SPSS version 28.0.0.1 (IBM Corp.).

RESULTS

A total of 21 patients (7 males, 14 females) with an average age of 20.38 ± 1.67 years were included (Table 1). Sport played by each patient is displayed in Table 2. All patients had undergone primary ACLR with bone-patellar tendon-bone autograft and were an average of 6.62 ± 1.69 months since surgery. Descriptive statistics (means and standard deviations) for all outcome measures are included in Table 3.

<table>
<thead>
<tr>
<th>Demographic variable</th>
<th>All (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male: Number (%)</td>
<td>7 (33%)</td>
</tr>
<tr>
<td>Female: Number (%)</td>
<td>14 (67%)</td>
</tr>
<tr>
<td>Age, years</td>
<td>20.38 ± 1.67</td>
</tr>
<tr>
<td>Height, meters</td>
<td>1.74 ± 1.12</td>
</tr>
<tr>
<td>Weight, kilograms</td>
<td>73.31 ± 14.81</td>
</tr>
<tr>
<td>Body mass index, kilograms/meters²</td>
<td>24.05 ± 2.54</td>
</tr>
<tr>
<td>Time since surgery, months</td>
<td>6.62 ± 1.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sport Played</th>
<th>All (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Women’s Soccer</td>
<td>3</td>
</tr>
<tr>
<td>Men’s Soccer</td>
<td>1</td>
</tr>
<tr>
<td>Women’s Lacrosse</td>
<td>5</td>
</tr>
<tr>
<td>Men’s Lacrosse</td>
<td>3</td>
</tr>
<tr>
<td>Field Hockey</td>
<td>2</td>
</tr>
<tr>
<td>Volleyball</td>
<td>1</td>
</tr>
<tr>
<td>Gymnastics</td>
<td>2</td>
</tr>
<tr>
<td>Track &amp; Field</td>
<td>1</td>
</tr>
<tr>
<td>Football</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcome Measure</th>
<th>Mean ± Standard Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHD LSI</td>
<td>88.64 ± 13.92%</td>
</tr>
<tr>
<td>THD LSI</td>
<td>90.09 ± 11.63%</td>
</tr>
<tr>
<td>CHD LSI</td>
<td>92.31 ± 12.38%</td>
</tr>
<tr>
<td>T6H LSI</td>
<td>96.31 ± 14.95%</td>
</tr>
<tr>
<td>SLVH LSI</td>
<td>76.25 ± 14.68%</td>
</tr>
<tr>
<td>ACL-RSI</td>
<td>78.76 ± 16.73%</td>
</tr>
</tbody>
</table>

There were significant correlations found between ACL-RSI and SHD, THD, CHD, and SLVH (Figure 1). Overall, the correlation was strong when comparing ACL-RSI and the LSI for SHD (r = 0.704, p < 0.001), moderate when comparing ACL-RSI and the LSI for THD (r = 0.617, p = 0.003), CHD (r = 0.580, p = 0.006), and SLVH (r = 0.582, p = 0.006). There was a poor correlation (non-significant) between ACL-RSI and the LSI for the T6H (r = 0.252, p=0.271).

While the LSI for SHD, THD, CHD, and SLVH were significantly correlated with ACL-RSI, when all four of these vari-

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Table 1. Patient demographics (Nominal data are displayed as number (%), interval and ratio data are displayed as mean ± standard deviation)

Table 2. Sport Played by Patients

Table 3. Descriptive Statistics (Means ± Standard Deviations) for Primary Outcome Measures
Figure 1. Relationship between ACL-RSI and LSI for each of the five hop tests, with ACL-RSI (y-axis) compared to each horizontal hop tests (A-E, x-axis)


Table 4. Regression model developed to predict ACL-RSI

<table>
<thead>
<tr>
<th>Predictor variables</th>
<th>R</th>
<th>R²</th>
<th>Adjusted R²</th>
<th>R² change</th>
<th>SE of estimate</th>
<th>Regression coefficients</th>
<th>Unstandardized B</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.812</td>
<td>0.66</td>
<td>0.642</td>
<td>0.66</td>
<td>10.02</td>
<td>-22.529</td>
<td>0.197</td>
<td></td>
</tr>
<tr>
<td>Crossover hop for distance (CHD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.097</td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Excluded variables</th>
<th>β in</th>
<th>t</th>
<th>p</th>
<th>Partial correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single hop for distance (SHD)</td>
<td>0.127</td>
<td>0.528</td>
<td>0.604</td>
<td>0.123</td>
</tr>
<tr>
<td>Triple hop for distance (THD)</td>
<td>0.107</td>
<td>0.43</td>
<td>0.673</td>
<td>0.101</td>
</tr>
<tr>
<td>Single limb vertical hop (SLVH)</td>
<td>0.31</td>
<td>1.747</td>
<td>0.098</td>
<td>0.381</td>
</tr>
</tbody>
</table>

DISCUSSION

The initial hypothesis that SLVH LSI would be more highly correlated with ACL-RSI score than all horizontal hop tests was not supported. The correlation between ACL-RSI and SLVH was moderate, as were the correlations between ACL-RSI and THD and CHD. The correlation was strongest between ACL-RSI and SHD. Additionally, the CHD explained 66% of the variance in ACL-RSI and was the strongest predictor variable shown in the regression analysis.

The SHD, THD, and CHD require the patient to decelerate horizontal momentum in the sagittal plane. These tests may simulate deceleration and landing in the context of sport and explain their correlation with ACL-RSI. Furthermore, the patients can self-reflect on their outcomes as the tape measure in the testing area provides immediate feedback regarding hop distance while providing an exter-
nal focus of attention. The perception of successful performance on horizontal hop tests may influence ACL-RSI scores as patients may be more likely to believe that they will perform well on deceleration and landing tasks in sport.

Furthermore, the CHD provides an additional challenge to frontal and transverse plane stability that may be more related a change of direction or cutting activity, directly stressing the function of the ACL.6,35 Approximately 70% of ACL injuries are non-contact and caused by multidirectional forces during landing, cutting, and deceleration movements during sport.36-38 Patients may be familiar with these tasks and their relationship to injury mechanism which may indicate why performance on the CHD explained approximately two-thirds of the variance in ACL-RSI score and remained the best predictor variable in the overall regression model.

Despite not demonstrating the highest correlation with ACL-RSI, the SLVH was moderately correlated and does carry clinical value. For example, this test requires concentric impulse to achieve high jump heights, likely making it a good proxy for quadriceps function which may influence overall psychological status.11,13,14,16,39,40 Previous research has demonstrated that SLVH is sensitive to capacity at the knee joint and patients typically exhibit greater asymmetries when compared to horizontal hop tests suggesting it is relevant to a comprehensive evaluation.11,14,16

Testing order may also have affected the results as SLVH was performed as the final hop test. Though there has been no published research specifically evaluating the effect of test order on performance after ACLR, there is evidence that neuromuscular fatigue can diminish functional performance, knee stability, and increase forward tibial translation.41 This is problematic as authors have proposed that neuromuscular fatigue is a risk factor for ACL injury and reinjury.42 Interestingly, during RTS testing, fatigue may decreased performance more in the involved limb than the involved limb after ACLR.43 In the case of the present study, SLVH performance could be decreased on the uninjured limb as it was tested last, altering LSI asymmetry. This may result in a weaker correlation and variance relationship with ACL-RSI compared to horizontal hop tests performed earlier in the testing battery and should be considered in future studies.

Criterion- and performance-based testing remains a critical component of the return-to-sport process. Without these objective measures, the clinical decision process would rely on time since surgery or other non-performance related factors.44 However, there is considerable need to optimize criterion-based return-to-sport testing batteries that typically include a series of strength, performance, neuropsychological, and patient reported outcome measures. Webster and Hewett indicate that only 25% of athletes fully pass a testing battery before returning to sport.25 Further, passing a return-to-sport test may not reduce the overall risk of a subsequent ACL injury, potentially reducing the risk of graft rupture but increasing the risk of contralateral injury.25 A 2021 consensus statement suggested that return-to-sport testing should also involve the assessment of specific functional skills, psychological readiness, and contextual factors such as type of sport, time of season, and level of competition.44

Both the ACL-RSI and single-leg hop tests used in this study can inform return to play decisions. They require minimal equipment or expertise to reliably carry out in a standard clinical setting. Most standard paradigms utilize distances or LSIs as outcome measures of these hop tests, though advanced technology like three-dimensional motion capture systems and force platforms may allow for more discrete measures and analysis and may become more available in the future.45,46

While the data and interactions between ACL-RSI and hop tests is interesting, there are several limitations to consider. First, the study was retrospective in nature, which could introduce selection bias and is limited by the accuracy of the electronic medical record. Strict inclusion and exclusion criteria and careful data extraction by two authors were emphasized to reduce error. Similarly, despite exceeding the number of subjects determined by power analysis, the sample included twice as many females than males and were all NCAA Division 1 collegiate athletes; therefore, the results cannot be generalized to all patients after ACLR. Lastly, as psychological status is multifactorial, the present study is unable to draw conclusions regarding several important variables such as gender, injury mechanism, or playing surface, which likely have a large influence on ACL-RSI. Future studies should investigate these variables to improve the overall understanding of predictors of psychological status after ACLR.

CONCLUSION

The results of this study suggest that physical function has the capacity to influence psychological status after ACLR. To improve outcomes, clinicians should consider this important relationship and recognize that SLVH, SHD, THD, and CHD are correlated with ACL-RSI but the psychomotor properties of each test likely relate to their clinical utility. Specifically, CHD explained the greatest variance in ACL-RSI and may be relevant due to the multiplanar nature of ACL injury. All horizontal hop for distance tests are valuable in that deceleration and landing in the sagittal plane are important qualities to consider as well. The clinical relevance of SLVH lies with its ability to assess knee function with a vertical propulsion bias. Lastly, the T6H did not correlate with ACL-RSI however continuous hopping for speed may still be part of the overall clinical picture. All together these tests appear to influence ACL-RSI through different, yet converging, avenues and carry value as combining them may enhance the robustness of clinical assessment after ACLR. Clinicians should consider the emerging data regarding the benefits and shortcomings of various hop tests to promote a comprehensive approach to rehabilitation and optimize outcomes after ACLR and better appreciate the intersection between physical and psychological function.
CONFLICTS OF INTEREST

The authors have no conflicts of interest to report.

Submitted: February 08, 2023 CDT, Accepted: August 05, 2023 CDT

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Kinematics, Kinetics and Muscle Activity Analysis during Single-leg Drop-jump Landing Followed by an Unanticipated Task: Focusing on Differences in Neurocognitive Function

Satoshi Shibata, Masahiro Takemura, Shumpei Miyakawa

Keywords: anterior cruciate ligament injury, motion analysis, neurocognitive function, unanticipated landing motion

Background
Lower neurocognitive function is a risk factor for anterior cruciate ligament (ACL) injury. However, the mechanism by which lower neurocognitive function increases the risk of ACL injury remains unclear.

Purpose
To clarify the effect of differences in neurocognitive function on landing mechanics during a single-leg drop-jump landing motion followed by an unanticipated task.

Study Design
Cross-sectional study

Methods
Fifteen collegiate female athletes were recruited (20.1 ± 1.3 years, 166.6 ± 7.3 cm, 60.6 ± 6.9 kg) and were divided into two groups (the high-performance (HP) group and the lower-performance (LP) group) using the median Symbol Digit Modalities Test (SDMT) score. Three-dimensional motion analysis was employed for the analysis during the experimental task of a single-leg drop-jump followed by an unanticipated landing task from a 30-cm high box. Joint angular changes of the trunk, pelvis, hip, and knee were calculated within the interval from initial contact (IC) to 40ms. Knee and hip moments were calculated as the maximum values within the interval from IC to 40ms. Surface electromyography data from key muscles were analyzed 50ms before and after IC. Independent t-tests were used to compare the effects of different neurocognitive function on the measurement items. Statistical significance was set at p < 0.05.

Results
The SDMT score was significantly higher in HP group (HP: 77.9 ± 5.5; LP: 66.0 ± 3.4; p < 0.001). The LP group had a significantly greater trunk rotation angular change to the stance leg side (HP: 0.4 ± 0.8; LP: 1.2 ± 0.4; p = 0.020). There were no significant differences between the two groups in terms of joint moments, and muscle activities.

Conclusion
Differences in neurocognitive function by SDMT were found to be related to differences in motor strategies of the trunk in the horizontal plane. Although trunk motion in the sagittal and frontal planes during single-leg drop-jump landing increases the ACL injury risk by affecting knee joint motion, the effect of trunk motion in the horizontal plane remains unclear.
Level of Evidence

3
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INTRODUCTION

Recently, it has been suggested that lower neurocognitive function is a risk factor for anterior cruciate ligament (ACL) injury.1 Swainik et al.1 utilized the "ImPACT" neurocognitive assessment test, primarily used to evaluate function after a concussion, to measure neurocognitive function. This computer-based test can be used to establish a pre-season baseline score. They conducted a retrospective comparison of mean scores between the non-contact ACL-injured group and the healthy control group. Lower scores were present in the non-contact ACL-injured group for reaction time, processing speed, and visual/verbal memory.1 Consequently, it was proposed that diminished neurocognitive function may contribute to the risk of non-contact ACL injuries. However, the precise mechanism by which lower neurocognitive function increases this risk remains incompletely understood.

The hypothesis that reduced neurocognitive function serves as a risk factor for non-contact ACL injuries suggests a need for assessment of alterations in neuromuscular control within the trunk, pelvis, and lower limbs.2,3 Sporting activities entail complex athletic tasks that do not afford athletes the luxury of pre-planning their movements. Moreover, athletes have limited time for cognitive processing during motion selection. Therefore, athletes experience a high cognitive load during sports activities.4 In other words, athletes with poor neurocognitive function may struggle to address postural control during landing motion due to the dual-task demands of situational judgment and movement selection. Specifically, deficiencies in visual attention, self-monitoring, agility/fine motor performance, processing speed/reaction time, and dual-tasking are believed to predispose individuals to landing mechanics that afford a heightened risk of ACL injury within complex sporting environments.5

The effects of difference neurocognitive function on lower limb kinematics and kinetics during unanticipated jump-landing task have been studied in male and female recreational athletes using the Concussion Resolution Index (CRI).6 From the six subtests of the CRI, three indices of Simple Reaction Time, Complex Reaction Time, and Processing Speed have been created and divided into a two groups based on the following criteria: the higher performers group was defined as participants scoring above the 80th percentile in one score and with two scores no lower than 60th percentile, and the low performers group were defined as participants with one subtest score below the 40th percentile and with two scores no higher than the 70th percentile, or with at least two scores below the 50th percentile.2 The low performers group exhibited significantly increased peak vertical ground reaction force (GRF), peak anterior tibial shear force, knee abduction moment, knee valgus angle, and decreased trunk flexion angle.2 Additionally, the landing biomechanics of the low performers group were more consistent with landing biomechanics which have been identified as a risk factor for non-contact ACL injury.6,7 It is important to note that the prior study participants consisted of mixed male and female recreational athletes. Although ACL injuries are more prevalent in males, the incidence is higher in females.8 Analysis of unanticipated single-leg drop-jump landing and cutting motion shows that female athletes have a higher incidence of ACL injury than male athletes due to an increased tendency to demonstrate increased knee valgus angle moment.3,9 In a previous study, only female athletes were included to examine the effects of neurocognitive function on landing mechanics. Moreover, the authors have previously examined the effects of differences in neurocognitive function on an unanticipated cutting motion.10 Female athletes with lower neurocognitive function were found more likely to produce significant greater quadriceps muscle activity patterns, thereby increasing their susceptibility to ACL injuries.10 The present study is an addition to prior projects and focuses on the single-leg drop-jump landing motion from a 50-cm high box.

The purpose of this study was clarify the effect of differences in neurocognitive function on landing mechanics during single-leg drop-jump landing motion followed by an unanticipated task. The authors hypothesized that female athletes with lower neurocognitive function would demonstrate higher knee joint valgus angle and moments, lower trunk forward flexion angle, and show quadriceps dominant muscle activities, all of which are associated with elevated ACL injury risk.

METHODS

PARTICIPANTS

Fifteen female athletes who played basketball or soccer in university athletic clubs were recruited. They belonged to the highest national competition level, and they practiced two to three hours a day, five to six days a week. Exclusion criteria included a history of lower limb injury and concussin within the prior six months, any disorder of the peripheral sensory system, a history of surgery on the lumbar spine or lower limbs, and ADHD or anxiety, which may influence psychomotor speed. Furthermore, alcohol and caffeine intake were restricted on the night before the experiment. All participants provided written informed consent prior to their participation. This study was approved by the Ethical Committee of the Faculty of Health and Sports Sciences at the University of Tsukuba (approval number. 28-37).

NEUROCOGNITIVE TEST

Neurocognitive testing was performed using the Symbol Digit Modalities Test (SDMT). SDMT was performed on the same day as the motion analysis and before the landing task.
operation. Participants were asked to fill out 110 boxes under symbols with a corresponding number within 90 seconds while referring to a key on top of the test form to identify which number goes with each symbol. The number of correct answers was counted.

The SDMT has been widely used to evaluate information processing speed (IPS) and selective attention. It has been utilized for neurocognitive assessment of patients with impaired IPS, as well as for functional evaluation before and after a concussion and for evaluation of neurocognitive function in patients with Multiple Sclerosis. The SDMT is suitable for serial neurocognitive function testing because it is easy to administer, inexpensive, and requires a short assessment time. Inter-rater reliability (ICC 2,1) of the SDMT was reported to be 0.72, and test-retest reliability was reported to be acceptable with r = 0.70-0.80 for healthy adults measured at 1-month or 2-week intervals. This assessment was adopted in this study as a neurocognitive function assessment test because it can be easily measured in sports situations. Furthermore, the SDMT has been reported to have a learning effect, albeit less pronounced compared to the Trail Making Test-B or the Stroop Interference Test. The mean SDMT score has been reported to be 58.2 ± 9.1 (range = 51.87-63.93) for young adults (<30 years), and 55.2 ± 8.9 (range = 44.4-58.7) for middle adulthood (30-55 years). Another study reported a mean score of 53.06 ± 11.50 for male college athletes.

Participants were grouped according to SDMT score. The median SDMT score was used as a cut-off value to group the participants, since the mean of the participants in this study was higher than the reference value (the mean SDMT score: 71.5 ± 7.5). The upper group was the high-performance group (HP group), and the lower group was the lower-performance group (LP group).

EXPERIMENTAL TASKS

The experimental task involved a single-leg drop-jump task from a 30-cm high box using only the dominant leg, followed by three types of unanticipated tasks: side-step cutting, single-leg drop-jump landing, and forward stepping. The dominant leg was defined as the leg with which the participants preferred to kick a ball. In this study, only the single-leg drop-jump landing task was analyzed, since side-step cutting motion had been previously verified.

First, the participants stood on single-leg with the dominant leg on a 30-cm high box placed at the edge of the force platform. They then jumped down toward the center of the force platform and landed on their dominant leg. Immediately after leaving the box, one of the tasks was randomly presented on the personal computer (PC) monitor, and the participants were instructed to execute the one of the three tasks before contact on the force platform. (Figure 1).

In the single-leg drop-jump landing task, the participants were required to maintain a single-leg standing position for two seconds after landing. During the experimental task, both hands were kept on the iliac crests. A failed trial was defined as a case in which participants were unable to maintain a standing position with a single leg for two seconds after landing, if their free leg made contact with the ground, or if their upper limb separated from the waist due to significant rotation and lateral flexion of the trunk. The experiment was terminated when participants successfully completed at least three trials, and the mean values over the three trials for the analysis. Prior to the actual experiment, participants performed five practice trials until they were comfortable with the tasks after sufficient warm-up. The specific content of the warm-up was not specified, and participants were instructed to perform their usual warm-up routine for approximately 15 to 20 minutes.

DATA COLLECTION AND PROCESSING

A three-dimensional motion analysis system, the VICON MX motion analysis system (VICON, Oxford, UK), was used to capture the tasks using 10 infrared cameras with a sampling rate of 250 Hz. Thirty-five retroreflective markers were placed over the whole body of each participant, according to the standard Plug-in Gait model (Helen Hays marker-set). GRF data were obtained at 1,000 Hz from two force platforms (Kistler Instruments, Inc. model 9281C, Winterthur, Switzerland), which were synchronized with the kinematic data. Joint moments were calculated on the side of the dominant leg using a full inverse-dynamic model implemented using the VICON Plug-in Gait. The estimated joint moments were normalized to the body mass of the participants. The joint angles were calculated for the trunk, pelvis, hip joint, and knee joint, while the joint moments were calculated for the hip and knee joints.

Surface electromyography (EMG) data were recorded at 1,500 Hz using a seven-channel EMG system (Telemyo DTS, Noraxon Inc., Scottsdale, AZ, USA) and collected synchronously with motion and force platform data. Bipolar surface electrodes (Ag-AgCl) were separated by 2 cm and placed on the following seven muscles: gluteus medius (GM), adductor longus (Add), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), and semimembranosus (SM). Each electrode was placed as follows: GM, approximately 2 cm below the midpoint of the iliac crest over the muscle belly; Add, approximately 10 cm below the pubic symphysis over the muscle belly; RF, approximately halfway between the upper patella and the anterior superior iliac spine over the muscle belly; VM, approximately 5 cm from the medial patella at 45° over the muscle belly; VL, approximately two-third distal to the point between the patellar lateral side and the anterior superior iliac spine over the muscle belly; SM and BF, approximately halfway between the tibial lateral epicondyle and the ischial tuberosity over the muscle belly. The skin was shaved and cleaned with an alcohol swab before electrode placement.

DATA ANALYSIS

The raw kinematic and GRF data were filtered based on a frequency content analysis of the digitized coordinate data. Marker trajectories were filtered at 7 Hz using a 4th-order Butterworth filter with VICON Nexus 1.6.1 software (Oxford Metrics Ltd., UK). Since ACL injury has been reported to oc-
cur around 40 ms after IC, the analysis window of this study was set from IC to 40 ms. For the analysis of joint angles, the joint angular changes within the analysis window were calculated. Joint moments were calculated by determining the maximum value within the analysis window and using it for the analysis. The IC was defined as the time at which vertical GRF was higher than 10 N.

For EMG data, the stored raw signals were band-pass filtered (20–500 Hz), and root mean square (RMS) processed with a 10 ms time constant using Myomouse (Noraxon Inc., Scottsdale, AZ, USA). Prior to data collection, the RMS data were normalized using the maximum voluntary contraction (MVC) for each muscle (%MVC). The MVC was recorded for five seconds, and the average amplitude was determined from the stable RMS for three seconds. The average activity of the knee flexors (HAM) was calculated from the BF and SM, and activity of the knee extensors (QUAD) was calculated from the VM and VL. The co-contraction ratio (CCR) was calculated as the relative muscle activity of QUAD to HAM. EMG data were recorded for 50 ms before IC (pre-IC), as in the previous study. I chose 50 ms before IC because this is suitable for evaluation of an individual’s pre-planned muscle recruitment strategy. The authors chose 50 ms after IC to assess muscle activation immediately after IC (post-IC). The analysis of muscle activity immediately after IC was conducted to analyze the muscle activity that occurs near the potential timing of ACL injury.

**Figure 1. The procedure of the unanticipated single-leg drop-jump landing task.**

1. Participant stood by stepping on the footswitch with their dominant leg on a 30 cm high box.
2. Immediately after the participant jumped off the box, an experimental task was displayed on the monitor.
3. Participant reacted to the instruction displayed on the monitor.
4. Single-leg drop-jump landing was performed by landing on the force platform with the dominant leg and holding that posture for 2 seconds.

**STATISTICAL ANALYSIS**

Results are presented as means ± standard deviation (SD). Initially, the Shapiro–Wilk test was conducted to check the normality of each measurement. There were no variables for which normality could not be confirmed. Independent t-tests were utilized to compare the differences between the LP and HP groups with respect to the SDMT scores, age, height, body weight, joint angular change, peak joint moment, and muscle activities. The effect size (Cohen’s d) was also calculated and interpreted as weak (0.20), moderate (0.50), and strong (0.80). Statistical significance was set at p < 0.05. All statistical analyses were performed using SPSS Statistics 22.0 (IBM, SPSS Tokyo, Japan).

**RESULTS**

Means and standard deviations for these participants were: age of 20.1 ± 1.3 years, height of 166.6 ± 7.3 cm, weight of 60.6 ± 6.9 kg. For all participants, the mean SDMT score was 71.5 ± 7.5, with a median score was 70. The SDMT score in the HP group was significantly higher than that of the LP group (HP: 77.9 ± 5.5; LP: 66.0 ± 5.4; p < 0.001) (Table 1).

The LP group exhibited a significantly greater trunk rotation angular change toward the stance leg side compared to the HP group (HP: 0.4 ± 0.8; LP: 1.2 ± 0.4; p = 0.020) (Figure 2). There were no significant differences between the two groups in terms of joint moments, and muscle activities (Tables 2, 3). However, the large effect sizes were observed...
Table 1. HP and LP group characteristics, mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>HP (n = 7)</th>
<th>LP (n = 8)</th>
<th>P value</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDMT score</td>
<td>77.9 ± 5.5</td>
<td>66.0 ± 3.4</td>
<td>&lt; 0.001</td>
<td>2.65</td>
</tr>
<tr>
<td>Age (years)</td>
<td>20.0 ± 1.4</td>
<td>20.3 ± 1.3</td>
<td>0.930</td>
<td>0.22</td>
</tr>
<tr>
<td>Body Height (cm)</td>
<td>166.8 ± 8.4</td>
<td>166.4 ± 6.7</td>
<td>0.912</td>
<td>0.05</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>60.8 ± 8.2</td>
<td>60.5 ± 6.0</td>
<td>0.725</td>
<td>0.04</td>
</tr>
</tbody>
</table>

SDMT = Symbol Digit Modalities Test, HP = High-performance group, LP = Lower-performance group
* Significant difference between HP and LP (p<0.05).

Figure 2. Comparison of trunk rotational angular change
* Significant difference between HP and LP (p<0.05)

in the pre-IC CCR (HP: 145.0 ± 113.4%; LP: 74.6 ± 17.5%; p = 0.112, d=0.89) (Table 4).

DISCUSSION

This investigation was conducted to examine the influence of neurocognitive function differences, as measured by SDMT, on kinematics, kinetics, and muscle activation during single-leg drop-jump landing followed by an unanticipated task in female athletes. The findings revealed that the LP group exhibited a significantly larger trunk rotation angular change to the stance leg side during the early landing phase.

Trunk position variations have been reported as potential risk factors for ACL injuries. Previous analyses of single-leg drop-jump landing and cutting motions have indicated a consensus that limited trunk forward flexion and increased lateral trunk flexion towards the injured leg side are associated with a higher risk of ACL injury. However, there have been inconsistent findings regarding trunk rotational movement. Several authors have observed trunk rotation away from the injured leg at the time of ACL injury. Critchley et al. demonstrated that axial trunk rotation during double-leg landing leads to decreased knee flexion angles, increased peak impact vertical GRF, internal knee extension moments, and increased knee abduction and internal rotation angles for the ipsilateral leg when compared to the neutral trunk condition. Furthermore, it has been suggested that cutting motions involving trunk rotation and lateral flexion in the direction of cutting may reduce the risk of ACL injury and enhance performance.

In the current study, participants with lower neurocognitive function exhibited a greater change in trunk rotation angle towards the stance leg side during the early landing phase. Therefore, it is plausible that differences in neurocognitive function are linked to variations in motor strategies of the trunk in the horizontal plane during single-leg drop-jump landing. However, the precise effect of trunk and pelvis movements in the horizontal plane on the occurrence of ACL injuries remains unclear or the amount that is potentially injurious is also not known. Furthermore, the amount of trunk rotation angular change observed in this study was very small and may not be clinically significant. Future studies should concentrate on investigating trunk and pelvis rotational movements and their relationship to the risk of ACL injury.

In this study, a large effect size was observed in the pre-IC CCR, indicated that the LP group had relatively larger quadriceps muscle activity relative to the hamstring just prior to landing. Many previous studies have pointed out that an imbalance between quadr and ham muscle activity during landing may induce ACL injury, and in particular, activity with a predominantly large quadriceps muscle is considered dangerous. Therefore, I would say that the muscle activity observed in this study is muscle activity at high risk for ACL injury.

It is thought that the neurocognitive functions required for athletes were: selective attention for simultaneously processing various information at all times, and instantly performed IPS in a limited time. The authors thought that the SDMT could measure the neurocognitive functions required during sports activities of athletes because it could measure functions such as the ability to IPS and selective attention. Another reason for employing SDMT in the current study is that it can evaluate neurocognitive func-
Table 2. Comparison of joint angular change, mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>HP</th>
<th>LP</th>
<th>p-value</th>
<th>Cohen's d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip angle (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion</td>
<td>6.0 ± 1.5</td>
<td>7.0 ± 2.1</td>
<td>0.318</td>
<td>0.54</td>
</tr>
<tr>
<td>adduction</td>
<td>2.9 ± 1.7</td>
<td>2.9 ± 1.9</td>
<td>0.974</td>
<td>0.00</td>
</tr>
<tr>
<td>internal rotation</td>
<td>4.4 ± 2.1</td>
<td>5.5 ± 2.8</td>
<td>0.431</td>
<td>0.44</td>
</tr>
<tr>
<td>Knee angle (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion</td>
<td>16.4 ± 2.6</td>
<td>18.0 ± 3.1</td>
<td>0.289</td>
<td>0.56</td>
</tr>
<tr>
<td>valgus</td>
<td>-4.1 ± 3.2</td>
<td>-2.6 ± 3.0</td>
<td>0.363</td>
<td>0.19</td>
</tr>
<tr>
<td>internal rotation</td>
<td>9.1 ± 3.0</td>
<td>9.7 ± 4.6</td>
<td>0.769</td>
<td>0.15</td>
</tr>
<tr>
<td>Trunk angle (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>forward tilt</td>
<td>1.3 ± 1.0</td>
<td>1.5 ± 1.0</td>
<td>0.735</td>
<td>0.20</td>
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<tr>
<td>lateral inclination (to free leg)</td>
<td>0.3 ± 0.6</td>
<td>-0.1 ± 0.6</td>
<td>0.265</td>
<td>0.25</td>
</tr>
<tr>
<td>rotation (to free leg)</td>
<td>-0.4 ± 0.8</td>
<td>-1.2 ± 0.4</td>
<td>0.020</td>
<td>* 1.30</td>
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<tr>
<td>Pelvic angle (°)</td>
<td></td>
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<tr>
<td>forward tilt</td>
<td>-0.5 ± 1.2</td>
<td>-0.6 ± 0.9</td>
<td>0.788</td>
<td>0.10</td>
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<tr>
<td>lateral inclination (to free leg)</td>
<td>1.0 ± 0.7</td>
<td>1.3 ± 1.0</td>
<td>0.586</td>
<td>0.34</td>
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<tr>
<td>rotation (to free leg)</td>
<td>-0.9 ± 1.0</td>
<td>-1.3 ± 0.5</td>
<td>0.316</td>
<td>0.52</td>
</tr>
</tbody>
</table>

HP = High-performance group, LP = Lower-performance group, IC = Initial Contact
* Significant difference between HP and LP (p<0.05)

Table 3. Comparison of kinetics data, mean ± SD

<table>
<thead>
<tr>
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<th>HP</th>
<th>LP</th>
<th>P-value</th>
<th>Cohen's d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip moment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion (Nm/kg)</td>
<td>2.2 ± 1.8</td>
<td>2.1 ± 2.4</td>
<td>0.484</td>
<td>0.005</td>
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<tr>
<td>adduction (Nm/kg)</td>
<td>2.9 ± 1.6</td>
<td>2.1 ± 1.1</td>
<td>0.149</td>
<td>0.57</td>
</tr>
<tr>
<td>internal rotation (Nm/kg)</td>
<td>0.004 ± 0.006</td>
<td>0.007 ± 0.006</td>
<td>0.202</td>
<td>0.50</td>
</tr>
<tr>
<td>Knee moment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>flexion (Nm/kg)</td>
<td>1.8 ± 0.4</td>
<td>2.1 ± 0.7</td>
<td>0.108</td>
<td>0.54</td>
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<tr>
<td>abduction (Nm/kg)</td>
<td>4.3 ± 5.5</td>
<td>5.8 ± 4.7</td>
<td>0.286</td>
<td>0.30</td>
</tr>
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</table>

HP = High-performance group, LP = Lower-performance group,

Table 4. Comparison of muscle activity, mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>HP</th>
<th>LP</th>
<th>P-value</th>
<th>Cohen's d</th>
</tr>
</thead>
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<tr>
<td>HAM (% MVC)</td>
<td></td>
<td></td>
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<tr>
<td>pre-IC</td>
<td>46.2 ± 11.4</td>
<td>44.1 ± 23.3</td>
<td>0.837</td>
<td>0.11</td>
</tr>
<tr>
<td>post-IC</td>
<td>44.5 ± 16.9</td>
<td>47.3 ± 21.9</td>
<td>0.793</td>
<td>0.14</td>
</tr>
<tr>
<td>QUAD (% MVC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-IC</td>
<td>41.9 ± 18.8</td>
<td>66.0 ± 39.3</td>
<td>0.162</td>
<td>0.76</td>
</tr>
<tr>
<td>post-IC</td>
<td>84.7 ± 31.0</td>
<td>116.0 ± 67.5</td>
<td>0.151</td>
<td>0.58</td>
</tr>
<tr>
<td>CCR (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-IC</td>
<td>145.0 ± 113.4</td>
<td>74.6 ± 27.5</td>
<td>0.112</td>
<td>0.89</td>
</tr>
<tr>
<td>post-IC</td>
<td>57.7 ± 24.2</td>
<td>53.2 ± 38.8</td>
<td>0.795</td>
<td>0.14</td>
</tr>
</tbody>
</table>

HP = High-performance group, LP = Lower-performance group, IC = Initial Contact, HAM = Knee Flexors, QUAD = Knee Extensors, CCR = Co-Contraction Ratio
tion without the need for specialized equipment before sports activities. Previous research investigating the effects of neurocognitive function on landing and cutting motions have utilized computer tests such as CRI and ImPACT, with no reports using pencil tests. Computer-based tests offer the advantage of simultaneously measuring multiple components of neurocognitive function separately. However, they require special equipment and are difficult to administer easily before engaging in sports activities. This study proposes that differences in SDMT scores, which can be easily assessed before sports activities, may be associated with changes landing mechanics representing the trunk rotation angle during single-leg drop-jump landing followed by an unanticipated task.

Although the current study identified differences in trunk rotation angles during single-leg drop-jump landing followed by an unanticipated task between groups based on SDMT scores, no variations were observed in other kinematic, kinetic, or muscle activity parameters due to differences in neurocognitive function. This may be attributed to the relatively high mean SDMT scores of the participants in our study. The mean SDMT score for all participants in this study was 71.5 ± 7.5, the mean for the LP group was 67.3 ± 5.0, and the lowest score was 61. In comparison, previous studies reported a mean SDMT score of 58.2 ± 9.1 (range = 51.87-63.95) for young adults (<30 years),22 and 53.06 ± 11.50 for male college athletes.25 Therefore, the current study participants exhibited good SDMT scores, and may represent the absence of individuals with low neurocognitive function which may have contributed to the lack of group differences in lower limb mechanics during single-leg drop-jump landing motion. Because ACL injuries occur more frequently in athletes involved in sports activities and less frequently in the general population,38 it was appropriate to focus on highly competitive athletes. The results of the current study suggest that SDMT may be too easy of a task for assessment of neurocognitive function healthy competitive athletes. Future investigations should examine which tests are more likely to identify neurocognitive differences among competitive athletes by employing additional paper-and-pencil tests such as the Trail Making Test or the Stroop Interference Test.

LIMITATION

This study had several limitations. Firstly, the method used for simulation during the unanticipated tasks used in this study was to display a symbol such as a simple arrow on a monitor. This stimulus method was not necessarily consistent with a situation during actual games and might be too simple. To create tasks more closely resembling real sporting scenarios, it may be necessary to employ images of games, models of opposing players, or virtual reality images. Secondly, the authors selected the single-leg drop-jump landing motion from the platform as the experimental task, but this is not a motion that occurs during sports activities. In this study, the single-leg drop-jump landing motion was analyzed to examine the effect of neurocognitive function on the motion as directly as possible. Future studies should incorporate tasks that more closely align with sports activities, such as landing from a rebound in basketball, landing from a header in soccer, or cutting from a dribble. Thirdly, there is always a problem of reliability in three-dimensional motion analysis using surface markers. It has been reported that the use of body surface markers during motion analysis may cause errors in recording actual joint motion, because the position of the marker shifts on the skin.39 Therefore, it is important to recognize that the joint angular changes in the current study may contain some measurement errors. Lastly, the small sample size resulted in insufficient statistical power. However, since there were several items with large effect sizes, it is possible that different results could be obtained by increasing the number of participants. Future studies should strive to enhance the generalizability of my findings by increasing the sample size and conducting similar analyses on male athletes.

CONCLUSION

The female athletes who had low SDMT scores had a statistically greater amount of change in the trunk rotation angle toward the stance leg side during single-leg drop-jump landing followed by an unanticipated task. However, there were no significant differences in other kinematic, kinetic, or muscular activation values due to differences in neurocognitive function. Therefore, differences in neurocognitive function as measured by SDMT affect horizontal trunk movement during single-leg drop-jump landing followed by an unexpected task, but the relationship with ACL injury risk is not clear.

Submitted: January 18, 2023 CDT, Accepted: July 19, 2025 CDT
REFERENCES


Longitudinal Invariance Testing Of The Knee Injury Osteoarthritis Outcome Score For Joint Replacement Scale (KOOS-JR)

Alexandra Dluzniewski¹, Caleb Allred², Madeline P Casanova³, Jonathan D Moore¹, Adam C Cady², Russell T Baker¹

¹ WWAMI Medical Education, University of Idaho, ² Kaiser Permanente

Keywords: structural validity, psychometrics, arthroplasty, patient reported outcome measures

Background
The Knee Osteoarthritis Outcome Score for Joint Replacement (KOOS-JR) is a seven-item patient reported outcome measure used to assess perceived knee health. Though commonly used, the longitudinal psychometric properties of the KOOS-JR have not been established and further characterization of its structural validity and multi-group invariance properties is warranted.

Purpose
The purpose of this study was to evaluate psychometric properties of the KOOS-JR in a large sample of patients who received care for knee pathology.

Study Design
Original research.

Methods
Longitudinal data extracted from the Surgical Outcome System (SOS) database of 13,470 knee pathology patients who completed the KOOS-JR at baseline, three-months, six-months, and one-year. Scale structure was assessed with confirmatory factor analysis (CFA), while multi-group and longitudinal invariance properties were assessed with CFA-based procedures. Latent group means were compared with statistical significance set at \( \alpha \leq 0.05 \) and Cohen's d effect size as \( d = 0.2 \) (small), \( d = 0.5 \) (medium), and \( d = 0.8 \) (large).

Results
CFA results exceeded goodness-of-fit indices at all timepoints. Multi-group invariance properties passed test requirements. Longitudinal analysis identified a biased item resulting in removal of item #1; the retained six-item model (KOOS-JR-6) passed longitudinal invariance requirements. KOOS-JR-6 scores significantly changed over time (\( p \leq .001 \), \( \text{Mdiff} = 1.08 \), Cohen's \( d = 0.57 \)): the highest scores were at baseline examination and the lowest at 12-month assessment.

Conclusions
The KOOS-JR can be used to assess baseline differences between males and females, middle and older aged adults, and patients receiving total knee arthroplasty or non-operative care. Caution is warranted if the KOOS-JR is used longitudinally due to
potential measurement error associated with item #1. The KOOS-JR-6 may be a more viable option to assess change over time; however, more research is warranted.

**Level of Evidence**

3

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**INTRODUCTION**

Osteoarthritis (OA) is a debilitating disease that causes activity limitations for an estimated 14 million Americans.\(^1\)\(^,\)\(^2\) Most individuals suffering from OA are over the age of 65, and a substantial portion (~three million) are racial or ethnic minorities.\(^1\)\(^,\)\(^2\) Those who suffer from OA experience diminished quality of life (QOL)\(^2\) and often need to undergo total knee replacement (TKR);\(^1\) many may also suffer from the development of depressive symptoms\(^3\) and cardiovascular disease.\(^4\) Therefore, understanding the patient’s perception of their OA treatment is essential to providing quality care for these individuals, while also allowing providers to better support a patient’s health status and QOL.

One method for gaining insight into the OA patient experience is the use of patient-reported outcome measures (PROMs). PROMs are often used to assess the patients’ perspective of their QOL, pain, symptoms, or functional status,\(^5\)\(^,\)\(^6\)\(^,\)\(^7\) which can then be used by clinicians to inform patient care.\(^6\)\(^,\)\(^7\)\(^,\)\(^8\) Though the implementation of PROMs to guide care for OA has been recommended, providers must carefully select PROMs with sound psychometric properties to effectively measure the patient experience or assess treatment effectiveness. A specific PROM developed for patients with OA or those who have had a TKR is the Knee Injury and Osteoarthritis Outcome Score for Joint Replacement (KOOS-JR). The KOOS-JR is a seven-item short form developed from the 42-item Knee Injury and Osteoarthritis Outcome Score (KOOS) to reduce patient response burden and improve implementation with OA patients in clinical practice.\(^9\)\(^,\)\(^10\)\(^,\)\(^11\)

Numerous studies have been performed to validate the KOOS-JR and there has been growing support to extend the use of the KOOS-JR in clinical and academic settings.\(^12\) Initial work has identified moderate (0.46)\(^13\) to preferred (0.84)\(^13\) internal consistency, while construct validity was established by correlating the KOOS-JR to the KOOS Pain (Spearman’s correlation coefficient 0.89) and KOOS Activities of Daily Living (Spearman’s correlation coefficient 0.90) subscales.\(^12\) A recent study utilizing confirmatory factor analysis (CFA) procedures found acceptable structural validity (CFI = 0.976, TLI = 0.964, IFI = 0.976, RMSEA = 0.067\(^14\); and invariant multi-group solutions, indicating the KOOS-JR can be used to measure differences across certain sub-groups (i.e., sex, older adults, intervention groups).\(^14\) However, concerns with ceiling effects,\(^13\) an inability to detect differences between groups,\(^15\) validity concerns when used in later stages of recovery,\(^15\) and an inability to assess outcomes in younger active patients\(^15\) suggests further assessment is needed. Another substantial concern is the lack of longitudinal assessment (e.g., CFA at multiple time points, longitudinal invariance testing) necessary for establishing scale measurement properties to guide scale use to assess group differences and patient recovery over time.\(^16\)\(^,\)\(^17\)\(^,\)\(^18\)

Further CFA assessment using responses from repeated patient assessment would help to establish the latent structure and structural validity of the KOOS-JR across time, while invariance (i.e., multi-group and longitudinal) testing would ensure the instrument is valid across groups and time for assessing group differences or change over time.\(^16\)\(^,\)\(^17\)\(^,\)\(^18\) Specifically, performing CFAs across multiple administrations would benefit clinicians and researchers by confirming scale structural validity across repeated use to address concerns that scale structure was biased by the timing of scale administration.\(^16\)\(^,\)\(^17\)\(^,\)\(^18\) Multi-group invariance testing would provide additional evidence that the items and dimensions were being operationalized in a similar fashion across sub-groups of the population (e.g., do males and females interpret the items in a similar fashion), which allows for substantive research questions regarding group differences to be answered when using the scale.\(^16\)\(^,\)\(^17\)\(^,\)\(^18\) Finally, longitudinal invariance testing establishes if the items and latent constructs are adequately measured (i.e., the items and constructs being operationalized similarly) across repeated testing to ensure participant response change is not a byproduct of item bias or measurement error, which allows the KOOS-JR to be used to assess perceived knee health at various stages throughout the injury recovery process.\(^16\)\(^,\)\(^17\)\(^,\)\(^18\)

While the KOOS-JR is widely used in research and clinical practice, further assessment of the multigroup and longitudinal psychometric properties of the KOOS-JR is warranted to conduct these additional analyses to further establish KOOS-JR measurement properties.\(^15\)\(^,\)\(^16\)\(^,\)\(^17\)\(^,\)\(^18\) Therefore, the purpose of this study was to evaluate psychometric properties of the KOOS-JR in a large sample of patients who received care for knee pathology. This occurred in three steps: (1) perform CFAs in a large and diverse patient population to further evaluate the structural validity of the KOOS-JR across multiple assessments; (2) conduct multi-group invariance testing to confirm the validity of the KOOS-JR in specific sub-groups; and (3) perform longitudinal invariance testing to establish the longitudinal properties of the KOOS-JR for use across time to assess if the scale can be used to measure improvement across repeated measures.

**METHODS**

**DATA SOURCE**

The Surgical Outcome System\(^20\) is an international de-identified patient-reported outcome database that adheres to the Health Insurance Portability and Accountability Act
(HIPPA) and has already received IRB approval. The SOS allows for retrospective analysis of the collected data from patients who provide informed consent for data use. The University Institutional Review Board (IRB) indicated IRB approval was not required as the deidentified dataset was not considered human-subject research; IRB approval was granted from the Cedar-Sinai Office of Research Compliance and Quality Improvement as part of a larger research project utilizing SOS data. The dataset used included KOOS-JR responses at four time points: 1) baseline, prior to receiving care (i.e., knee arthroplasty, non-operative care), 2) three-months post-intervention, 3) six-months post-intervention, and 4) one-year post-intervention.

INSTRUMENTATION

The KOOS-JR is comprised of seven items to assess stiffness, pain, and function of the knee. Patients respond to items using a 5-point Likert scale (none = 0, mild = 1, moderate = 2, severe = 3, extreme = 4). The KOOS-JR is scored by summing the raw scores (0-28); higher scores correspond to worse knee health (i.e., 0 = "perfect knee health"; 28 = "total knee disability"). KOOS-JR scores may also be converted to an interval score (0-100), where a converted interval score of 100 represents "perfect knee health" while a score of 0 represents "total knee disability". Raw scores (i.e., Likert scale responses) and the 0-28 scale were used for the purposes of this study.

STATISTICAL ANALYSIS

All data and demographic information were extracted from the SOS database in Excel and uploaded to the Statistical Package for Social Sciences (IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp) and Analysis of Moment Structure (AMOS, SPSS, Inc.) Version 27 for data analysis. Individuals with incomplete KOOS-JR responses at baseline evaluation were removed from the dataset; however, responses from individuals missing only demographic information were retained for analysis. Individuals who did not respond to the KOOS-JR at all time points were used for initial analysis but were excluded from longitudinal analyses. The dataset was then assessed for outliers across all time points: univariate and multivariate outliers were assessed using z-scores (≥3.5) and Mahalanobis distance (cases with a p < 0.001 according to the Chi-square test) were removed from the dataset. Data normality was also assessed using histograms and descriptive statistics (i.e., skewness and kurtosis values).

SCALE STRUCTURE

Scale structure of the KOOS-JR was assessed using AMOS to conduct a CFA at each time point. The CFA was specified as a unidimensional seven-item factor. Model fit was assessed with the following a priori criteria: Comparative Fit Index (CFI; ≥ 0.95), Tucker-Lewis Index (TLI; ≥ 0.95), Standardized Root Mean Square Residual (SRMR ≤ 0.08), Root Mean Square Error of Approximation (RMSEA ≤ 0.06), and Bollen’s Incremental Fit Index (IFI; ≥ 0.95). Greater weight in assessment of model fit was given to CFI and SRMR because those criteria are less susceptible to effects from the small degrees of freedom present when performing CFA on the KOOS-JR. Model fit was also assessed by considering localized areas of strain, as well as the interpretability, size, and statistical significance of the model’s parameter estimates (i.e., factor variances, covariances, and indicator errors).

MULTI-GROUP INVARINACE TESTING

Multi-group invariance testing was performed to assess whether items were being interpreted equally across subgroups (i.e., age, sex, knee group) at the initial examination (i.e., baseline exam; time point 1). Multi-group invariance testing was completed across a multi-step process where each step was progressively more restricted: configural model (i.e., to assess equal factor structure), metric model (i.e., to assess equal factor loadings), and scalar model (i.e., to assess equal loadings and intercepts). The CFI difference test (CFI_diff) and Chi-square difference test ($\chi^2_{\text{diff}}$) were used to assess invariance. Model fit was considered adequate at each step if CFI_diff was ≤ 0.01 when compared back to the configural model. While the $\chi^2_{\text{diff}}$ was assessed with each model, CFI_diff was given greater weight in assessing model fit because of the sensitivity of $\chi^2_{\text{diff}}$ with large sample sizes. Thus, if a model exceeded the $\chi^2_{\text{diff}}$ test recommendation but passed the CFI_diff test, invariance testing procedures continued. If the measurement properties met the criteria, then substantive analyses (e.g., comparing group latent means) were performed. Latent group means were compared with statistical significance set at p ≤ .05; Cohen’s d effect sizes were calculated and evaluated using the guidelines of d = 0.2 as a small effect size, d = 0.5 as a medium effect size, and d = 0.8 as a large effect size.

LONGITUDINAL INVARINACE TESTING

Longitudinal invariance testing was also performed using the analysis procedures outlined in the multi-group invariance section; however, the analysis was now performed to confirm similar interpretation of items and common factors across time points for all participants. If all tested measurement parameters (e.g., metric, intercepts) met the criteria, the model was further tested to assess if substantive properties (e.g., change over time) could be evaluated, allowing for assessment of KOOS-JR scores over time (e.g., did scores change from baseline to 12-months post-arthroplasty). Latent group means were compared with statistical significance set at p ≤ .05; Cohen’s d effect size was calculated and evaluated using the guidelines of d = 0.2 as a small effect size, d = 0.5 as a medium effect size, and d = 0.8 as a large effect size.

RESULTS

Of the 15,470 cases, five had missing data and 374 were flagged as univariate and multivariate outliers across all time points. A total of 379 cases, which consisted of 295 cases...
Table 1. Demographics

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<td></td>
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</tr>
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<td>0.1</td>
</tr>
<tr>
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</tr>
<tr>
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<td>41-65 years</td>
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<td>66+ years</td>
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Knee Intervention Classification

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</tr>
<tr>
<td>Non-operative</td>
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</tr>
<tr>
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Table 2. Goodness-of-Fit Indices for KOOS-JR at Each Time Point

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<th></th>
<th>χ²</th>
<th>df</th>
<th>CFI</th>
<th>TLI</th>
<th>IFI</th>
<th>SRMR</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (n = 13091)</td>
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<td>14</td>
<td>0.970</td>
<td>0.954</td>
<td>0.970</td>
<td>0.029</td>
<td>0.066</td>
</tr>
<tr>
<td>3 months (n = 13091)</td>
<td>587.407</td>
<td>14</td>
<td>0.981</td>
<td>0.972</td>
<td>0.981</td>
<td>0.022</td>
<td>0.056</td>
</tr>
<tr>
<td>6 months (n = 13091)</td>
<td>537.443</td>
<td>14</td>
<td>0.986</td>
<td>0.979</td>
<td>0.986</td>
<td>0.019</td>
<td>0.053</td>
</tr>
<tr>
<td>12 months (n = 13091)</td>
<td>757.884</td>
<td>14</td>
<td>0.984</td>
<td>0.976</td>
<td>0.984</td>
<td>0.020</td>
<td>0.064</td>
</tr>
</tbody>
</table>

CFI= Confirmatory Factor Analysis, TLI= Tucker Lewis index, IFI= Bollen’s Incremental Fit Index, SRMR= Standardized Root Mean Square Residual, RMSEA= Root Mean Square Error of Approximation

(78.9%) arthroplasty knee group participants, 208 (58.6%) females (mean age of 65.30 ± 9.57 years), were removed from the dataset, leaving 13,091 cases for analysis. The mean age of the sample was 64.82 ± 9.10 years (range = 12-89 years) with males accounting for 40.9% (n = 5,354) and females accounting for 54.9% (n = 7,189) of the sample. Additionally, most respondents (n = 11,268, 86.1%) were classified in the knee arthroplasty intervention group. In the knee arthroplasty group, 42.7% (n = 4,601) were males and 57.3% (n = 6,171) were females; and 52.7% (n = 5,802) were in the middle-aged adult group (i.e., 41-65 years) and 46.7% (n = 5,146) were in the older aged adult group (i.e., 66+ years). A full participant demographic breakdown is presented in Table 1.

SCALE STRUCTURE

A total of 13,091 participants completed the KOOS-JR at baseline and were used for analysis. The baseline model met goodness-of-fit indices (χ² (14) = 801.332; CFI = 0.970; TLI = 0.954; IFI = 0.970; SRMR = 0.029; RMSEA = 0.066; Table 2) as did the three-month model (CFI = 0.981; χ² (14) = 587.407; TLI = 0.972; IFI = 0.981; SRMR = 0.026; RMSEA = 0.056; Table 2), the six-month model (CFI = 0.986; χ² (14) = 537.443; TLI = 0.979; IFI = 0.986; SRMR = 0.019; RMSEA = 0.053; Table 2), and the one-year model (CFI = 0.984; χ² (14) = 757.884; TLI = 0.976; IFI = 0.984; SRMR = 0.020; RMSEA = 0.064; Table 2).

MULTI-GROUP INVARiance

AGE GROUP ANALYSIS

A total of 12,661 individuals reported their age (middle-aged adults [41-65 years] n = 6,935; older adults [66+ years] n = 5,728) and were used for analysis. The configural model (i.e., equal form) goodness-of-fit indices met recommended values (CFI = 0.969; χ² (28) = 791.22; RMSEA = 0.046; Table 3). The metric model (i.e., equal loadings) passed both the χ²diff test and the CFIdiff test, allowing for testing of the equal latent variance model. The equal latent variance model passed both the χ²diff test and the CFIdiff test, indicating variances were equal across groups. The scalar model (i.e., equal indicator intercepts) did not pass the χ²diff test but passed the CFIdiff test. As the CFIdiff test was weighted more heavily, the equal means model was tested for substantiate group differences. When means were not constrained to be equal, the CFIdiff was greater than 0.01, indicating the differences in mean scores between groups was statistically significant. Follow-up analyses indicated the middle-aged adult group had significantly (p < .001) higher scores (i.e., high “total knee disability”/low knee health) on the KOOS-JR than the older adult group at baseline examination (Mdiff = 0.15, Cohen’s d = 0.23).

SEX GROUP ANALYSIS

A total of 12,543 individuals reported their sex (males n = 5,354; females n = 7,189) and were used for analysis.
The mean age of males was 64.82 ± 9.07 with 54.1% in the middle-aged adult group and 44.7% in the older adult age group. The mean age of females was 64.84 ± 9.12 with 54.1% in the middle-aged adult group and 44.9% in the older adult age group. The configural model (i.e., equal form) goodness-of-fit indices met recommended values (CFI = 0.970; χ² (28) = 752.187; RMSEA = 0.045; Table 4). The metric model (i.e., equal loadings) did not pass the χ²diff test, but passed the CFIdiff test, allowing for testing of an equal latent variance model. The equal latent variance model did not pass the χ²diff test, but passed the CFIdiff test, indicating variances were equal across groups (Table 4). The scalar model (i.e., equal indicator intercepts), did not pass the χ²diff test, but passed the CFIdiff test allowing for testing of the equal latent means model. When means were not constrained to be equal, the CFIdiff was greater than 0.01, indicating the differences in mean scores between groups was statistically significant. Follow-up analyses indicated the female group had significantly (p < .001) higher scores (i.e., higher “total knee disability”/lower knee health) on the KOOS-JR than the male group at baseline examination (Mdiff = 0.15, Cohen’s d = 0.27).

INTERVENTION GROUP ANALYSIS

Because the knee arthroplasty group included 86.1% of the total sample and variance testing recommendations include having subgroups with a similar number of participants in each group [16,18], a random subsample of the knee arthroplasty group was selected. A total of 2,656 participants (i.e., knee arthroplasty n = 1,563; knee non-operative n = 1,273) were used for analysis. The knee arthroplasty group was composed of 643 males (51.4%) and 608 females (48.6%) with 50.0% (n = 682) in the middle-aged adult group (i.e., 44-65 years) and 50.0% (n = 681) in the older adult group (i.e., 66+). The knee non-operative group was composed of 627 males (51.4%) and 594 females (48.6%), with 48.0% (n = 602) in the middle-aged adult group and 46.4% (n = 582) in the older adults group.

The configural model (i.e., equal form) goodness-of-fit indices met recommended values (CFI = 0.974; χ² (28) = 190.703; SRMR = 0.029; RMSEA = 0.047; Table 5). The metric model (i.e., equal loadings) did not pass the χ²diff test, but passed the CFIdiff test, which supports testing the equal latent variance model. The equal latent variance model did not pass the χ²diff test, but passed the CFIdiff test, indicating variances were equal between groups. The scalar model (i.e., equal indicator intercepts) did not pass the χ²diff test but passed the CFIdiff test which supports assessing the equal latent means model. When means were not constrained to be equal, the CFIdiff criterion was exceeded, indicating the difference in means between groups was statistically significant. Follow-up analyses found that the knee arthroplasty group had significantly higher scores (i.e., higher “total knee disability”/lower knee health) on the KOOS-JR than the knee non-operative group at baseline examination (Mdiff = 0.38, Cohen’s d = 0.60).

LONGITUDINAL INVARIANCE

A total of 13,091 participants completed the KOOS-JR at all four time points and were used for analysis. The configural model (i.e., equal form) goodness-of-fit indices met recommended values (CFI = 0.984; χ² (302) = 5208.074; RMSEA = 0.027; Table 6) indicating equal form across repeated assessment. The metric model (i.e., equal loadings) did not pass the χ²diff test, but passed the CFIdiff test, warranting analysis of an equal latent variance model. The equal latent variance model did not pass the χ²diff test, but passed the CFIdiff test, indicating variances were equal across time. The scalar model (i.e., equal indicator intercepts), exceeded both the χ²diff test and CFIdiff test, which prevents comparison of reported levels of the latent variable (i.e., “total knee disability”) across repeated assessment and suggested item-level bias across repeated use of the scale. Upon inspection of the model, item #1 was found to be the source of non-invariance; when item #1 was not constrained to be equal, the model passed the CFIdiff test. Therefore, item #1

| Table 3. Goodness-of-Fit Indices for Measurement Invariance Analyses Across Age Groups |
|---------------------------------|---------|---------|---------|---------|---------|---------|---------|
| Middle aged adults             | 444.623 | 14      | 0.969   | 0.954   | 0.969   | 0.290   | 0.067   |
| (n = 6,933)                     |         |         |         |         |         |         |
| Olders (n = 5,728)              | 346.499 | 14      | 0.968   | 0.952   | 0.968   | 0.030   | 0.064   |
| Configural (equal form)         | 791.22  | 28      | 0.969   | 0.953   | 0.969   | 0.029   | 0.046   |
| Metric (equal loadings)         | 801.626 | 34      | 10.406(6) | 0.969 | 0.000 | 0.961 | 0.029 | 0.042 |
| Equal factor variances          | 806.437 | 35      | 15.217(7) | 0.968 | 0.001 | 0.962 | 0.029 | 0.042 |
| Scalar (equal indicator intercepts) | 942.582 | 40      | 151.362(12) | 0.963 | 0.006 | 0.961 | 0.029 | 0.042 |
| Equal Means                     | 1084.847| 41      | 293.627(13) | 0.957 | 0.012 | 0.956 | 0.029 | 0.045 |

<table>
<thead>
<tr>
<th>χ²</th>
<th>df</th>
<th>χ² difference [df]</th>
<th>CFI</th>
<th>CFI difference</th>
<th>TLI</th>
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<td>444.623</td>
<td>14</td>
<td>0.969</td>
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<tr>
<td>Metric (equal loadings)</td>
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<td>10.406(6)</td>
<td>0.969</td>
<td>0.000</td>
<td>0.961</td>
<td>0.029</td>
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<tr>
<td>Equal factor variances</td>
<td>806.437</td>
<td>35</td>
<td>15.217(7)</td>
<td>0.968</td>
<td>0.001</td>
<td>0.962</td>
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<td>Scalar (equal indicator intercepts)</td>
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<td>151.362(12)</td>
<td>0.963</td>
<td>0.006</td>
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<tr>
<td>Equal Means</td>
<td>1084.847</td>
<td>41</td>
<td>293.627(13)</td>
<td>0.957</td>
<td>0.012</td>
<td>0.956</td>
<td>0.029</td>
<td>0.045</td>
</tr>
</tbody>
</table>

* df = degrees of freedom
b Indicates the value is not calculated at this step.
* Indicates the model did not pass invariance criteria.
CFI= Confirmatory Factor Analysis, TLI= Tucker Lewis index, IFI= Bollen’s Incremental Fit Index, SRMR= Standardized Root Mean Square Residual, RMSEA= Root Mean Square Error of Approximation

Bold indicates that χ² difference criterion was exceeded.
Table 4. Goodness-of-Fit Indices for Measurement Invariance Analyses Across Sex

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<td>b</td>
<td>0.950</td>
<td>0.967</td>
<td>0.030</td>
</tr>
<tr>
<td>Configural (equal form)</td>
<td>752,187</td>
<td>28</td>
<td>b</td>
<td>0.970</td>
<td>b</td>
<td>0.955</td>
<td>0.970</td>
<td>0.027</td>
</tr>
<tr>
<td>Metric (equal loadings)</td>
<td>772,936</td>
<td>34</td>
<td>20.749 (6)</td>
<td>0.970</td>
<td>0.000</td>
<td>0.963</td>
<td>0.970</td>
<td>0.028</td>
</tr>
<tr>
<td>Equal factor variances</td>
<td>778,196</td>
<td>35</td>
<td>26.009 (7)</td>
<td>0.969</td>
<td>0.001</td>
<td>0.963</td>
<td>0.969</td>
<td>0.029</td>
</tr>
<tr>
<td>Scalar (equal indicator intercepts)</td>
<td>936,819</td>
<td>40</td>
<td>184.632 (12)</td>
<td>0.963</td>
<td>0.007</td>
<td>0.961</td>
<td>0.963</td>
<td>0.028</td>
</tr>
<tr>
<td>Equal Means</td>
<td>1131,552</td>
<td>41</td>
<td>379.365 (13)</td>
<td>0.955</td>
<td>0.015</td>
<td>0.954</td>
<td>0.955</td>
<td>0.029</td>
</tr>
</tbody>
</table>

a $df$ = degrees of freedom
b Indicates the value is not calculated at this step.
Indicates the model did not pass invariance criteria.
CFI= Confirmatory Factor Analysis, TLI= Tucker Lewis index, IFI= Bollen’s Incremental Fit Index, SRMR= Standardized Root Mean Square Residual, RMSEA= Root Mean Square Error of Approximation

Bold indicates that $\chi^2$ difference criterion was exceeded.

Table 5. Goodness-of-Fit Indices for Measurement Invariance Analyses Across Intervention Group

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
<th>$df$</th>
<th>$\chi^2$ difference ($df$)</th>
<th>CFI difference</th>
<th>TLI</th>
<th>IFI</th>
<th>SRMR</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee arthroplasty (n = 1,363)</td>
<td>105,924</td>
<td>14</td>
<td>b</td>
<td>0.973</td>
<td>b</td>
<td>0.959</td>
<td>0.973</td>
<td>0.029</td>
</tr>
<tr>
<td>Knee non-operative (n = 1,273)</td>
<td>84,779</td>
<td>14</td>
<td>b</td>
<td>0.976</td>
<td>b</td>
<td>0.965</td>
<td>0.977</td>
<td>0.027</td>
</tr>
<tr>
<td>Configural (equal form)</td>
<td>190,703</td>
<td>28</td>
<td>b</td>
<td>0.974</td>
<td>b</td>
<td>0.962</td>
<td>0.975</td>
<td>0.029</td>
</tr>
<tr>
<td>Metric (equal loadings)</td>
<td>218,248</td>
<td>34</td>
<td>27.545 (6)</td>
<td>0.971</td>
<td>0.003</td>
<td>0.964</td>
<td>0.971</td>
<td>0.032</td>
</tr>
<tr>
<td>Equal factor variances</td>
<td>335,489</td>
<td>35</td>
<td>144.786 (7)</td>
<td>0.970</td>
<td>0.004</td>
<td>0.964</td>
<td>0.970</td>
<td>0.038</td>
</tr>
<tr>
<td>Scalar (equal indicator intercepts)</td>
<td>269,554</td>
<td>40</td>
<td>78.851 (12)</td>
<td>0.964</td>
<td>0.010</td>
<td>0.962</td>
<td>0.964</td>
<td>0.033</td>
</tr>
<tr>
<td>Equal Means</td>
<td>484,382</td>
<td>41</td>
<td>293.679 (13)</td>
<td>0.930</td>
<td>0.044</td>
<td>0.929</td>
<td>0.930</td>
<td>0.037</td>
</tr>
</tbody>
</table>

a $df$ = degrees of freedom
b Indicates the value is not calculated at this step.
Indicates the model did not pass invariance criteria.
CFI= Confirmatory Factor Analysis, TLI= Tucker Lewis index, IFI= Bollen’s Incremental Fit Index, SRMR= Standardized Root Mean Square Residual, RMSEA= Root Mean Square Error of Approximation

Bold indicates that $\chi^2$ difference criterion was exceeded.

(i.e., “How severe is your knee stiffness after first wakening in the morning?”) was identified as a problematic item and was removed; longitudinal invariance was retested with the new structure (i.e., KOOS-JR-6).

The new configural model (KOOS-JR-6) met recommended values (CFI = 0.986; $\chi^2 (210) = 2388.504$; RMSEA = 0.028; Table 7). Both the metric and equal factor variances models exceeded the $\chi^2$ test but passed the CFI test, indicating variances were similar across time. The scalar model exceeded the $\chi^2$ test, but passed the CFI test, allowing assessment of equal latent means. When means were not constrained to be equal, the CFI test was exceeded, indicating means were significantly different across time. Follow-up analyses found that at baseline, scores were the highest (i.e., higher "total knee disability")/lower knee health) and group means incrementally decreased (i.e., improved) across time with the lowest group mean scores (i.e., lowest "total knee disability") being reported at the 12-month assessment ($M_{diff} = 1.08$, Cohen’s $d = 0.57$).

**DISCUSSION**

The purpose of this study was to assess the psychometric properties of the KOOS-JR using a large and diverse longitudinal sample of patient responses. Using maximum likelihood CFA, we assessed the structural validity of the KOOS-JR and conducted invariance analysis across groups and time in a large sample of patients who sought care for various knee pathologies to ensure the KOOS-JR can be used between groups and across time. Contemporary analytic methods were used to assess multi-group and longitudinal model fit and structural validity of the KOOS-JR, with the multi-group analysis being conducted in a larger and more heterogenous population than previously used in the literature. Multi-group and longitudinal invariance results suggest the KOOS-JR demonstrates structural validity and can be used with specific sub-groups of the population (e.g., different sexes, age groups). Longitudinal analy-
The analysis met version, however, identified a biased item resulting in a modified version of the KOOS-JR (i.e., KOOS-JR-6); the modified version met longitudinal analysis recommendations.

STRUCTURAL VALIDITY - CONFIRMATORY FACTOR ANALYSIS

The CFA results indicated sound structural properties of the KOOS-JR in a large, heterogeneous sample of patients who completed the scale during a baseline examination when seeking care. The model fit exceeded recommended fit indices$^{18,21}$; thus, the findings supported prior Rasch analysis$^9$ and CFA$^{14}$ assessment, with a structurally sound unidimensional model at initial (i.e., baseline) patient completion being found. Identification of a sound structural model justified further multi-group and longitudinal invariance testing to further determine scale measurement properties and guide use of the scale in clinical practice and research related to hypothesis testing, assessing group differences, and examining change across time.

Table 6. Goodness-of-Fit Indices for Measurement Invariance Analyses Across Time Points

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
<th>df$^a$</th>
<th>$\chi^2$ difference (df)</th>
<th>CFI</th>
<th>CFI difference</th>
<th>TLI</th>
<th>IFI</th>
<th>SRMR</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (n = 13091)</td>
<td>801.332</td>
<td>14</td>
<td>b</td>
<td>0.970</td>
<td>b</td>
<td>0.954</td>
<td>0.970</td>
<td>0.029</td>
<td>0.066</td>
</tr>
<tr>
<td>3 months (n = 13091)</td>
<td>587.407</td>
<td>14</td>
<td>b</td>
<td>0.981</td>
<td>b</td>
<td>0.972</td>
<td>0.981</td>
<td>0.022</td>
<td>0.056</td>
</tr>
<tr>
<td>6 months (n = 13091)</td>
<td>537.443</td>
<td>14</td>
<td>b</td>
<td>0.986</td>
<td>b</td>
<td>0.979</td>
<td>0.986</td>
<td>0.019</td>
<td>0.053</td>
</tr>
<tr>
<td>12 months (n = 13091)</td>
<td>757.884</td>
<td>14</td>
<td>b</td>
<td>0.984</td>
<td>b</td>
<td>0.976</td>
<td>0.984</td>
<td>0.020</td>
<td>0.064</td>
</tr>
<tr>
<td>Configural (equal form)</td>
<td>3208.074</td>
<td>302</td>
<td>b</td>
<td>0.984</td>
<td>b</td>
<td>0.980</td>
<td>0.984</td>
<td>0.019</td>
<td>0.027</td>
</tr>
<tr>
<td>Metric (equal loadings)</td>
<td>3888.173</td>
<td>320</td>
<td>$680.099$ (18)</td>
<td>0.981</td>
<td>0.003</td>
<td>0.977</td>
<td>0.981</td>
<td>0.023</td>
<td>0.029</td>
</tr>
<tr>
<td>Equal factor variances</td>
<td>4196.661</td>
<td>323</td>
<td>$988.587$ (21)</td>
<td>0.979</td>
<td>0.005</td>
<td>0.975</td>
<td>0.979</td>
<td>0.028</td>
<td>0.030</td>
</tr>
<tr>
<td>Scalar (equal indicator intercepts)</td>
<td>6254.532</td>
<td>338</td>
<td>$3046.458$ (36)</td>
<td>0.968</td>
<td>$0.016^c$</td>
<td>0.964</td>
<td>0.968</td>
<td>0.027</td>
<td>0.037</td>
</tr>
</tbody>
</table>

$^a$ df = degrees of freedom
$^b$ Indicates the value is not calculated at this step.
$^c$ Indicates the model did not pass invariance criteria.

CFI: Confirmatory Factor Analysis, TLI: Tucker Lewis index, IFI: Bollen’s Incremental Fit Index, SRMR: Standardized Root Mean Square Residual, RMSEA: Root Mean Square Error of Approximation

Bold indicates that CFIadj or $\chi^2$ difference criterion was exceeded.

Table 7. Goodness-of-Fit Indices for Measurement Invariance Analyses Across Time Points with Item #1 Removed

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$</th>
<th>df$^a$</th>
<th>$\chi^2$ difference (df)</th>
<th>CFI</th>
<th>CFI difference</th>
<th>TLI</th>
<th>IFI</th>
<th>SRMR</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (n = 13091)</td>
<td>493.932</td>
<td>9</td>
<td>b</td>
<td>0.977</td>
<td>b</td>
<td>0.962</td>
<td>0.977</td>
<td>0.025</td>
<td>0.064</td>
</tr>
<tr>
<td>3 months (n = 13091)</td>
<td>435.897</td>
<td>9</td>
<td>b</td>
<td>0.983</td>
<td>b</td>
<td>0.972</td>
<td>0.983</td>
<td>0.022</td>
<td>0.060</td>
</tr>
<tr>
<td>6 months (n = 13091)</td>
<td>410.508</td>
<td>9</td>
<td>b</td>
<td>0.987</td>
<td>b</td>
<td>0.979</td>
<td>0.987</td>
<td>0.019</td>
<td>0.058</td>
</tr>
<tr>
<td>12 months (n = 13091)</td>
<td>651.245</td>
<td>9</td>
<td>b</td>
<td>0.984</td>
<td>b</td>
<td>0.973</td>
<td>0.984</td>
<td>0.021</td>
<td>0.074</td>
</tr>
<tr>
<td>Configural (equal form)</td>
<td>2388.504</td>
<td>210</td>
<td>b</td>
<td>0.986</td>
<td>b</td>
<td>0.981</td>
<td>0.986</td>
<td>0.019</td>
<td>0.028</td>
</tr>
<tr>
<td>Metric (equal loadings)</td>
<td>2908.794</td>
<td>225</td>
<td>$520.29$ (15)</td>
<td>0.983</td>
<td>0.003</td>
<td>0.979</td>
<td>0.983</td>
<td>0.023</td>
<td>0.030</td>
</tr>
<tr>
<td>Equal factor variances</td>
<td>3168.579</td>
<td>228</td>
<td>$780.075$ (18)</td>
<td>0.981</td>
<td>0.005</td>
<td>0.977</td>
<td>0.981</td>
<td>0.027</td>
<td>0.031</td>
</tr>
<tr>
<td>Scalar (equal indicator intercepts)</td>
<td>4194.661</td>
<td>240</td>
<td>$1806.157$ (30)</td>
<td>0.974</td>
<td>0.010</td>
<td>0.971</td>
<td>0.974</td>
<td>0.025</td>
<td>0.035</td>
</tr>
<tr>
<td>Equal Means</td>
<td>21025.091</td>
<td>243</td>
<td>$18636.587$ (33)</td>
<td>0.866</td>
<td>0.12</td>
<td>0.847</td>
<td>0.866</td>
<td>0.228</td>
<td>0.081</td>
</tr>
</tbody>
</table>

$^a$ df = degrees of freedom
$^b$ Indicates the value is not calculated at this step.
$^c$ Indicates the model did not pass invariance criteria.

CFI: Confirmatory Factor Analysis, TLI: Tucker Lewis index, IFI: Bollen’s Incremental Fit Index, SRMR: Standardized Root Mean Square Residual, RMSEA: Root Mean Square Error of Approximation

Bold indicates that $\chi^2$ difference criterion was exceeded.
MULTI-GROUP INVARIENCE ANALYSIS ACROSS AGE, SEX, AND INTERVENTION GROUPS

The presence of multi-group invariance supports scale use for hypothesis testing (e.g., are levels of “total knee disability” different across sexes), while providing valuable insight on if the scale items or underlying construct (i.e., total knee disability) are being operationalized similarly across the groups. The multi-group invariance testing results confirmed the structural validity of the scale across the tested groups (e.g., sex, age groups), which then allowed between group differences to be assessed at baseline examination. The findings provide clinicians and researchers with evidence that identified group differences are true group differences as opposed to differences that may result from measurement error (e.g., how an item is interpreted, how a latent construct is operationalized, etc.).

The results confirmed prior multi-group invariance testing that found the KOOS-JR to be invariant in an older adult population (i.e., 41 year of age or older). Because the KOOS-JR was invariant in middle-aged and older (i.e., 41+ years of age) populations, assessment of latent mean differences was warranted in these groups. We found significant mean differences across groups at the baseline examination: the middle-aged adult group (41–66 years) reported substantially higher scores (i.e., worse knee health) than the older adult group (66+ years) at the baseline examination. The results confirmed prior research findings of the middle-aged group reporting higher levels of self-reported knee disability than the older age group on the KOOS-JR. The findings, however, conflict with prior research which indicated older age groups (i.e., 65 years or age or older) perceived greater impairments of knee health on the KOOS and that patient reported functional impairment increases across the life span. The differences could be the result of sample differences or the KOOS-JR having fewer items designed for those who will undergo knee arthroplasty. It may also be important to note that while the difference was statistically significant, the effect size was small, and the group differences may not be that meaningful in clinical practice or research without further research that also considers physical activity levels and how this might influence KOOS or KOOS-JR scores.

Lower levels of physical activity level before the onset of OA or before a total hip arthroplasty (THA) intervention in older (i.e., 66+ years) age groups have been reported. Self-reported physical activity decreases related to knee health impairment could be explained by numerous factors (e.g., greater levels of joint degeneration, number of comorbidities, body composition, etc.) in patient population and it is conceivable that increased prevalence of these variables (e.g., greater knee degeneration, etc.) and decreased physical activity would result in greater perceived impairments in knee health as measured by the KOOS or KOOS-JR. A limitation of the SOS data available for this study was a lack of demographic patient information; thus, further analysis to explore how these variables affected KOOS-JR scores at baseline or across time could not be performed. Further research is warranted to better understand the influence of these variables on KOOS-JR scores prior or after intervention or the onset of OA. Additional multi-group invariance testing is also warranted with younger patient populations. Assessment of group differences in KOOS-JR scores in patient populations under the age of 41 should be performed with caution because multi-group invariance testing could not be conducted in this population due to insufficient sample sizes in the data.

The multi-group invariance testing between sexes also confirmed prior findings of the KOOS-JR being invariant between males and females. Thus, differences in latent mean scores can be viewed as true group differences as opposed to measurement error, and comparison of group mean scores differences across the sexes is supported. The analysis identified statistically significant group mean differences between males and females: male participants reported lower scores (i.e., less perceived “total knee disability”) than female participants at the baseline examination. The findings support prior KOOS-JR findings of females reporting higher levels of knee disability on the KOOS-JR compared to males. Sex differences at the baseline examination could be related to differences in psychological variables, such as coping strategies. For example, females have been reported to have reduced capacity to cope with musculoskeletal pain and this may explain higher baseline levels of perceived knee health impairment on the KOOS-JR. Other research, however, found females to have higher pain acceptance and more social support than males, while males were reported to have higher levels of kinesiphobia, more mood disturbances, and lower activity levels than females.

It should be noted that the effect size of the latent mean difference between sexes in the study was small and differences in condition, response to pain, prior treatment adherence, age, and physical activity level could explain the latent mean sex difference. The role of physical activity and patient awareness of physical limitations for participating in physical activity (e.g., sports) with an injury or degenerative joint condition might be relevant in understanding this phenomenon. For example, researchers have reported that females have higher levels of physical activity compared to males while other researchers indicated males reported higher levels of physical activity before the onset of OA and prior to THA. Limitations in the SOS dataset prevent further analysis of the role of these variables (e.g., physical activity levels, coping strategies, etc.) in affecting KOOS-JR scores and further research is warranted to identify when these sex differences occur and better understand how other variables influence or predict KOOS-JR scores.

The findings are also congruent with prior research which indicated the KOOS-JR was invariant when tested with a sample of patients who received knee arthroplasty or non-operative care. The assessment of latent mean scores indicated the arthroplasty group reported higher perceived knee disability (i.e., lower levels of perceived knee health) at baseline than the non-operative group and the difference was statistically significant with a medium effect size. The two groups had similar demographic profiles for age and sex, indicating the identified group difference was unlikely
to be explained by sex or age differences. This finding confirms prior research\textsuperscript{14} and fits the expectation that those who have knee degeneration and warrant surgical intervention would demonstrate higher scores on the KOOS-JR. The findings provide preliminary evidence that KOOS-JR scores may be elevated in those with more substantial pathology requiring more substantial intervention; however, the demographic information available in the SOS database does not allow for further group comparison (e.g., pathology, pathology severity, length of symptomatology, psychosocial variable assessment, etc.) to better understand the variables or antecedents that influence patient responses on the KOOS-JR at baseline examination or for predicting who will respond favorably to specific interventions. Further research into patient perceptions of knee health and relevant variables and antecedents may be useful to determine when these differences arise and what might be the mechanism for these differences. Additional research is also needed to determine if diagnostic-cut-off criteria or other clinical guidelines could be created to aid clinicians in using patient reported scores to inform the intervention decision-making process.

LONGITUDINAL INVARIANCE

The study also provides novel insight into the longitudinal properties of the KOOS-JR and its validity for assessing post-intervention effects across time. Longitudinal invariance was established for the equal forms, equal loadings, and equal variances models, but did not pass the equal intercepts model. Failure to meet this standard indicates the respondents did not interpret the construct (i.e., "total knee disability") similarly across time, and assessment of changes in mean scores was not warranted without further inspection of the model and individual items. The presence of this finding identifies measurement bias which creates a challenge in assessing levels ("i.e., "amounts") of knee health/disability over time with the KOOS-JR. Subsequent analysis identified item \#1 (i.e., "How severe is your knee stiffness after first wakening in the morning?") as the problematic item and indicates respondents are not interpreting this item similarly across repeated assessment. Thus, caution is warranted when examining changes across time or patient recovery with the KOOS-JR because score changes may not be the result of change over time or improvement (i.e., healing) from an intervention alone.\textsuperscript{18} The removal of the problematic item from the model, however, resulted in a more psychometrically sound scale that met the contemporary recommendations for longitudinal measurement invariance.

The new model (i.e., KOOS-JR-6) was invariant across each step of the longitudinal measurement invariance process, indicating this model can be used to assess changes in patient recovery across time or examine group mean changes across time. Thus, the results supported examining the mean scores across repeated assessment on the KOOS-JR-6 to determine if scores changed after receiving treatment. The findings indicated the participants reported statistically significant and meaningful improvements in knee health across repeated measures: the lowest scores (i.e., highest "total knee disability") were reported at the baseline examination and the highest scores (i.e., lowest "total knee disability") occurred at the 12-month follow-up. The KOOS-JR-6 findings provide some support for scale validity as patients who receive surgery or who participate in the rehabilitation process would be expected to identify significant improvement over time, whether from the effects of intervention, placebo, or natural healing. The findings are congruent with researchers\textsuperscript{35,36} who have previously reported patient improvement on the KOOS after patients received care (e.g., arthroplasty, arthroscopy, and exercise therapy, etc.) from six months to two years post-intervention.

LIMITATIONS AND FUTURE RESEARCH

While the current study had many strengths, limitations also existed. For example, lack of complete demographic information from the dataset prohibited analysis of all possible subgroups (e.g., surgical approach; younger populations; ethnicity; socioeconomic status; psychosocial variables, etc.), thus limiting invariance testing across all relevant subgroups and the understanding of potential mechanisms for the identified group differences. Therefore, clinicians and researchers should exercise caution when examining KOOS-JR score group differences for populations where multi-group invariance is not yet established. Further, the lack of other relevant demographic information (e.g., pathology, pathology severity, surgical intervention, or approach, etc.) prevents the completion of other analyses to answer other measurement (e.g., multi-group invariance across surgical approaches) or substantive (e.g., assess differences in intervention effectiveness) questions valuable to research and clinical practice. Finally, despite the strengths of using a large, heterogenous sample of patient responses, it should be noted that instrument validation is a multi-step process. The study provides strong evidence for the tested measurement properties of the KOOS-JR-6; however, further research is necessary to establish other needed scale measurement properties (e.g., responsiveness, reliability, minimal clinically important differences [MCIDs], etc.).

Future research should test multi-group invariance across additional subgroups to further inform use of the KOOS-JR in those populations. Establishing multi-group invariance in other relevant subgroups (e.g., different socioeconomic groups, age groups, activity levels, health literacy levels, pathologies, etc.) could help ensure the scale is appropriate to use across diverse patient populations. Researchers should also confirm the KOOS-JR-6 measurement findings in a cross-validation sample of patients who only respond to those six items to ensure the measurement properties are consistent. Additionally, further psychometric studies should be performed to establish other relevant measurement properties (e.g., MCIDs, responsiveness, internal consistency, reliability, etc.) to inform and guide use of the KOOS-JR and KOOS-JR-6 in research and clinical practice.
CONCLUSIONS

Findings in the present study suggest that the KOOS-JR demonstrates structural validity and can be used to compare patient reported outcomes between sex, age groups (e.g., middle aged vs. older adults), and intervention categories (i.e., arthroplasty vs. non-operative care). However, the KOOS-JR did not demonstrate sound longitudinal measurement invariance; researchers and clinicians who desire to use the scale longitudinally should do so with caution. Longitudinal use of the KOOS-JR should include consideration of how patients conceptualize knee health over time due to differences in patient interpretation of item #1 and its influence on overall KOOS-JR scores. Thus, follow-up questions of the patient’s perception of knee stiffness and its influence on overall knee health is warranted; researchers and clinicians could also choose not to score that item and instead only use the items in the KOOS-JR-6 when examining change in knee health over time. Future research is still needed to establish all the necessary measurement properties for effective use of the KOOS-JR-6 in clinical practice and research.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

This publication was supported by an Institutional Development Award (IDeA) from the National Institute of General Medical Sciences of the National Institutes of Health under Grant #P20GM103408 and an Idaho WWAMI Research Training Support Award

Submitted: May 08, 2023 CDT, Accepted: July 19, 2023 CDT

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REFERENCES


Original Research

Changes in Running Kinematics and Kinetics Following a 10 km Run

Mark Reinking1, Emily Hill1, Kathryn Marr1, Kasey Melness1, Dominique Ortiz1, Elsa Racasan1, Nicholas Wedl1, Joshua White1, Brian Baum1

1 School of Physical Therapy, Regis University, 2 Physical Therapy, Hanover College, 3 MIT Lincoln Laboratory

Keywords: Running, Biomechanics, Injury risk

https://doi.org/10.26603/001c.87631

International Journal of Sports Physical Therapy

Background
Little is known about changes in kinetics or kinematics following a 10 km training run. This information has implications on risk of running-related injury.

Purpose
The purpose of this study was to examine the effect of a 10 km run on running kinematics and kinetics in a sample of experienced runners.

Study Design
Cross-Sectional Study

Subjects
Nineteen runners ages 18-48 (7 female, 12 male) consented to participate including eight (3 female, 5 male) ultra-runners, and 11 (4 female, 7 male) recreational runners.

Methods
Following collection of demographic data and completion of a short running survey, participants did a 6-minute run at their self-selected running speed to acclimate to the instrumented treadmill. Reflective markers were placed over designated anatomical landmarks on both sides of the pelvis as well as the left lower extremity and marked with a skin pen. Subjects then ran on the treadmill and 30 seconds of video data were recorded at 240 frames/sec using a high-speed camera for the sagittal plane and the frontal plane. Simultaneously, ground reaction forces (GRFs) were recorded at 1200 Hz through the treadmill’s embedded force plates. Each runner then ran 10 km on a paved trail at their self-selected pace. Immediately following the run, reflective markers were reattached, guided by markings placed before the run, and a 30-second post-run trial of the video and GRF data were recorded. Video data were analyzed using Kinovea software to measure the kinematic variables of interest. Paired t-tests with Bonferroni corrections were used to find if significant differences existed between pre- and post-run data for all kinematic and kinetic variables.

Results
No significant or clinically relevant differences existed between the pre- and post-run measurements for the kinematic or kinetic variables. The only significant difference noted between the ultra-runners and recreational runners was that the ultra-runners had significantly higher cadence (p=0.045).

Corresponding Author:
Mark F. Reinking
Regis University, School of Physical Therapy
mreinking@regis.edu
303-964-6471
Conclusions
A 10 km run at a self-selected pace did not result in change in the mean kinematic or kinetic variables in this group of experienced runners. Ultra-runners employ higher cadence than recreational runners, but their kinematics and kinetics are similar.

Level of Evidence
Level 3

INTRODUCTION
Running remains one of the most popular fitness activities, as it is convenient, inexpensive, and a recognized way to maintain good health and wellness. Distance runners are consistently pushing the envelope of their sport, trying to run further and faster than ever before. As such, there has been an increase in ultra-distance running events, characterized as being 50 km or longer, and along with it an increase in musculoskeletal injuries brought on by the repeated stresses of running such long distances.1

Several previous studies have examined the effect of fatigue on running kinematics and kinetics in novice and competitive runners. Maas et al.2 found that after an exhaustive run, both novice and competitive runners showed kinematic changes at the trunk, pelvis, hip, and knee, but that the changes in novice runners were more pronounced. Novice runners were defined as individuals who ran less than 10 km/week and neither had a history of competitive running nor were following a running program. Similarly, Koblbauer et al.3 found that novice runners had increased trunk flexion and ankle eversion with running-induced fatigue. Mohler et al.4 defined expert runners as those individuals who 1) trained more than 50km/week, 2) were able to run a 10km in less than 35 minutes, and 3) maintained an active membership with a running club. Expert runners showed increased stance time and decreased double foot time with increased upper body movements during an exhaustive run.

Considering the effect of the foot-ground impact, which generates ground reaction forces (GRFs) associated with overuse musculoskeletal injury, the act of running actually imposes less stress on the body when compared to other sports.5 However, as running mileage increases, the magnitude of the foot-ground impact can become significant. Derrick et al.6 found that although the changes in kinematics due to exhaustive running did potentially increase impact shock, overall shock attenuation also increased which counteracted the increased impact shock, thus negating potential increased injury risk.

The systematic review by Ceyssens6 revealed that while multiple studies have shown an association between kinematics and kinetics variables and running-related injury (RRI), there is still not strong evidence about the relationship between these biomechanical variables and RRI. Furthermore, the effect of a 10 km training run at a self-selected speed on running kinematics and kinetics is unknown. Do runners alter their running form over the course of a training run at a self-selected pace? Do the changes in running form result in altered GRFs? Do these changes result in an increased risk of a RRI? These research questions led to the primary research purpose, which was to investigate the effects of a 10 km run on running kinematics and kinetics in a sample of experienced runners. The secondary purpose was to determine if these effects were different between the recreational runners and the ultra-runners.

PARTICIPANTS
This study was a cross-sectional study of experienced distance runners with a single data collection session for each runner. An "experienced" runner was operationally defined as a runner who had averaged at least 20 miles/week running over the past year. Participants were recruited from the Denver metro area using posted flyers around the university and in gyms. Running clubs were also contacted and asked to distribute the recruitment flyers. Inclusion criteria included: age 18-50 years, an average of at least 20 miles running per week over the prior year, experience running on a treadmill, comfortable with running a 10 km, no history of limb deformity or surgery to correct limb deformity, and no RRI for the past three months that led to an inability to run for at least three consecutive days. If the runner had completed an ultra-running event (50 km or greater) within the past three years they were classified as an ultra-runner; all others were classified as recreational. The final sample consisted of 12 males and seven females between ages 18-48, eight of whom were ultra-runners, and 11 who were recreational runners.

METHODS
This study was approved by the Regis University Institutional Review Board. Upon arrival, participants reviewed and if agreeable to the terms of the consent, completed the IRB-approved consent form. Runners then took a web-based survey regarding their running training and RRI history. Height, weight, and vitals (blood pressure and heart rate) were measured and recorded. The protocol for treadmill analysis has been used in previous studies7 and the reliability of the 2D measures has been established.8 Each participant was asked to identify their preferred running speed for a typical training run and then were gradually brought to that speed on a fully instrumented treadmill (Bertec Corporation, Columbus, OH). Runners wore their own running shoes and completed at least six minutes of running at their self-selected speed so that they could acclimate to the treadmill. During the final minute of the acclimatization run, running cadence was counted by one of the researchers (KM).
Once the participant had completed at least six minutes on the treadmill and indicated they were acclimated to it, the treadmill was slowed to a stop and reflective markers were placed on the lower limbs in the following locations: left anterior superior iliac spine, bilateral posterior superior iliac spine, lateral condyle of the left femur, left lateral malleolus, left posterior calf above the Achilles tendon (two markers), and over the midline of the left heel (two markers). These locations are consistent with the marker set used in a previous study examining the reliability of 2-D kinematic analysis. To maximize consistent placement of the reflective marker for the post-run analysis, the runner’s skin was marked with a skin marker at the reflective marker locations.

After all markers were in place, the participant was asked to resume running on the treadmill at their pre-selected running speed. When the subject indicated they were comfortable on the treadmill, video data were recorded for the left sagittal plane (lateral view, Figure 1) and frontal plane (posterior view, Figure 2) for 30 sec each using a single high-speed camera (Model# EX FH25, Casio America Inc., Dover, NJ 07801) at 240 frames/sec. Simultaneous to the video capture, GRFs were recorded at 1200 Hz through the instrumented treadmill deck.

Each runner then ran a 10 km run on a paved trail followed by two members of the research team on bicycles. All runners completed the same running course at their self-selected training pace. When the runner returned to the lab after the 10 km run, the reflective markers were immediately reattached to the runner’s skin guided by the skin markings placed before the run. Once all markers were attached, the participants were asked to start running on the treadmill at the same speed as was selected for the pre-run analysis. As soon as the subject indicated they were comfortable on the treadmill, video data and GRF data were recorded in the same fashion as for the pre-run data collection.

DATA ANALYSIS

The video clips for each runner were assessed by a single rater (MFR) who has over 15 years of experience performing 2-dimensional video-based running analyses on runners. All angles were measured in degrees and all distance measurements were recorded in centimeters using a free-access video analysis software program (Kinovea, version 0.9.5, http://www.kinovea.org). A series of t-tests were performed to determine if there were differences between pre-run and post-run data for all kinematic variables assessed in this study, including shoe angle, leg angle, knee flexion at initial contact, knee flexion at midstance, total knee flexion, hip extension at toe-off, trunk lean, change in pelvic angle between initial contact and midstance, change between hip adduction angle at initial contact and midstance, change in rearfoot angle between initial contact and midstance, and vertical excursion of center of mass. Additionally, measured vertical ground reaction force, average loading rate, and braking impulse were compared between pre- and post-run. All statistical analyses were performed using SPSS Statistics, Version 26 (IBM Corporation, Armonk, New York 10504). Bonferroni adjustment of an alpha level of .05 was used for all tests of significance.

RESULTS

Participant demographics are provided in Table 1. A significant difference existed for cadence as measured pre-10 km
Changes in Running Kinematics and Kinetics Following a 10 km Run

run between recreational runners and ultra-runners, with ultra-distance runners having a higher cadence (p=0.045). Only two runners had been running less than two years with 12 athletes running regularly for over five years. Six of the runners were training over 40 miles/week with the remaining 13 runners training between 20 and 40 miles/week, and most runners (n=15) were running at a pace between 7 min/mile and 9 min/mile. Most of the runners exhibited a rearfoot strike pattern (n=14); the four participants who were forefoot strikers were equally split between ultra-runners and recreational-runners.

**Table 1. Mean participant demographics (SD)**

<table>
<thead>
<tr>
<th>Demographics</th>
<th>All Runners (n=19)</th>
<th>Ultra-Runners (n=8)</th>
<th>Recreational Runners (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>28 (8.4)</td>
<td>30 (9.3)</td>
<td>26 (7.7)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.76 (0.11)</td>
<td>1.72 (0.13)</td>
<td>1.79 (0.10)</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>68.9 (12.1)</td>
<td>65.1 (12.3)</td>
<td>68.2 (12.4)</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>21.5 (2.3)</td>
<td>21.9 (2.3)</td>
<td>21.2 (2.3)</td>
</tr>
<tr>
<td>Pre-10 km Cadence</td>
<td>170 (9)</td>
<td>175 (8.5)*</td>
<td>166 (8.1)*</td>
</tr>
</tbody>
</table>

* Indicates significant difference with p<0.045

ultra-distance runners having a higher cadence (p=0.045). Only two runners had been running less than two years with 12 athletes running regularly for over five years. Six of the runners were training over 40 miles/week with the remaining 13 runners training between 20 and 40 miles/week, and most runners (n=15) were running at a pace between 7 min/mile and 9 min/mile. Most of the runners exhibited a rearfoot strike pattern (n=14); the four participants who were forefoot strikers were equally split between ultra-runners and recreational-runners.

**Table 2** provides the kinematic data of all participants before and after the 10 km run. The mean differences between the pre-run and post-run were less than 1.5° for all kinematic variables. The spatiotemporal variables (Table 3) for all participants include stride length as represented by the distance between heel at foot strike and a vertical line from the estimated center of mass normalized by body height and the vertical excursion of the estimated center of mass also normalized by body height. The pre-run and post-run differences were less than 0.5% for both variables. **Table 4** provides mean values for all kinetic variables. There were also no significant differences in these variables comparing pre-run and post run data. For the kinematic, spatiotemporal, and kinetic data, there were no differences between the ultra-runners and the recreational runners.

**DISCUSSION**

The objective of this study was to compare the effect of a 10 km run on running kinematics and kinetics in a sample of experienced distance runners, including both ultra-runners and recreational runners. No significant differences between pre-run and post-run values were found for the kinematic, spatiotemporal, and kinetic data.

There are only a few studies examining kinematic and kinetic changes following a run. Derrick et al. examined kinematic adjustments in recreational runners during a two-mile exhaustive run and found that after the run, knee angle increased at initial contact and rearfoot inversion increased as well. Willwacher et al. found significant changes in frontal and transverse plane joint kinematics in competitive and recreational male runners following a 10 km fatiguing run. Möhler et al. examined 13 expert runners who ran on a treadmill to exhaustion. These researchers reported a significant increase in range of motion at the knee and ankle following the exhaustive run as a result of fatigue. Specifically, there was an increase in dorsiflexion and external rotation prior to toe-off, knee flexion increased during late-swing and stance phases, and hip flexion decreased at initial contact and increased prior to toe-off. In a second study using subjects who were novice runners, Möhler et al. found that following a run to exhaustion at 13 km/h, the runners showed a decrease in ankle dorsiflexion and increased rearfoot pronation. In the current study, the authors did not observe any significant differences in joint kinematic or running kinetics comparing pre-run and post-run values in the included participants. One key difference between the current study design and previous studies is that the runners ran a self-selected pace for 10 km based on their typical training pace, while in the other studies discussed, runners ran to fatigue or exhaustion. The authors intentionally designed this study to examine the effect of a 10 km overground run at a self-selected pace as this is more representative of how distance runners train.

These findings indicate that running kinematics and kinetics did not change after a 10 km run at a self-selected training pace. These findings are promising as they suggest that in a group of experienced runners, running form and forces are stable after a 10 km run and, as such, there does not appear to be an increased risk of injury with training related to changes in form or forces. The authors chose to allow the participants to self-select their running pace rather than requiring an exhaustive effort to better generalize these findings to a larger population and because the majority of training is not an exhaustive effort. Additionally, this study included a subset of ultra-runners, which is a population that has not been well studied at the time of this publication. No significant differences were found when comparing the changes in kinematics or kinetics comparing ultra-runners and experienced runners other than cadence as previously described.

There are several limitations of this study, with the first being the sample size and pool of participants. Having only 19 runners, with an uneven distribution of recreational to
Table 2. Mean participant kinematics in degrees (standard deviation).

<table>
<thead>
<tr>
<th>Kinematics</th>
<th>All Runners (n=19)</th>
<th>Ultra-Runners (n=8)</th>
<th>Recreational Runners (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Tibial Angle</td>
<td>5.38</td>
<td>4.52</td>
<td>4.76</td>
</tr>
<tr>
<td>Knee Angle at Initial Contact</td>
<td>12.22</td>
<td>13.72</td>
<td>12.93</td>
</tr>
<tr>
<td>Knee Angle at Midstance</td>
<td>40.39</td>
<td>40.71</td>
<td>39.46</td>
</tr>
<tr>
<td>Total Knee Angle</td>
<td>28.17</td>
<td>27.00</td>
<td>26.53</td>
</tr>
<tr>
<td>Trunk Lean</td>
<td>8.42</td>
<td>7.27</td>
<td>8.25</td>
</tr>
<tr>
<td>Hip Extension</td>
<td>19.92</td>
<td>20.08</td>
<td>18.71</td>
</tr>
<tr>
<td>Knee Angle at Mid-Swing</td>
<td>91.96</td>
<td>93.05</td>
<td>89.09</td>
</tr>
<tr>
<td>Total Pelvic Drop</td>
<td>6.04</td>
<td>5.77</td>
<td>5.59</td>
</tr>
<tr>
<td>Hip Adduction Change from Heel Strike to Midstance</td>
<td>6.35</td>
<td>6.01</td>
<td>6.51</td>
</tr>
</tbody>
</table>

Table 3. Mean participant spatiotemporal variables in percentage of body height (standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>All Runners (n=19)</th>
<th>Ultra-Runners (n=8)</th>
<th>Recreational Runners (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Normalized distance from heel to center of mass line*</td>
<td>7.36</td>
<td>7.00</td>
<td>6.67</td>
</tr>
<tr>
<td>Normalized total vertical excursion*</td>
<td>0.036</td>
<td>0.038</td>
<td>0.0373</td>
</tr>
</tbody>
</table>

*Value normalized by dividing by subject height (cm)

ultra-runners, decreased the power of the study. However, the differences between the pre-run and post-run measures were very small, in fact, less than the standard error of the mean for all temporospatial and kinetic variables and for seven of the eleven kinematic variables. Consequently, the authors believe that there was, in reality, no differences between the two time-points. Another limitation of the study was the use of a self-selected pace for the run, rather than requiring participants to run at a percentage of their race pace. This made it difficult to control the effort of each participant and resulted in some runners completing the 10 km run slower than their reported training pace and others completing it faster. No measure of fatigue was used in the study to identify the relative fatigue of the runners after the training run. There was also a limitation with the use of markers for data capture. Since runners did not run the 10 km with the markers attached, there may have been some error in the placement of the markers following the 10 km run. However, the authors attempted to minimize this error by using the same researcher to place the markers on all runners and outlined the initial placement of the reflective markers with a skin marker. Lastly, due to the set-up of the testing environment and placement of the instrumented treadmill, data were collected only for the left lower extremity for all participants, whereas previous studies collected data for both limbs.

CONCLUSION

In conclusion, three questions were addressed in this study. The results indicate that there were very minor and non-significant differences between the pre-run and post-run kinematic measures and consequently, indicating that runners do not alter their form during this length of a training run. The results also indicated that alongside no changes in running form and, there were not changes in running kinet-
Table 4. Mean participant kinetic data (standard deviation).

<table>
<thead>
<tr>
<th></th>
<th>All Runners (n=19)</th>
<th>Ultra-Runners (n=8)</th>
<th>Recreational (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Vertical Peak (BW)</td>
<td>2.42 (0.16)</td>
<td>2.41 (0.16)</td>
<td>2.46 (0.16)</td>
</tr>
<tr>
<td>Vertical Impact Peak (BW)</td>
<td>1.72 (0.31)</td>
<td>1.66 (0.28)</td>
<td>1.68 (0.33)</td>
</tr>
<tr>
<td>Vertical Instantaneous Loading Rate (BW/sec)</td>
<td>76.91 (19.83)</td>
<td>73.97 (17.94)</td>
<td>72.92 (23.33)</td>
</tr>
<tr>
<td>Vertical Average Loading Rate (BW/sec)</td>
<td>62.94 (16.42)</td>
<td>60.97 (14.21)</td>
<td>59.90 (19.65)</td>
</tr>
<tr>
<td>Vertical Impulse (BW*sec)</td>
<td>0.35 (0.02)</td>
<td>0.34 (0.02)</td>
<td>0.33 (0.02)</td>
</tr>
<tr>
<td>Braking Peak (BW)</td>
<td>-0.36 (0.053)</td>
<td>-0.37 (0.063)</td>
<td>-0.37 (0.064)</td>
</tr>
<tr>
<td>Braking Impulse (BW*sec)</td>
<td>-0.02 (0.00)</td>
<td>-0.02 (0.00)</td>
<td>-0.02 (-0.00)</td>
</tr>
<tr>
<td>Propulsion Impulse (BW*sec)</td>
<td>0.02 (0.00)</td>
<td>0.02 (0.00)</td>
<td>0.02 (0.00)</td>
</tr>
</tbody>
</table>

ics. Finally, as no changes in running form or forces were detected there is no evidence that a runner increased the risk of a RRI as a consequence of fatigue from a 10 km run.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

ACKNOWLEDGEMENTS

The authors thank the running athletes who consented to participate in this study and both Mohamed Aziz and Danielle Colvin for their assistance in data collection.

Submitted: May 30, 2023 CDT, Accepted: August 22, 2023 CDT

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International Journal of Sports Physical Therapy
REFERENCES


Original Research

The Accuracy of Ankle Eccentric Torque Control Explains Dynamic Postural Control During the Y-Balance Test

Shojiro Nozu 1, Kristin A. Johnson 2, Tsukasa Tanaka 1, Mika Inoue 1, Hirofumi Nishio 1, Yuji Takazawa 1

1 Faculty of Health and Sports Science, Juntendo University, 2 Department of Physical Therapy and Rehabilitation Science, The University of Iowa

Keywords: dynamic postural control, ankle, sensorimotor function, eccentric muscle contraction

https://doi.org/10.26603/001c.87760

International Journal of Sports Physical Therapy

Background

The Y-Balance Test (YBT), especially the posteromedial (PM) reach direction (PM-YBT), is able to identify dynamic postural control deficits in those who have ankle instability. However, there still exists a need to understand how sensorimotor function at the ankle explains the performance during the PM-YBT.

Hypothesis/Purpose

The purpose of this study was to determine whether the ability to accurately control eccentric ankle torque explained PM-YBT performance. It was hypothesized that eccentric dorsiflexion/plantarflexion torque control would be positively related to the maximum reach distance (MRD) of PM-YBT.

Study Design

Cross-sectional study

Methods

Twelve healthy subjects performed the PM-YBT, maximum voluntary isometric contractions (MVIC) for both dorsiflexion and plantarflexion muscle strength, and then the torque control testing of the ankle. The torque control testing provided a target torque level on a screen in front of the subject and passive rotations of the ankle joint in the sagittal plane at 10 deg/sec between plantarflexion to dorsiflexion. Subjects were then instructed to eccentrically contract the dorsiflexors and plantar flexors to generate torque while the ankle joint rotated. The accuracy of torque control during eccentric dorsiflexion and plantarflexion by calculating absolute errors, the area between the target torque and the produced torque were evaluated. Tibialis anterior and soleus muscle activities were simultaneously recorded during testing. A step-wise linear regression model was used to determine the best model predicted the MRD of the PM-YBT (PM-MRD).

Results

A step-wise linear regression developed a model explaining only eccentric dorsiflexion torque control predicted higher PM-MRD score ($R^2 = 44\%$, $F_{1,10} = 7.94$, $\beta = -0.67$, $p = 0.02$).

Conclusion

The accuracy of torque control during eccentric dorsiflexion predicts better performance in the PM-YBT.

Corresponding author at:
Dr. Shojiro Nozu
Graduate School of Health and Sports Science, Juntendo University, Hiraka-gakuendai, Inzai, Chiba 270-1695, Japan
E-mail: s.nozu.hw@juntendo.ac.jp
INTRODUCTION

Ankle sprain is the most common sports injury\(^1\) and it becomes recurrent when sensorimotor dysfunction persists including muscle weakness and/or impaired processing of somatosensory information.\(^2,3\) Sensorimotor dysfunction that occurs after an initial ankle sprain alters an individual’s ability to stabilize the ankle joint which impairs dynamic postural control.\(^2,4-6\) People who develop this dysfunction after ankle sprains are commonly described as having “ankle instability.”\(^2,4\) Thus, current clinical practice guidelines recommend assessing dynamic postural control in people with ankle instability to determine their risk for recurrent injury.\(^7\)

A scoping review revealed that clinicians and researchers commonly assess dynamic postural control in people with ankle instability by measuring the maximum reach distance (MRD) of the posteromedial reach direction of Y-Balance Test (PM-YBT).\(^8\) The PM-YBT requires a person to maintain balance while they stand on a single limb and reach their opposite limb as far as possible in a posteromedial direction.\(^9\) While the MRD of the PM-YBT provides a measure of dynamic postural control that distinguishes people with ankle instability from healthy people,\(^10,11\) it remains to be shown whether motor output or sensory processing\(^3\) predict MRD performance. Thus, to better understand the extent that PM-YBT performance reflects underlying ankle impairments, there is a need to determine the influence of deficits in muscle activation or sensory processing on MRD. A previous study showed that artificial disruption of somatosensory input in healthy people decreases the MRD of PM-YBT by 4.6%.\(^12\) It remains to be shown whether torque control of ankle musculature contributes to PM-YBT performance.

In general, the ability to accurately control ankle torque in isometric and isotonic contractions is necessary to maintain single limb stability. The relationship between maximum isometric ankle torque and dynamic postural stability was investigated by Chotara et al\(^13\) who showed that maximum isometric torque of ankle dorsiflexion and plantarflexion explained 21-30% of the MRD of the PM-YBT. However, that study did not show consistent results between the dominant and non-dominant stance limbs and torque was assessed with a handheld dynamometer.\(^13\) In addition, Hubbard et al\(^14\) found that concentric ankle torque does not relate to dynamic postural control in people with ankle instability. While concentric torque does not explain YBT performance and isometric ankle torque may partially explain YBT performance, the ability of eccentric ankle torque to predict dynamic postural control is not known.

Eccentric activation of lower extremity muscles is necessary during most athletic movements.\(^15,16\) The ability to eccentrically control the ankle joint is also necessary to maintain balance during single limb stability.\(^17\) For example, performance of the PM-YBT requires eccentric activation of ankle musculature acting in the sagittal plane to stabilize the ankle joint during the reaching phase.\(^12,18\) Taken together, the ability to modulate eccentric muscle force at the ankle joint may be an indicator of dynamic postural control assessed by the PM-YBT. To our knowledge it is currently unknown whether the ability to control eccentric ankle torque output is predictive of YBT performance.

Therefore, the purpose of this study was to determine whether the ability to accurately control eccentric ankle torque explained PM-YBT performance. It was hypothesized that eccentric dorsiflexion/plantarflexion torque control would be positively related to the MRD of PM-YBT.

MATERIALS AND METHODS

PARTICIPANTS

Twelve healthy subjects were recruited for the study. Subjects with a history of lower extremity surgery, injuries in the six months prior to the study, or neurological disease including balance impairments were excluded. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the Juntendo University (protocol ID: 2021-95; date of approval: 22 September 2021). The subjects signed the informed consent before starting the test protocol.

PROCEDURES

A cross-sectional study was conducted. Before all testing, the subjects’ height (cm), body mass (kg), and limb length (distance from the anterior-superior iliac spine to the medial malleolus, cm) were measured. The testing limb was the dominant limb defined as the limb used to kick a ball. The subjects performed the PM-YBT, five-second maximum voluntary isometric contractions (MVIC) for both the dorsiflexors and plantarflexors, and then the torque control testing of the ankle. Subjects rested as needed between each testing.

DYNAMIC POSTURAL CONTROL MEASUREMENT

The YBT kit™ (Move2Perform, Evansville, IN), which contains a center board and indicator boxes with poles that indicate the reach distances in centimeters, was used to assess dynamic postural control ability (Figure 1). Only the posteromedial direction with the pipe positioned 135 degrees from the anterior pipe (PM-YBT) was used. The subjects were instructed to place the testing limb (stance limb) on the center board with their second toe positioned at the red line on the board and to push the indicator box as far as possible in the posteromedial direction. Before completing the PM-YBT trials, subjects were allowed to practice the PM-YBT task at least four times followed by a short rest break.\(^9\) While performing the PM-YBT, the subjects were asked to reach as far as possible while satisfying the following rules: (1) maintain hands on hips; (2) maintain the heel
of the test/stance limb on the floor at all times; (3) complete contralateral limb maximum reach in three seconds; (4) avoid kicking, slinging, or putting too much weight onto the push box; and (5) return the reach limb to the starting position without losing their balance.

MAXIMUM VOLUNTARY ISOMETRIC CONTRACTION TESTING

The Biodex System 4 Dynamometer (Biodex Medical Systems Inc, Shirley, NY) was used to determine the isometric peak torque value for both dorsiflexion (DF-MVIC) and plantarflexion (PF-MVIC) muscle torque. The subjects were secured at the trunk, thigh, and foot with a belt and seated on the chair with 45° of seatback tilt, the hip in 80° flexion, and the tibia parallel to the floor. The ankle was in 0° for plantarflexion isometric torque testing and 10° of plantar flexion for dorsiflexion torque testing (Figure 2). Surface electromyography (EMG) data were simultaneously recorded for the tibialis anterior (TA) and soleus (SOL) muscles using wireless electrodes (Ultium EMG, Noraxon, Scottsdale, AZ, USA) placed according to SENIAM guidelines. Before affixing the electrodes, the skin was cleaned with alcohol. Bipolar surface electrodes (Ag/AgCl, 35 mm interelectrode center-to-center distance) were attached to the skin overlying the TA and SOL muscles. EMG signals collected at a sampling frequency of 2,000 Hz were synchronized with the data obtained from the dynamometer.

TORQUE CONTROL TESTING

The subjects performed the torque control testing in the same setup as the MVIC testing (Figure 2). The dynamometer provided five continuous ankle rotations through the defined range from 15° of dorsiflexion to 30° of plantar flexion (45° range) at 10°/s. Torque control was defined as the ability to match eccentric torque output to a target torque level. As the dynamometer moved the ankle into dorsiflexion, the subjects were instructed to eccentrically contract the plantar flexors to 50% of their maximum isometric plantarflexion torque, which was determined after pilot testing. As the dynamometer moved the ankle into plantarflexion, the subjects were instructed to eccentrically contract the dorsiflexors to 50% of their maximum isometric dorsiflexion torque. The target torque level and the subject’s generated torque were displayed on a computer monitor (size: 27 inch) for visual feedback. The torque produced by the subject, the target torque, and the joint angle were collected at a sampling frequency of 100 Hz. Muscle activities of TA and Sol were simultaneously recorded during the torque control testing and synchronized with the data from the dynamometer using an analog to digital data acquisition (DAQ) board (2400 ISO, Noraxon, Scottsdale, AZ, USA). Prior to the testing, the subjects were allowed to practice five continuous ankle rotations in the sagittal plane for both plantarflexion and dorsiflexion. Each testing trial took approximately 22.5 second (10°/s, five rotations though 15° of dorsiflexion to 30° of plantar flexion).

DATA PROCESSING

Maximum reach distances of the YBT were recorded in centimeters, normalized to leg length, and multiplied by 100 (PM-MRD, %). Three scores from successful trials of the PM-YBT were recorded. The mean value of the three PM-MRD was used for data analysis. The isometric peak torque value for both DF-MVIC and PF-MVIC was normalized by subjects’ body mass (Nm/kg). Accuracy of eccentric torque control was calculated as the absolute error between the target torque and the produced torque (AE, Nm). While the torque control assessment occurred from 15° of dorsiflexion to 30° of plantarflexion (45° range), AE was analyzed from 10° of the dorsiflexion to 10° plantarflexion (20° range) during the ankle rotation. For both torque accuracy of dorsiflexion (AE-DF) and plantarflexion (AE-PF), the area between the target torque and the produced torque within the analysis range was used to assess the performance of torque control (Figure 3). Out of the five torque control trials, the mean AE-DF/AE-PF from the middle three trials (trials 2,3,4) was used for data analysis. Muscle activity during the torque control task was measured as the mean EMG within the analysis range which was normalized and expressed as a percentage of muscle activity obtained from the MVIC (EMG-TA; EMG-SOL, %MVIC). All EMG signals were subsequently bandpass filtered (between 20 and 500 Hz) with a 2nd order filter on the high-pass and a 4th order filter on the low-pass. All the data were analyzed offline using a custom-written program in MATLAB (The MathWorks, Natick, MA, USA) and confirmed visually for each trial. Figure 3 depicts a representative example of a subject’s produced torque, target torque, and EMG recorded during eccentric dorsiflexion torque control testing.

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**Figure 1. The posteromedial reach direction of Y-Balance Test**

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Figure 2. Testing position for the maximum voluntary isometric contraction testing and torque control testing

Figure 3. A sample analysis of absolute error and muscle activity of the tibialis anterior during the torque control testing. Absolute error was defined as the difference between the produced torque and the target torque.

STATISTICAL ANALYSIS

A simple linear regression was used to test whether eccentric dorsiflexion/plantarflexion torque accuracy predicted the PM-MRD performance. A stepwise linear regression model with all of the assessed variables (DF-MVIC, PF-MVIC, AE-DF, AE-PF, EMG-TA, EMG-SOL) was then run to determine whether isometric strength or muscle activity during the torque control task contributed to the prediction of dynamic postural control. Pearson product-moment correlation coefficients (r) were calculated during the process of computing the regression analysis. At each step, if a probability of F value satisfied the entry criterion (p-value \( \leq 0.05 \)) or elimination criterion (p-value \( \geq 0.1 \)), the variable was entered in the model or removed from the model, respectively. Standardized partial regression coefficients (\( \beta \)) were calculated to compare the degree that the independent variable influenced the dependent variable. Coefficients of determination (\( R^2 \)) were used to interpret the meaningfulness of the relationships. As a secondary analysis, a simple linear regression was used to examine whether muscle activity during the torque control task explained
eccentric dorsiflexion/plantarflexion torque accuracy. Mean and standard deviations (SD) of all values were calculated. These analyses were completed using SPSS software (Version 28; SPSS Inc, Chicago, IL). The significance level was set at 0.05.

RESULTS

The characteristics of the study participants were follow- ing: five females and seven males; age: 22.4 ± 2.2; weight: 65.6 ± 9.4 kg; height: 167.1 ± 8.0 cm. Simple linear regression revealed that the accuracy of torque control during eccentric dorsiflexion predicted a higher PM-MRD score (R² = 44%, F₁,₁₀ = 7.94, β = -0.67, p = 0.02, Figure 4).

The accuracy of torque control during eccentric plan tarflexion did not predict PM-MRD performance (β of AE- PF = 0.02, p = 0.94). Also, isometric strength and muscle activity during the torque control task did not contribute to the PM-MRD (β of DF-MVIC = -0.08, p = 0.82; β of PF-MVIC = 0.05, p = 0.87; β of EMG-TA = -0.29, p = 0.4; β of EMG- SOL = -0.02, p = 0.99). A step-wise linear regression model using all of the assessed variables revealed that only eccentric dorsiflexion torque control remained in the model. All relationships between the PM-MRD and independent vari- ables are described in Table 1.

Simple linear regression for the secondary analysis re- vealed that higher muscle activity in tibialis anterior during the torque control testing predicted greater accuracy of torque control during eccentric dorsiflexion (R² = 0.46, F₁,₁₀ = 8.4, β = -0.68, p = 0.02, Figure 5). The SOL muscle activity during the torque control testing did not explain the accuracy of torque control during eccentric plantarflexion (R² = 0.002, F₁,₁₀ = 0.02, β = 0.04, p = 0.89). All mean and SD of each outcome measure are described in Table 2.

DISCUSSION

This is the first study to show that accurate control of dor- siflexion torque relates to dynamic postural control as measured by the PM-YBT. As mentioned above, few studies have shown the relationship between sensorimotor function at the ankle and dynamic postural control as measured by the PM-MRD. The results of this study showed that the PM-MRD can be estimated by the accuracy of eccentric dorsiflexion torque control. In addition, it determined that greater accuracy of eccentric dorsiflexion torque control was predicted by greater activity of the tibialis anterior. Taken together, these findings indicate that the ability to activate and control ankle musculature as it is lengthening is important for dynamic balance.

The ability to control eccentric torque requires not only sufficient motor output but also adequate sensory processing. During the torque control test developed for this study, the subjects likely relied on sensory information from visual input (target torque and produced torque displayed on the screen) and somatosensory input (muscle spindles, Golgi tendon organs, cutaneous receptors). Thus, greater ability to control ankle torque output during an eccentric contraction, or lower AE as measured in this task, likely reflects accuracy in muscle recruitment and joint position sense.

The current findings suggest that the ability to accu- rately control eccentric ankle dorsiflexion may play an im- portant role in stabilizing the body during dynamic move-
Table 1. Relationships with the PM-MRD

<table>
<thead>
<tr>
<th></th>
<th>Pearson's r</th>
<th>p-value</th>
<th>95% CI Lower</th>
<th>95% CI Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE-DF</td>
<td>-0.67*</td>
<td>0.02</td>
<td>-0.90</td>
<td>-0.15</td>
</tr>
<tr>
<td>AE-PF</td>
<td>-0.10</td>
<td>0.75</td>
<td>-0.64</td>
<td>0.50</td>
</tr>
<tr>
<td>DF-MVIC</td>
<td>-0.47</td>
<td>0.13</td>
<td>-0.82</td>
<td>0.15</td>
</tr>
<tr>
<td>PF-MVIC</td>
<td>0.33</td>
<td>0.30</td>
<td>-0.30</td>
<td>0.76</td>
</tr>
<tr>
<td>EMG-TA</td>
<td>0.29</td>
<td>0.36</td>
<td>-0.34</td>
<td>0.74</td>
</tr>
<tr>
<td>EMG-SOL</td>
<td>-0.08</td>
<td>0.81</td>
<td>-0.62</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*: p < 0.05

AE-DF = Absolute error for dorsiflexion; AE-PF = Absolute error for plantarflexion; EMG-TA = Electromyography of the tibialis anterior; EMG-SOL = Electromyography of the soleus; DF-MVIC = Isometric peak torque value for dorsiflexion; PF-MVIC = Isometric peak torque value for plantarflexion; 95% CI = 95% confidence interval

Figure 5. The relationship between the AE-DF and EMG-TA. X-axis represents the mean value of muscle activities in tibialis anterior during eccentric dorsiflexion torque control testing. Y-axis represents the summation of absolute error during eccentric dorsiflexion torque control testing.

Table 2. Mean and SD of each outcome measure

<table>
<thead>
<tr>
<th>Outcome measure</th>
<th>Unit</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-MRD</td>
<td>%</td>
<td>111.43</td>
<td>6.53</td>
</tr>
<tr>
<td>AE-DF</td>
<td>Nm</td>
<td>68.07</td>
<td>10.80</td>
</tr>
<tr>
<td>AE-PF</td>
<td>Nm</td>
<td>37.38</td>
<td>12.27</td>
</tr>
<tr>
<td>EMG-TA</td>
<td>%MVIC</td>
<td>39.91</td>
<td>9.12</td>
</tr>
<tr>
<td>EMG-SOL</td>
<td>%MVIC</td>
<td>43.34</td>
<td>17.82</td>
</tr>
<tr>
<td>DF-MVIC</td>
<td>Nm/kg</td>
<td>0.67</td>
<td>0.10</td>
</tr>
<tr>
<td>PF-MVIC</td>
<td>Nm/kg</td>
<td>1.04</td>
<td>0.35</td>
</tr>
</tbody>
</table>

PM-MRD = Maximum reach distance of the posteromedial direction of Y-Balance Test; AE-DF = Absolute error for dorsiflexion; AE-PF = Absolute error for plantarflexion; EMG-TA = Electromyography of the tibialis anterior; EMG-SOL = Electromyography of the soleus; DF-MVIC = Isometric peak torque value for dorsiflexion; PF-MVIC = Isometric peak torque value for plantarflexion
ment. The findings of Fournier Belley et al.\textsuperscript{24} support the importance of precision sensorimotor function in the ankle dorsiflexors for maintaining dynamic postural control. They showed that the ability to detect a torque perturbation applied to the ankle dorsiflexors while they were passively lengthening was strongly associated with the PM-MRD score. Also, a recent systematic review\textsuperscript{25} revealed that during performance of the PM-YBT people with ankle instability do not activate tibialis anterior as much as healthy people, again highlighting the importance of this muscle in postural stability. In light of the findings, the detection and production of eccentric dorsiflexion may be an important indicator of one's ability to control posture during dynamic movement.

Interestingly, the ability to accurately control eccentric plantarflexion did not predict the PM-MRD. The association between the postomedial reaching task to eccentric torque control in dorsiflexion but not plantarflexion may be explained by differential actions of these muscle groups as the dorsiflexors muscles act in multiple planes but the plantar flexors muscles act in a single plane. This finding may be expected as ankle plantar flexors are activated similarly by healthy people and people with ankle instability during the PM-YBT.\textsuperscript{26} The lack of an association between soleus muscle activity and eccentric plantarflexion torque control may be due to contributions from other plantar flexor muscles. Also, this result suggests that the ability to accurately control eccentric plantarflexion torque (AE-PF) may not merely be influenced by soleus muscle activity.

Maximal isometric dorsiflexion and plantarflexion torques were not related to PM-YBT performance. Even more, the data suggests greater dorsiflexion torque was associated with worse PM-YBT performance although this did not reach the metric for significance (p=0.06, Table 1). These findings are contrary to those of Chata et al.\textsuperscript{13} who showed moderate relationships between isometric dorsiflexion and isometric plantarflexion torques with the PM-MRD. This discrepancy is likely due to the differences in participant demographics and methodology as they assessed isometric torque of elite soccer players using a hand-held dynamometer.\textsuperscript{15} The lack of relationships between isometric ankle torque and PM-YBT performance supports the premise of this study that when predicting postural control the ability to control muscle torque through a lengthening motion may be more important than other commonly assessed factors (isometric or concentric muscle strength).

One of the strengths of this study was that ankle torque was measured by an isokinetic dynamometer which is considered the "gold standard" device in the field of sports medicine.\textsuperscript{27} Previous studies that examined the accuracy of ankle torque control used a custom-built or robotic device,\textsuperscript{28,29} which are difficult to replicate by other researchers or clinicians. By using an isokinetic dynamometer, it can be confident in the reliability of the findings and this methodology may be more accessible for others to replicate.

Future studies investigating torque control capabilities in people with ankle instability will help to clarify the importance of this finding for predicting dynamic postural control in populations who are at risk for injury. These findings also raise the question as to whether eccentric torque control training improves postural control. Torque control testing relies on visual feedback, muscle sensory feedback, and neuromuscular excitability, all potential areas that may contribute to motor learning.\textsuperscript{30,31} To apply this idea in clinical practice, future studies need to examine the effectiveness of this approach as a sensorimotor control exercise to improve dynamic postural control for those who have ankle instability.\textsuperscript{32,33}

LIMITATIONS

There are several limitations that need to be considered in the findings. The current study had a small sample size that limited the ability to establish correlations among all the assessed sensorimotor factors. However, this study was able to establish the relationship between eccentric ankle dorsiflexion torque control and PM-MRD which was the primary aim. Given that the model explained 44% of the variance in PM-MRD score, there are other variables that also need to be considered such as the vestibular system, cutaneous receptors, joint mechanoreceptors, or other measures of joint stability for future study. This study is specific to healthy people without neurological impairment which may limit the generalizability of these findings to people with balance disorders. A more comprehensive assessment of multiple sensorimotor factors with a larger sample size will further improve an understanding of factors contributing to dynamic postural control during the YBT. This study focused on ankle musculature, the primary area affected after ankle strain, but knee and hip functions are also considered key contributors to the PM-MRD.\textsuperscript{34} Thus, eccentric knee and eccentric hip extension/flexion torque control may also be important to consider.\textsuperscript{16} Additionally, similar investigations of ankle inversion and eversion torque control may also provide important information regarding dynamic postural control ability.\textsuperscript{32,35,36} This initial study of eccentric torque control of ankle musculature, though small, provides the groundwork for future investigation that will continue to improve the understanding of contributing factors to postural control.

CONCLUSION

The accuracy of eccentric dorsiflexion torque control, which is influenced by the magnitude of tibialis anterior muscle activity, predicts better performance in the PM-YBT. The ability to control ankle torque eccentrically may be important for maintaining postural control during dynamic performance.

DISCLOSURES

Shojo Nozu received a research grant from JSPS KAKENHI (Grant Number: JP 21K21229), and Yuji Takazawa received
a research grant from The Joint Research Program of Jun- tendo University, Faculty of Health and Sports Science

Submitted: February 06, 2023 CDT, Accepted: July 16, 2023 CDT

The Accuracy of Ankle Eccentric Torque Control Explains Dynamic Postural Control During the Y-Balance Test

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REFERENCES


Original Research

Injury, Training, Biomechanical, and Physiological Profiles of Professional Breakdancers

Amelia J.H. Arundale1,2, Roisin McNulty2, Cory Snyder2,3, James O’Brien2,3, Thomas Stöggl2,3

1 Rehabilitation, Icahn School of Medicine at Mount Sinai Health System, 2 Red Bull Athlete Performance GmbH, 3 Sport and Exercise Science, University of Salzburg

Keywords: Dance, injury prevention, testing, hip-hop, endurance

International Journal of Sports Physical Therapy

Background
Breakdancing or breaking will enter the Olympics in 2024, however, there is a paucity of literature exploring the epidemiology, demands, and performance.

Purpose
The purpose of this study was to describe injury and training profiles, along with the results of a short performance test battery, in a group of elite breakers.

Study Design
Cross-sectional study (retrospective).

Methods
Fourteen breakdancers (breakers) (4 Bgirls, 10 Bboys) participated in an interview regarding their injury and training history, endurance test (cycle VO2max testing), counter movement jump, squat jump, drop jump, isometric hip abduction, adduction, shoulder external and internal rotation strength testing on a fixed-frame dynamometer. Breakers were divided into elite (n=10) and developing (n=4) based on their qualification for a world finals competition; Wilcoxon rank sums were used to compare the two groups, or in the case of strength testing between those with and without an injury history.

Results
The breakers had a median 11.0 [10.0 - 14.0] years breaking experience and trained 24.4 [20.5 - 30.0] hours per week. The knee was the most commonly injured body part and most frequently injured joint, with the thigh being the most common site for muscle injuries. There were no differences in endurance testing or jump height testing results between elite and developing breakers. There was no difference in shoulder external or internal rotation strength between athletes with a history of shoulder injury and those without. Similarly, there was no difference in hip abduction or adduction strength in those with a history of hip injury and those without.

Conclusion
The results of this study should be viewed with caution due to the small sample size. However, this study is the first to publish functional and physiological descriptives on breakers. The authors hope these results support clinicians treating breakers as well as encourages future research related to breaking.

Level of Evidence
2b
Table 1. Terminology Related to Breaking

<table>
<thead>
<tr>
<th>Breakers/Bboy/Bgirl</th>
<th>Athletes that participate in breaking.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking</td>
<td>The act of breakdancing</td>
</tr>
<tr>
<td>Top Rock</td>
<td>Dance moves performed on the feet, often involving variations on skipping and jumping movements</td>
</tr>
<tr>
<td>Footwork (also known as Down Rock or Floor work)</td>
<td>Movements on the floor supported by the hands or hands and feet</td>
</tr>
<tr>
<td>Power Moves</td>
<td>Movements that require speed, momentum, and acrobatics, often performed on the floor, common examples are head spins or flares (similar to the gymnastics pommel horse)</td>
</tr>
<tr>
<td>Flips</td>
<td>Acrobatic motion where the hips pass over the head without the hands touching the ground, performed either forwards or backwards.</td>
</tr>
<tr>
<td>Flares</td>
<td>Movement like the pommel horse (i.e Hands planted and legs moving) in men's gymnastics, however performed on the floor</td>
</tr>
<tr>
<td>Battles</td>
<td>A breakdancing competition</td>
</tr>
</tbody>
</table>

For more breaking terminology as well as photos the authors recommend www.olympics.com/en/news/breaking-breakdancing-rules-format-moves

INTRODUCTION

Break or breakdancing is a subgenre of hip-hop dancing originating from New York in the 1970s. It incorporates elements of music, dance, and acrobatics, with athletes (breakers) performing complex footwork, flips, and power moves, including weight bearing through their hands and head (Table 1). Breakers are unique in that they can be categorized as both overhead athletes and reverse chain athletes. Following a rise in global popularity, breakdancing made its Youth Olympic Games debut in 2018 and will make its full Olympic debut in Paris 2024. Breaking battles involve two breakers competing against each other for three rounds. Each round involves one breaker performing for around 30-45 seconds before the opponent responds. A panel of judges determines the battles’ winner based on the breakers’ style, moves, athleticism, artistry, and the fluidity in which moves connect. Despite breakdancing’s growing popularity and Olympic status, there is a paucity of knowledge about the performance, competition demands and medical aspects of the sport.

Breakdancing carries a high-risk of musculoskeletal injury, but only four published epidemiological studies exist. In 2009, Cho et al. reported the results of a survey and medical examination in 42 Korean Bboys. Over 95% of the participants reported past or present musculoskeletal injury, with the wrist, finger, knee, and shoulder being the most commonly injured areas. A subgroup of 23 professional breakers reported significantly more injuries than their 19 amateur counterparts. Kauffer et al. surveyed 144 breakers (40 professionals and 104 amateurs) at the “Battle of the Year World Final” in Germany. The wrist, spine, shoulder, and ankle were the most commonly injured areas. Their study also reported a higher number of injuries among professional breakers. A further survey including 138 breakers reported a higher injury rate among breakers than in other forms of hip-hop. The annual injury incidence of hip-hop dancers has been reported to be over three times the rate of modern dancers and eight times that of ballet dancers. Most recently, Tsouli et al. surveyed 520 breakers (16% professional and 65% student-recreational) from multiple countries. Over 40% of the participants reported current injuries and over 70% reported an injury within the previous year. The most frequently injured areas were the arm-hand, shoulder, knee, and neck. Taken together, these preliminary research findings indicate that injuries are common in breakdancing, with a higher injury risk than other dance forms, particularly for injuries of the upper-extremity and spine.

Beyond epidemiological analyses, published information on medical or performance aspects of breakers is sparse. One study reported medical imaging in breakers and small, preliminary studies on the physiology, biomechanics, well-being and gene profiles of hip-hop dancers have been published. In a cross-sectional observational study, Wyon et al. investigated the cardiorespiratory profiles and performance demands of nine male breakers and nine female new style dancers (a different style of hip-hop). During a performance simulation, breakers’ maximal oxygen consumption (VO_{2peak}) was significantly greater than published findings from contemporary dance, and mean heart rate (HR) was higher than previous reports from ballet, contemporary dance and dance sport.

In view of the high injury risk and growing popularity of breakdancing, further research on medical and performance aspects of this sport is crucial. While there is a general paucity of research on this topic, the lack of published information on specific performance testing (e.g., endurance, strength and jump testing) is particularly apparent. It is also notable that elite level breakers are under-represented in published studies to date. Gaining a better understanding of the injury and performance profiles of breakers is essential to support injury prevention, rehabilitation, and performance training efforts. For example, establishing specific strength profiles in the shoulder and hip can inform injury monitoring and management, as evidence in other sports.

The use of isometric strength as well as vertical jump profiles for screening and monitoring athletes is common. For example, measurement of isometric shoulder strength is widely employed in upper limb dominant or overhead sports and isometric hip adduction strength...
has been identified as a risk factor for subsequent injury across a variety of sports.\textsuperscript{20,21} Normative data in vertical jump testing has been reported in numerous sports, including gymnastics and parkour\textsuperscript{22–25} which are similar to breaking with regards to physical demands. Profiling breakers using clinically accessible tools such as isometric strength and vertical jump testing will allow clinicians to compare data and researchers to begin to establish areas of further research.

The purpose of this study was to describe injury and training profiles, along with the results of a short performance test battery, in a group of elite breakers. The findings can inform the development of future test batteries and support the efforts of medical and performance staff working with breakers.

MATERIALS AND METHODS

ATHLETES

This study retrospectively examined the clinical and performance data that was collected on fourteen professional breakers who were invited to attend a 10 day breakdance performance summit. Breakers were invited based on their previous breakdancing performance at international battles and having been identified as potential participants in the 2024 Olympic games. The breakers were categorized into elite and developing, based on successful qualification for a world finals competition.

Tests were chosen from a range of standard test procedures used frequently at a performance center. Clinicians and practitioners at the performance center selected tests to build a clinical perspective of the athletes in a limited amount of time. The testing that was conducted was not designed for research purposes, but as standard procedure at the performance center. All breakers gave verbal and written consent to participate in all tests. All breakers also gave written consent for their anonymized data to be published. This study was IRB exempt as it was a retrospective analysis.

INJURY AND TRAINING HISTORY

Injury and training history was collected via a detailed interview with an experienced Sports Physiotherapist (AA or RM) in conjunction with a physical musculoskeletal assessment (associated with another study). The interpretation and definition of 'injury' was left open to the athlete so as not to exclude any relevant information. If clarification was required, it was explained broadly as any musculoskeletal issue that resulted in pain, the breaker having to modify their training / performance, or being unable to train / perform. Injuries were categorized according to Fuller et al.\textsuperscript{26} with regards to body area and injury type. Athletes were asked to detail their weekly training routines regarding hours per day, days per week, training modalities, and breaking surface. When training modalities other than breaking were discussed, the Sports Physiotherapists followed up with the amount of time per day and week these modalities were used, and the number of years the breaker had been performing that modality. In addition, each breaker was asked the number of years they had been breaking.

ENDURANCE TESTING

To make sure testing was similar across all breakers and since not all were familiar with running, particularly at high speed, biking was selected to determine endurance performance. Endurance testing was performed by an exercise physiologist (RH). The endurance test was performed on a cycle ergometer (Cyclus 2, Leipzig, Germany) to determine maximal oxygen uptake ($\text{VO}_2\text{max}$) (Cortex Metalyzer 3B, Leipzig, Germany), peak power output (PPO), maximal heart rate ($\text{HR}_\text{max}$) and lactate threshold (LT). Breakers were instructed to refrain from strenuous exercise and alcohol for 24 hours prior. Caffeine, food, and drinks containing sugar were to be avoided for three hours prior to the endurance tests. The testing protocol used was a two-phase test consisting of an incremental, sub-maximal exercise test (Phase 1) (50 W; increment: 25 W every 3 min, cadence $> 80$ rpm) until blood lactate increased by $> 1$ mmol/L compared to the previous stage, followed by a ramp test (Phase 2) interspersed with an 8 min break (4-min low intensity cycling at 40 W followed by 4 min passive rest). The ramp test started with the power output of the stage during the incremental test before the lactate increase of $> 1$ mmol/L and increased in 25 W steps per minute until voluntary exhaustion. During the last 30-s of each increment capillary blood from the earlobe was collected to determine blood lactate and blood glucose (Biosen S-Line Clinic, EKF diagnostic GmbH, Magdeburg, Germany). A modified version of the concept of Thoden et al.\textsuperscript{27} was introduced to determine LT.\textsuperscript{28}

JUMP TESTING

Following a general warm-up, reflective markers were placed on bony landmarks of the pelvis of each subject (left and right/anterior and posterior iliac spines) to record jump height. Jump testing was performed by a biomechanist (CS) with 10 years’ experience. All trials were recorded by a 12-camera motion capture system (Bonita 10, Vicon Oxford, UK) at 200 Hz synchronized with 2 AMTI force plates (OR6, AMTI Watertown, MA, USA) sampling at 2000 Hz. Prior to testing a static trial was performed to record upright standing height. All participants performed three vertical jumps, squat jumps (SJ), counter movement jumps (CMJ), and drop jumps (DJ). Participants performed as many familiarization trials as necessary prior to recording until they were comfortable with the movements. Participants held their hands on their hips during the entire jump to reduce the influence of arm-swing on jumping performance. The participants then performed up to five trials, with the mean of the best three – determined by jump height – being retained for further analysis. Jump test order was performed in block order for all participants (SJ, CMJ, DJ).
SQUAT JUMP

Participants were instructed to squat down to a "comfortably deep" knee angle (approximately 80-90°) and hold that position for three seconds before performing a maximal vertical jump. If the squat position was not held long enough, or a counter-movement was observed, the trial was repeated.

COUNTER MOVEMENT JUMP

Participants were instructed to stand erect on the force plates, rapidly flexing the hips, knees, and ankles before performing a maximal vertical jump. Counter-movement depth was not controlled.

DROP JUMP

Participants started standing on a 34 cm box placed just behind the force plates. Participants were instructed to lean forward and fall vertically onto the force plates. Participants were given the instruction to perform a maximal vertical jump immediately upon landing while minimizing ground contact time ("Try not to even let your heels touch the ground"), landing again on the force plates.

PARAMETER EXTRACTION

Jump height for each jump was calculated using the difference between the height of the mean of the four pelvis markers in each trial and the standing height. Limb symmetry index (LSI) was calculated as the difference between the net impulse of the right and left leg expressed relative to the greater side (negative values indicate left > right, positive values indicate right > left). For the DJ, reactive strength index (RSI) was also calculated as the ratio between jump height (m) and ground contact time (ms) during the initial landing/jump phase.

HIP AND SHOULDOR SCREENING

Previous interaction with the group revealed prevalence of shoulder, hip/groin, and knee injuries. Therefore, reproducible isometric muscle tests for shoulder external/internal rotation and hip abduction/adduction were selected to profile these muscle groups and to allow comparison to other sports and dance genres. Fixed frame dynamometry is a valid and reliable tool in assessing hip adductor and abductor strength.29,30

All maximal isometric strength tests were performed on a fixed-frame portable dynamometer (KangaTech, Melbourne, Australia) by an experienced sports physiotherapist (RM) immediately following jump testing. After three to five familiarization trials, three 5-second maximal trials were performed. Test order was fixed (shoulder internal rotation, shoulder external rotation, hip adduction, hip abduction). For shoulder tests, the right limb was always tested first, followed by the left. For hip tests, both legs were tested simultaneously. Peak force was averaged across trials for analysis.

SHOULDER STRENGTH

Maximal isometric shoulder internal and external rotation were both performed in a supine position with the shoulder in 90° of abduction, 0° of shoulder external rotation, and the elbow flexed to 90°, resulting in a vertical forearm with the hand pronated. A towel was placed underneath the elbow to ensure that the humeral axis remained in the plane of the scapula (without horizontal add-/abduction). For external rotation test, participants pushed against a pad set at the height of the dorsal aspect of the wrist at a right angle to the forearm. For the internal rotation test, participants pushed against a circular pad set at the height of the palmar aspect of the wrist at a right angle to the forearm.

HIP STRENGTH

Hip maximal isometric strength tests were performed in a supine position, with the knees supported by a foam roller resulting in approximately 30° of hip flexion. For hip abduction, participants pushed outward against circular pads fixed at the height of the lateral femoral condyles. For hip adduction participants pressed inward against circular pads fixed at the height of the medial femoral condyles. During both abduction and adduction tests participants were instructed to keep their feet on the floor, and approximately in line with their patella/hip joints. Both add-/abduction tests were performed bilaterally.

PARAMETER EXTRACTION

The peak force averaged across trials was recorded for each movement and expressed relative to body weight (BW). The LSI was calculated similarly to the jump tests. Additionally, joint ratios were calculated for both the shoulder and the hip with the left and right sides calculated separately. Shoulder rotation ratio was expressed as the percentage ratio between the external to internal rotation F\text{max}. Hip ratio was expressed in percentage as the ratio between the adduction to abduction F\text{max}.

STATISTICS

All data are reported as median and interquartile range. Endurance testing and jump variables were compared between elite and developing breakers using Wilcoxon rank sum. Wilcoxon rank sums were used to compare shoulder internal and external F\text{max}, LSI, and shoulder ratio in athletes with and without a history of shoulder injury. Wilcoxon rank sums were also used to compare hip adduction and abduction F\text{max}, LSI, and hip ratio in athletes with and without a history of hip/groin injury. Level of significance was set to alpha ≤ 0.05.

RESULTS

Fourteen breakers participated in the study (4 Bgirls, 10 Bboys) ranging in age from 14 - 31 (median 23 [25-75% inter-quartile range 20.5 - 28.2] years). The breakers height was median 166.6 [153.8 - 170.4] cm and weight was a me-
median of 63.5 [range 153.8 - 170.4] kg. There were four breakers (all Boys) classified as developing (age 18.7 [15.5 - 21.8] years) and 10 breakers (4 Girls, 10 Boys) classified as elite (age 27.4 [23.0 - 29.5] years). The breakers came from five continents; North America (N=2), South America (N=2), Asia (including Russia, N=4), Europe (N=4), and Africa (N=2).

**TRAINING**

The group had a median of 11.0 [10.0 - 14.0] years breaking experience. The developing group had between 8 -12 years (median 10.0 [8.25 - 11.25]) experience. The elite group had 9 – 21 years (median 12.5 [10.0 - 15.5]) experience.

The group trained for median 24.4 [20.5 - 30.0] hours per week, including all training modalities. The majority of their training time was breaking, with 5.6 [2.8 - 9.1] hours per week dedicated to non-breaking training modalities. The developing group spent 29.0 [22.8 - 33.0] total hours per week training, with only 0.5 [0 - 1.25] hours per week of that training time dedicated to non-breaking training. In contrast, the elite group spent 35.1 [19.3 - 30] total training hours per week, with 8.5 [3.3 - 11.3] hours per week of that time dedicated to non-breaking training.

The most common non-breaking training modality was strength training. Twelve of the 14 breakers performed strength training. Interestingly, the only two who did not perform strength training were under 18 years old/developing breakers. Only one breaker had more than two years’ experience with strength training. Other non-breaking training modalities included cardiovascular training (n=7), running, biking, boxing, skipping rope, stretching/mobility (n=5), yoga/meditation (n=1), and acrobatics (n=1).

The most common surface for the breakers to train was linoleum or laminate (n=5), followed by wood floors (n=4), or a hard matt (n=5). Other floor surfaces included cement/concrete for one breaker or marble for another (note: some breakers trained on multiple surfaces).

**INJURY HISTORY**

The 14 breakers recalled 45 injuries, leading to an injury burden (average) of 3.2 injuries per breaker (median 3.5 [2 - 4]). The elite breakers had an average of 3.1 injuries per breaker, and the developing breakers had an average of 5.5 injuries per breaker.

The most common body part injured was the knee, followed by the elbow and shoulder (Table 2). The most frequently injured joint was the knee. The thigh was the most frequent site of muscle injuries (Figure 1).

**ENDURANCE TESTING**

The endurance testing results are found in Table 3. Predicted power at 2 mmol/L was also the only parameter to differ between the elite and developing breaker groups, where elite breakers had higher power output predicted at 2 mmol/L than the developing group (p < 0.01).

### Table 2. Number of injuries reported by breakers

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Number of Injuries</th>
<th>Number of Breakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head/Face</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Neck</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Spine</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Shoulder</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Elbow</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Lower Arm</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wrist</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hand/Finger</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hip/Groin</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Thigh</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Knee</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Calf/Lower Leg</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ankle</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Foot</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**JUMP TESTING**

Jump performance results are listed in Table 3. There were no significant differences between groups observed for any jumping parameters.

**HIP AND SHOULDER SCREENING**

Hip strength outcomes for all breakers are presented in Table 4. There were no differences in hip abduction or adduction strength between breakers with and without history of hip injury (Table 4). Shoulder strength measures are presented in Table 5. There were no differences in shoulder external or internal rotation strength in breakers with and without a history of shoulder injury (Table 5).

**DISCUSSION**

Although a small cohort, the results of this study are the first to describe functional data from breakers. The group had a median 11 years breaking experience and trained between 20 and 30 hours per week. The majority of that training was breaking. Although elite breakers dedicated more time to non-breaking training modalities, all had < 2 years’ experience. Breakers had approximately three injuries each with the knee, followed by the elbow being the most common locations. There were minimal differences between the elite and developing groups with regard to functional tests, and no significant differences between athletes with and without a history of shoulder or hip injury. The results of this study provide pilot data for future studies, a starting...
INJURY AND TRAINING HISTORY

Consistent with the previous epidemiological literature on breakers, knee and upper limb injuries (shoulder / elbow / arm / hand) were the most commonly injured areas in this cohort. The number of injuries reported appears low in comparison with previous studies. With some breakers in this cohort competing for 20 years, it is likely that the results were affected by significant recall bias. Additionally, interpretation of what constitutes an injury was variable across the group. There appears to be a culture of “pushing through pain” amongst breakers, and therefore any interpretation around epidemiology of this group should be taken with caution. Future qualitative studies could explore the culture around injuries in breaking, with quantitative studies using valid/reliable scales, such as the Oslo Sports Trauma Research Center (OSTRC) Questionnaire.

Figure 1. Types of Injuries

Joint/Ligament includes: ligament injuries, subluxation, dislocation, cartilage lesions, and meniscal lesions. Muscle/Tendon includes: muscle and tendon injuries. Bone includes: fractures, stress fractures, bone bruises, and other bone injuries. Contusion includes: contusions and hematomas. Nerve includes: nerve injuries. No concussions were reported, therefore not included in this table. Unknown injuries were injuries that the athlete had no specific diagnosis for and the authors were unable to retrospectively diagnose. Data were collected during detailed injury/training history interview.

There was a noticeable difference between the elite and developing groups in training. Elite breakers spent more time per week training, but with a greater amount of non-breaking training modalities. In contrast, it was rare for the developing breakers to perform any training outside of breaking. Strength training, followed by cardiovascular training, were the most common non-breaking training modalities used amongst the group. Of significant note, all breakers had a short training history (< 2 years) in non-breaking modalities. The data could indicate that elite breakers may have more understanding as to the importance/benefits of strength training and diversity in training modalities; knowledge that less experienced breakers could benefit from. In congruence with previous data indicating that breakers often train unsupervised and receive less medical support than other dance forms, this data seems to indicate that all breakers, regardless of experience level, may benefit from education regarding injury prevention, load management, as well as guidance and coaching with regards to training planning, strength training, cardiovascular training and recovery.

ENDURANCE

Endurance testing is a common assessment tool used in the authors’ center, giving clinicians and practitioners insight into the cardiovascular fitness of each athlete and areas where training might be supported. Given the lack of literature on breaking and in collaboration with the breakers’ coaches, the authors’ decided that endurance testing as a baseline could be valuable. Further, endurance capacity can be seen as an important general foundation for each type of sport (e.g. greater amount of high quality training, faster recovery from strenuous tasks, higher resilience and injury prevention). The majority of the aerobic and anaerobic training that the breakers in this cohort performed each week was through their breaking training.

To the authors’ knowledge there are no studies examining the energy demands of breaking. Individual battles often involve three rounds. Breakers decide who will perform first, and then each round they each have a maximum time (often 50-45 s but as long as 3 min) to perform as much
Table 3. Endurance and jumping performance for all breakers, elite and developing breakers.

<table>
<thead>
<tr>
<th></th>
<th>All Breakers</th>
<th>Elite</th>
<th>Developing</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_2) [W]</td>
<td>78 [67 - 116]</td>
<td>99 [78 - 121]</td>
<td>60 [43 - 67]</td>
<td>0.01</td>
</tr>
<tr>
<td>(P_{2rel}) [W/kg]</td>
<td>1.5 [1.1 - 1.8]</td>
<td>1.7 [1.5 - 2.1]</td>
<td>1.0 [0.9 - 1.2]</td>
<td>0.01</td>
</tr>
<tr>
<td>LR[L] [W/kg]</td>
<td>1.4 [1.3 - 1.9]</td>
<td>1.8 [1.3 - 2.0]</td>
<td>1.4 [1.3 - 1.4]</td>
<td>0.38</td>
</tr>
<tr>
<td>HR[L] [rel %]</td>
<td>69.9 [66.9 - 73.2]</td>
<td>69.8 [66.1 - 70.9]</td>
<td>73.7 [68.4 - 76.5]</td>
<td>0.50</td>
</tr>
<tr>
<td>(VO_{2LT}) [ml/kg/min]</td>
<td>28.6 [24.0 - 30.0]</td>
<td>28.7 [22.8 - 30.4]</td>
<td>25.0 [25.0 - 28.7]</td>
<td>1.00</td>
</tr>
<tr>
<td>(VO_{2LT}) [rel %]</td>
<td>55.3 [50.0 - 63.4]</td>
<td>55.6 [52.0 - 63.0]</td>
<td>52.4 [47.5 - 61.6]</td>
<td>0.50</td>
</tr>
<tr>
<td>(P_{max}) [W]</td>
<td>231 [150 - 266]</td>
<td>256 [206 - 278]</td>
<td>167 [125 - 228]</td>
<td>0.07</td>
</tr>
<tr>
<td>(P_{maxrel}) [W/kg]</td>
<td>3.6 [3.3 - 4.0]</td>
<td>3.8 [3.3 - 4.0]</td>
<td>3.5 [2.9 - 3.7]</td>
<td>0.41</td>
</tr>
<tr>
<td>HR (\text{max}) [bpm]</td>
<td>188 [183 - 193]</td>
<td>188 [183 - 191]</td>
<td>189 [179 - 200]</td>
<td>0.57</td>
</tr>
<tr>
<td>(VO_{2max}) [ml/kg/min]</td>
<td>47.8 [46.4 - 50.6]</td>
<td>47.8 [45.4 - 50.6]</td>
<td>48.0 [47.0 - 51.5]</td>
<td>0.71</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CMJ</th>
<th>Jump Height [cm]</th>
<th>LSI [%]</th>
<th>SJ</th>
<th>Jump Height [cm]</th>
<th>LSI [%]</th>
<th>DJ</th>
<th>Jump Height [cm]</th>
<th>LSI [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{max}) [kg/BW]</td>
<td>0.61 [0.46 - 0.66]</td>
<td>0.42 [0.36 - 0.56]</td>
<td>0.62 [0.58 - 0.66]</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{max}) [kg/BW]</td>
<td>0.59 [0.51 - 0.66]</td>
<td>0.49 [0.46 - 0.64]</td>
<td>0.61 [0.58 - 0.66]</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Ratio</td>
<td>98 [80 - 110]</td>
<td>77.15 [61.8 - 116.6]</td>
<td>100.6 [86.0 - 109.5]</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Add – Hip Adductors, Abd – Hip Abductors, \(F_{max}\) – maximum isometric force expressed relative to body weight, LSI – difference between left and right leg maximum force expressed relative to greater side, Hip Ratio – Aductor to Abductor maximum strength ratio.

Table 4. Hip strength for all breakers, and comparison of hip strength in breakers with and without history of hip injury

<table>
<thead>
<tr>
<th></th>
<th>All Breakers</th>
<th>History of Hip Injury</th>
<th>No History of Hip Injury</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add.</td>
<td>(F_{max}) [kg/BW]</td>
<td>0.61 [0.46 - 0.66]</td>
<td>0.42 [0.36 - 0.56]</td>
<td>0.62 [0.58 - 0.66]</td>
</tr>
<tr>
<td>LSI [%]</td>
<td>8.6 [2.9 - 10.8]</td>
<td>9.2 [7.0 - 13.4]</td>
<td>7.2 [2.5 - 10.8]</td>
<td>0.46</td>
</tr>
<tr>
<td>Abd.</td>
<td>(F_{max}) [kg/BW]</td>
<td>0.59 [0.51 - 0.66]</td>
<td>0.49 [0.46 - 0.64]</td>
<td>0.61 [0.58 - 0.66]</td>
</tr>
<tr>
<td>Hip Ratio</td>
<td>98 [80 - 110]</td>
<td>77.15 [61.8 - 116.6]</td>
<td>100.6 [86.0 - 109.5]</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Add – Hip Adductors, Abd – Hip Abductors, \(F_{max}\) – maximum isometric force expressed relative to body weight, LSI – difference between left and right leg maximum force expressed relative to greater value, Hip Ratio – Adductor to Abductor maximum strength ratio.

Table 5. Shoulder strength for all breakers, and comparison of shoulder strength in breakers with and without history of shoulder injury

<table>
<thead>
<tr>
<th></th>
<th>All Breakers</th>
<th>History of Shoulder Injury</th>
<th>No History of Shoulder Injury</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>(F_{max}) [kg/BW]</td>
<td>0.33 [0.26 - 0.40]</td>
<td>0.38 [0.32 - 0.42]</td>
<td>0.28 [0.24 - 0.38]</td>
</tr>
<tr>
<td>ER</td>
<td>(F_{max}) [kg/BW]</td>
<td>0.26 [0.22 - 0.30]</td>
<td>0.28 [0.25 - 0.32]</td>
<td>0.25 [0.20 - 0.30]</td>
</tr>
<tr>
<td>LSI [%]</td>
<td>11.4 [6.3 - 14.5]</td>
<td>11.4 [7.6 - 16.4]</td>
<td>12.0 [3.1 - 14.5]</td>
<td>0.82</td>
</tr>
<tr>
<td>Shoulder Ratio</td>
<td>78 [71 - 89]</td>
<td>69.7 [69.0 - 75.6]</td>
<td>80.1 [75.7 - 96.7]</td>
<td>0.14</td>
</tr>
</tbody>
</table>

IR – Shoulder internal rotation, ER – Shoulder external rotation, \(F_{max}\) – maximum isometric force expressed relative to body weight, LSI – difference between left and right shoulder maximum force expressed relative to greater value, Shoulder Ratio – External to Internal Rotator maximum strength ratio.

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or as little as they choose, and watch as the other breaker does the same. This individual battle format means that a breaker performs at high intensity for up to 3 min, followed by up to 3 min recovery, before performing again. Doubles or team battles are organized differently often allowing an athlete more recovery between rounds of breaking.

The analysis of selected breaking training sessions (Supplemental Material), revealed the intermittent nature and high intensity content of these sessions (E.g., almost 45% of the total training duration within Zone 2 and 3). Some breakers even reached higher HRacamax values compared with the endurance test to exhaustion on the bicycle (Supplemental Material Figure 1). Therefore, most of the breaking training can be classified as a specific High Intensity Training.

Putting the endurance performance of the breakers in the current study into perspective, their capacity is comparable to female rhythmic gymnasts and ballet (VO2max slightly above 50 ml/kg/min).34 Based on the reported training volume (mostly specific breaking training, and very little general endurance training), and high intensity nature of breaking, there is a clear potential to progressively improve the general endurance capacity of breakers by adding classical endurance and strength training, or by more systematically implementing the high intensity breaking content.

JUMP TESTING

Vertical jump measurements are very common in sports performance assessments.35 Vertical jumping while not necessarily sport-specific for breakers, was chosen as an initial testing method given the ease of use and comparison to normative data from other sports. There were no significant differences observed across the elite and developing groups. There were >10% LSI in SJ and DJ across the whole cohort. Such asymmetries could be normal for breakers (e.g., based on dominant side, preferred rotation direction, etc.), or as a result of an unfamiliar jumping pattern, however clinicians treating breakers in a rehabilitation setting may want to investigate any asymmetries they observe to explore potential injury implications.

Parkour and artistic gymnastics are likely the two closest sports for comparisons to breaking. This cohort of breakers had CMJ heights around 32cm. Cohorts of young male and female artistic gymnasts had average vertical jump heights > 40 cm.22-24 Stafford et al.25 investigated a small group of male parkour athletes, finding a CMJ height of 39.2 ± 5.9 cm. Direct comparison of results is difficult due to differences in demographics as well as jump assessment methodology, but it is also possible differences could be due to sporting demands. Breakers rarely produce or absorb purely vertical force. Although flips and jumps are common in power moves, they are usually the entrance to or exit from another move. In comparison, parkour athletes require vertical force to climb walls and artistic gymnasts to mount apparatus or land routines. It is possible that a different jump assessment in breakers could be more appropriate to assess the sport-specific demands.

SHOULDER STRENGTH

Little evidence exists regarding appropriate shoulder strength measures in reverse chain athletes. The limited published normative data on overhead athletes demonstrates differences across tennis, handball and volleyball.17 Reference values for isometric shoulder ER and IR strength in a large group of overhead athletes provide some comparison for this group of breakers.17 A 2016 study of competitive volleyball, tennis and handball players demonstrated values of 1.6 - 2.0 N/kgBW for ER and 1.6 - 2.2 N/kgBW for IR. In comparison the breakers demonstrated higher values of between 2.0 - 2.9 N/kgBW for ER and 2.5 - 3.9 N/kgBW for IR. There are a number of possible reasons for these differences including: the reverse chain nature of breaking involving higher loads through the shoulder than overhead sports; the training volume of the subjects being considerably higher in the breakers group (18.8 hours per week breaking training vs 5.4 - 5.8 hours per week overhead sports participation); the difference in testing positions: supine for the breakers which stabilizes the scapula vs seated for the overhead athletes; and differences in testing equipment – fixed frame vs hand held dynamometry.

While not reaching significant differences, breakers with a history of shoulder injury in this group demonstrated lower ER:IR strength ratios on the previously affected side compared to breakers who had no previous injury. It is not possible to deduce if this was a pre-existing risk factor for injury, or indicative of insufficient restoration of strength post injury.

Taking the suggested ER:IR ratio cut-off of 1.0 for overhead athletes,17 all of the breakers, regardless of shoulder injury history, demonstrated ratios below this value. Breakers may demonstrate lower ratio values as a result of differences in shoulder loading in comparison to overhead athletes. Overhead and throwing athletes have high eccentric external rotation loading, as demonstrated by strength data on dominant vs non-dominant arm.17 In contrast, depending on the breaking style used, a large amount of time can be spent loading the anterior shoulder and chest while on the floor, potentially creating an imbalance of loading on internal vs external rotators.

The use of the ER:IR ratio may have a place in the screening process of specific sports but should not be used in isolation. The absolute strength of external and internal rotators must be considered. Such measures can be useful when gathered preinjury to help refine RTS decisions as well as identify changes in strength over a season.2 Future considerations for strength testing in this group could consider reviewing the external and internal rotation strength in different ranges, in particular 0° shoulder abduction/0° external rotation position with the elbow by the side which mimics the ‘freeze’ move in breaking. There are a wide number of shoulder performance tests that could also be considered relevant for this group (Closed Kinetic Upper Extremity Stability Test [CKUEST],36 ASH,37 Plyometric Push up,38 isokinetic dynamometry,39 Upper Quarter Y-Balance Test40).
HIP STRENGTH

Reference values for hip strength exist across various sports including football (soccer),\(^1\) ice-hockey,\(^2\) gymnastics,\(^3\) and Australian football.\(^4\) However, indicating that ‘normal’ strength and hip abduction : adduction ratio are sport dependent. A recent study of elite female gymnasts reported lower scores than the current cohort (0.15 BW abduction, 0.17 BW abduction).\(^5\) While gymnastics could be considered one of the closer sports to breakdancing, the participants were considerably younger than the current cohort (age 10 - 15) and likely had much lower body mass (37 ± 10kg) therefore making comparison difficult.

Adductor injuries accounted for all previous muscle injuries in the hip/groin injury category. While not reaching significant differences, there were observed lower absolute strength in both adduction and abduction as well as a lower abduction : adduction ratio in the previously injured group vs non-injured. These scores could suggest pre-existing risk factors for injury or insufficient recovery of strength post injury. As a screening tool moving forward, variability should be observed within individuals until normative values and ratios are clear for breakers. Similar to differences observed in different playing positions within the same sport,\(^6\) the variety of breaking styles (power movers vs breakers whose style involves more top rock / footwork) may influence hip strength profiles.

LIMITATIONS

A primary limitation of this study is its sample size. With minimal literature available on breakers, following the breaking summit both the breakers and authors felt that sharing the data collected at the performance summit was an opportunity to expand knowledge beyond the elite level. However, given that data was collected at a professional camp with only 14 breakers, it is a very small cohort. Dividing the group further into developing and elite was a clinical decision to explore if differences might exist. Given the small sample size, all comparisons should be viewed with significant caution.

The breakers in this cohort all compete on an international level and are considered likely contenders for the 2024 Olympics. Therefore, the data from these breakers may not be generalizable to amateur breakers or breakers with less than eight years’ experience. That said, the breakers ranged in age from 14-31 years old, and most had minimal training history outside of breaking, thus the data presented are still clinically meaningful.

Tests were chosen based on the injury epidemiology available in the breaking literature and attempting to profile the breakers in a limited amount of time. Given the dynamic nature and variable styles involved in breaking, it was difficult to select tests that capture all breaking demands. For example, vertical jump tests may be more relevant for breakers who use a lot of power moves, as assessing explosive power production is applicable to their style. However, shoulder strength assessments, core strength or upper body plyometric assessments may be more relevant for breakers that use more footwork/floorwork.

The authors recognize that the technology used in this study could be considered cost prohibitive for some clinical settings. Table 6 offers less expensive alternatives to the testing methods used in this study.

CONCLUSIONS

The results of this study serve as the first published functional data on breakers. Although a small sample of professional breakers, the results indicate that the knee was the most common body part injured. Muscle injuries were most common at the femur/thigh, and joint injuries were most common at the knee. Breakers trained almost 30 hours per week with experienced breakers including more non-breaking training modalities into their weekly routines than developing breakers. The results indicate that breakers may benefit from education regarding non-breaking training modalities as well as injury prevention and recovery techniques. This study demonstrates the difficulty of standardizing tests for breaking, given the wide range of demands involved. Based on the results of this study, the authors recommend that future test batteries consider: 1) shoulder rotation strength testing at both 90° and 0° shoulder abduction, 2) strength endurance testing of the shoulders, 3) an upper body plyometric assessment, 4) lower body plyometric testing involving horizontal or rotational components, 5) heart rate monitoring during training in addition to endurance testing. Given the wide range of demands and paucity of literature the authors hope that the observations published here will help clinicians and researchers working with breakers in the future.

ACKNOWLEDGMENTS

The authors would like to thank all of the breakers who participated in this study. They would also like to thank the staff at Red Bull and the Red Bull Athlete Performance Center who participated and supported the breaker’s performance summit. Thanks especially to Roland Helmberger who performed all of the endurance testing.

COI

The authors have no conflicts of interest.

Submitted: January 02, 2023 CDT, Accepted: August 09, 2023 CDT
Table 6. Reliable lower cost alternatives to tests used in this study

<table>
<thead>
<tr>
<th>Equipment Utilized</th>
<th>Lower-Cost Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Endurance</strong></td>
<td></td>
</tr>
<tr>
<td>Cyclus 2 Bicycle ergometer</td>
<td>Heart-rate monitor via chest strap[46]</td>
</tr>
<tr>
<td>Cortex Metalyzer QB</td>
<td></td>
</tr>
<tr>
<td><strong>Jump</strong></td>
<td></td>
</tr>
<tr>
<td>AMTI Forceplates</td>
<td>Mobile applications (ex. My Jump Lab[47])</td>
</tr>
<tr>
<td>Vicon 12 camera motion capture system</td>
<td></td>
</tr>
<tr>
<td><strong>Hip and Shoulder Strength</strong></td>
<td></td>
</tr>
<tr>
<td>Kangatech fixed frame dynamometer</td>
<td>Hand-held dynamometer[17,29] or strain gauge</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES


Original Research

Reliability and Measurement Error of the Qualitative Analysis of Single Leg Loading (QASLS) Tool For Unilateral Tasks

Gemma N Parry1, Lee C Herrington2, Allan G Munro1
1 School of Health and Society, The University of Salford, 2 School Health and Society, The University of Salford

Keywords: kappa paradox, movement quality, QASLS, single leg squat, single leg land

https://doi.org/10.26603/001c.88007

International Journal of Sports Physical Therapy

Background

Movement quality assessment is popular within clinical and sporting practice, due to the contribution diminished or suboptimal movement quality is believed to have on musculoskeletal (MSK) injury risk. Various movement quality assessments exist, many are limited to bilateral or jumping movements evaluation. Qualitative analysis of single leg loading (QASLS) is a new clinical assessment tool for unilateral tasks that utilizes a dichotomous scoring system of ten questions relating to the segmental body regions of the trunk, lower and upper limb.

Purpose

To determine the intra and inter-rater, within- and between-session reliability of the QASLS tool during two unilateral movement tasks, and provide insight to measurement error and smallest detectable difference (SDD).

Study Design

Reliability Study

Methods

Fifteen healthy females (mean age 19 years SD2; height 167 cm, +/- 6; weight 56 kg, +/- 6) completed two unilateral tasks, single leg squat (SLS) and single leg landing (SLL), within session data collection occurred on the same day, with between session data collection occurring seven days later. Tasks were scored with the QASLS tool via video playback. Intra-Class correlation coefficients (ICCk,3) were used to measure within and between session reliability, and Kappa coefficients and percentage of exact agreement (PEA%) were used to determine intra and inter-rater reliability. Standard error of measurement (SEM) and the SDD for the compound score of each limb was calculated.

Results

Within session reliability of QASLS scores was good (ICC = 0.82-0.86) for SLS and moderate (ICC = 0.67-0.87) for SLL. Between session reliability was moderate (ICC = 0.69-0.87) for SLS and excellent (ICC = 0.92-0.93) for SLL. SEM was less than 1 point, and SDD for compound score ranging from 1.0-2.5 points. Intra-rater agreement of compound QASLS score was near perfect (k = 0.85-100; PEA% 90-100%) and agreement of individual components was substantial- near perfect (k = 0.13-0.74; PEA% 78-100%). Inter-rater agreement for compound QASLS scores ranged from non-substantial (k = 0.13-0.74; PEA% 43.3-90%) for SLS and non-slight (k =0.03-0.17; PEA% 45.3-60%) for SLL.

Corresponding Author:
Gemma N Parry
School of Health and Society, University of Salford, Manchester, M6 6PU, United Kingdom
0161 295 6222
G.Parry1@salford.ac.uk
Conclusions

The QASLS movement analysis tool can be used to analyze movement quality during two unilateral loading tasks with moderate to excellent within and between session reliability. PEA% was acceptable for inter-rater agreement, however rater education training is recommended to develop more acceptable levels of reliability.

Level of Evidence

INTRODUCTION

Musculoskeletal (MSK) profiling tools, particularly of the lower limb, are widely used to highlight injury risk, and influence the composition of rehabilitation and conditioning programming for return to training (RTT). Suboptimal movement quality, or movement that is impaired, inefficient, asymmetrical, functionally compensated or diminished is believed to have an impact on injury risk, as such, the assessment of movement quality by practitioners is popular in clinical practice. Movement quality is considered to be a modifiable factor that can influence injury risk, as research has continued to show associations between movement variability and musculoskeletal (MSK) injury, therefore tools that capture and monitor changes in movement quality are of growing interest to practitioners.

Quantitative and qualitative human movement analysis is widely utilized in sport and clinical practice. Laboratory-based three-dimensional (3D) analysis is revered as the "gold standard" however, in the non-research environment it is expensive, time consuming, and often unfeasible to set-up. The real-world need to capture data on large numbers of participants frequently, has led to several qualitative visual rating criteria emerging as a cheaper, more accessible means of human movement analysis.

Several authors cultivated and explored the use of lower limb qualitative scales during functional movements, to provide clinicians with simply applied means of identifying movement quality issues within the MSK system. The development of the Landing Error Scoring System (LESS) provided practitioners with a reliable and valid tool with minimal set-up time and efficient post-test evaluation through the assessment of a jump landing technique. Unfortunately, analysis of trunk position is limited, with no evaluation of the upper limb and evaluation of bilateral jumping movements only. Torso and upper limb positioning has been observed to influence the lower limb during landing potentially impacting lower limb loading, patterning, movement quality, and subsequent injury risk. While these studies have acknowledged the contributions and impact the torso and upper limb may have on the biomechanics of the lower limb, protocols measuring and capturing torso and upper limb movement within whole movement patterning are lacking. Additional investigation into developing a methodology via qualitative means is therefore warranted.

The Qualitative Analysis of Single Leg Loading (QASLS) tool incorporates biomechanical analysis of movement patterns of the lower limb, upper limb, and torso during single-leg loading tasks in addition to providing a compound score. This allows for comparison between limbs but is also arguably more replicative of the unilateral hopping, landing, and change of direction patterns observed in sport. Unilateral limb evaluation is important because it remains the most common mechanism of the majority of lower limb overuse and traumatic injuries. Furthermore, the effective evaluation of unilateral movement quality provides valuable markers for identifying both sporting and non-sporting individuals at risk of injury.

Research into QASLS use is limited, with only one study to date reporting on intra-rater reliability. However, the study was limited by sample size of participants and raters and no insight into absolute measurement error was presented. Measurement error values are an integral element of understanding the value of a tool, task, or intervention, as they inform a clinician if any notable changes have occurred and whether they are representative of a truly observed change and not attributed to systematic error, chance or an intervention. While ICCs allude to the reliability, they remain insensitive to sample variety. It is therefore recommended that a standard error of measurement (SEM) and the smallest detectable difference (SDD) also be presented to accurately identify and establish parameters to classify changes in performance. The SEM informs clinicians of the measurement error of a test, is presented in the same units as the measurements and therefore allows scrutiny to other SEM presented within the literature. The SDD provides a base value which should be surpassed to distinguish real change from random error.

Currently, no investigation has documented measurement error values or within and between session values of the QASLS system. If the measurement error, reliability and validity of the qualitative method can be established, practitioners will be able to use the QASLS system with certainty. This will assist with informing observation around individual and group performances, movement variability and associated injury risk, to support the development of better profiling practices. To determine the intra and inter-rater, within- and between-session reliability of the QASLS tool during two unilateral movement tasks, and provide insight to measurement error and smallest detectable difference (SDD). A secondary purpose was to report on the associated measurement error and SDD. It was hypothesised that QASLS scores would demonstrate good to excellent reliability for all tasks, however it was expected that rater reliability would demonstrate greater variability depending on rater experience.
SINGLE-LEG SQUAT (SLS) (FIGURE 2A)

Participants were asked to stand on one limb (self-selected) facing the frontal plane, they were verbally instructed to squat as low as possible as if sitting back and down on a chair and return to the start position. Participants were then asked to repeat on the opposite limb. No further instructions were provided so as not to influence the individual’s movement strategy.

SINGLE-LEG LAND (SLL) (FIGURE 2B)

Participants stood on a 50cm high box, they were asked to step forward and land onto the contralateral limb holding the landing for at least two seconds. No further instructions were provided so as not to influence the individual’s movement strategy.

QASLS PROCEDURE

QASLS is a visual rating tool that provides segmental scoring of an observed unilateral loaded movement pattern on a 10-point scale. Adopting a dichotomous scoring strategy of six body segments (Arm, Trunk, Pelvis, Hip, Knee and Ankle) the tool utilizes a region criteria where appropriate strategy scores a zero and suboptimal strategy scores a one (Figure 3). A higher QASLS score indicates a greater number of suboptimal strategies used to complete a task, and a lower QASLS score indicates fewer component strategies required to complete the tasks. Within the QASLS framework, operational definitions are provided in conjunction to the movement strategies observed at each segmental level, along with instruction relating to compound dichotomous scoring. The QASLS system is advocated to be used so that the compound score, regardless of if from a singular or multiple effort, is comprised of the total number of strategies required by an individual to complete the task irregardless of frequency. Namely, if three or five repetitions of a unilateral task are completed, even if a sub-optimal strategy is observed once or five times the practitioner awards one mark, resulting in the cumulation of a “sub-optimal” trial. Five repetitions were evaluated based on previous reported procedures within the only article to evaluate reliability of the tool,17 to designate a compound overall QASLS score.

Videos were analyzed using QASLS scoring sheet (Figure 3), the scoring performance was derived for each participant from both the frontal and sagittal plane views, with each video viewed then marked and scored. Three raters (LH, AM and BO) independently scored participants across the five trials via QASLS scoring sheet (Figure 3) having viewed both the frontal and sagittal place videos for each participant. The three raters were provided with written instructions on how to assess the movement tasks via QASLS, could review the videos as many times as required to obtain a score and were blinded to the other raters scores, to avoid potential bias.
Figure 2. Example of Single-Leg Squat (SLS) (A) and Single-Leg Landing (SLL) (B) movement tasks

Figure 3. QASLS Scoring Sheet, displaying the 10-point visual rating system. If a rater observes an appropriate strategy at the segmental region the participant scores zero, if a rater observes a suboptimal strategy the participant scores one. A higher QASLS score indicates a greater number of segmental strategies used to complete a unilateral loading task, and a lower QASLS score indicates a lesser number of required segmental strategies to complete the unilateral loading tasks.
STASTICAL ANALYSIS

SPSS for windows (version 25) (SPSS Inc, Chicago, IL.) was used to determine within and between session reliability agreement. Within and between session reliability agreement of the QASLS rating criteria was determined using intra-class correlations (ICC_{k,3}) for each limb and movement assessment task, with 95% confidence intervals (95%CI). A custom-made spreadsheet (Microsoft Excel Version 16.16.22) calculated standard error of measurement (SEM) and smallest detectable change (SDD) values. Within and between-session reliability of composite scores were calculated using a mean rating (ICC_{k,3}) 2-way mixed-effects absolute agreement model. ICC_{k,3} values were interpreted as >0.90 excellent, 0.75-0.9 good, 0.50-0.75 moderate, and <0.50 as poor. Statistical significance was set at p<0.05.

Due to the dichotomous nature of the QASLS system, intra and inter-rater compound scores and individual components of the QASLS tool were determined via the percentage of exact agreement (PEA%) and kappa co-efficient. Cohens Scales were selected to interpret kappa values where 0.81-1.00 is almost perfect agreement, 0.61-0.80 substantial, 0.41-0.61 moderate, 0.21-0.40 fair and 0.01-0.20 none to slight. Acceptable PEA% has been described as at least 75–90%, however, this remains specific to each study. As there are no current universally accepted interpretations, and in the absence of literature supporting clear interpretation of PEA, >66% has been chosen as a reflection of majority agreement (55–75%) as defined in other papers. SEM and SDD were calculated to represent and establish the smallest worthwhile change and identify random error scores between test sessions. With formulas taken from previously reported methods.

RESULTS

Fifteen participants originally volunteered for this study, due to corrupted video data, one participant was excluded resulting in an analysis of 14 participants (age 19±2 height 167±6 cm body mass 56±6 kg).

WITHIN AND BETWEEN SESSION RELIABILITY OF QASLS (TABLE 1)

No significant differences were noted between limbs (p = 0.20) or testing sessions for both tasks. Within and between-session reliability for both tasks were moderate to excellent (ICC > 0.67-0.93). Within-session reliability of the QASLS composite score (0-10) for SLS was good for both limbs (Right ICC = 0.82, 95%CI = .56-.96; Left ICC = 0.86, 95%CI = .49-.97). SEM for within-day reliability was 0.82 and 0.72 points the SDD 2.28 and 2.00 points on a ten-point scale for the right and left limbs respectively. Similar results were observed in the right SLL task (ICC = 0.87, 95% CI .42-.97, SEM 0.45, SDD 1.26) however, left limb performance was moderate (ICC = 0.67, 95% CI .25-.92, SEM 0.89, SDD 2.45).

Between-session reliability of the composite QASLS score for the SLL was slightly less than the within-session scores (Right ICC = 0.7295%CI .15-.93, Left ICC = 0.6995%CI .07-.92) graded as moderate. SEM for SLS between-session reliability was 0.96 and 0.99, the SDD was 2.65 and 2.75 for the right and left limbs respectively. The SLL task demonstrated greater between-session reliability than the SLS task (ICC = 0.92-0.93) with SEM of 0.41 and SDD of 1.14 for the right limb and 0.47 and 1.52 for the left limb. SEMs for both within-session and between-session were less than 1 with the SDD ranging from 1.0-2.5 points. This suggests an error measurement of 1 across testing time frames and that a change of 1-5 points would be necessary to demonstrate a minimal detectable change.

INTRA-RATER RELIABILITY OF QASLS

Intra-rater reliability was "perfect to excellent" agreement (k=0.85-1.0) for both movement tasks. Except for right SLL (k=0.85, PEA = 90%) where items 7 and 8 in the QASLS criteria were disagreed on for participants 1 & 5 respectively. Therefore, individual components of the QASLS tool were further analyzed with details found in Tables 2 and 3.

INTER-RATER RELIABILITY OF QASLS

Table 4 presents the inter-rater reliability for compound QASLS scores, rater reliability for SLS ranged from non-to substantial (k=0.13-0.74) and for SLS non-slight for SLL (k = 0.03-0.17). Single leg squat demonstrated the biggest discrepancy between PEA%. Rater 2 (R2) demonstrated the greatest difference between Rater 1 (R1) and Rater 3 (R3) (43%-90% respectively). R2 and R3 demonstrated the highest levels of PEA% (53.3%-90%) with each other, agreement with R1 was lower for both R2 (45-47%) and R3 (53-60%).

Inter-rater reliability for individual and categorical components ranged from non-substantial (k = .000-.80) (Table 5). Kappa values were unable to be established for all raters and participants scores, due to the lack of variance in 1 or both rater scores. Despite high values of PEA% (such as 100%) low kappa scores were still noted. During the SLS raters demonstrated the best agreement for pelvic, knee and touchdown components (items 3,4,7,8 and 9 on the criteria), however this was different for SLL where raters demonstrated the best agreement for upper limb, trunk and ankle components (items 1,2 and 10 on the criteria).

DISCUSSION

The purpose of this study was to determine the intra- and inter-rater and within- and between-session reliability of the QASLS tool during two unilateral movement tasks, the SLS and SLL. A secondary purpose was to report on the associated measurement error. Overall compound QASLS scores suggest moderate to excellent reliability (ICC = 0.82-0.87 and ICC = 0.69-0.93 for within and between session, respectively), indicating the QASLS tool is sufficiently reliable for movement analysis of the unilateral movement tasks of squatting and landing. Results highlighted that there was a measurement error of 1 between testing time-frames and that a change in 1-3 points is required to de-
termine a change in performance. This is believed to be the first study to provide within and between session reliability specifically for the QASLS tool, therefore there is no prior research to compare results to. Other qualitative movement screens that use dichotomous scales similar to QASLS such as the Functional Movement Screen (FMS®) and LESS have reported similar test-retest reliability values. Shultz et al. established that compound FMS scoring was relatively good (ICC = 0.6) for elite female athletes when tested seven days apart. The reliability values within this study are consis-

<p>| Table 1. Within and between session reliability of qualitative criteria (QASLS) for Single Limb (SL) tasks. Values are presented as mean ±SD |</p>
<table>
<thead>
<tr>
<th>Task/Limb</th>
<th>QASLS Score</th>
<th>SD</th>
<th>ICC</th>
<th>95%CI</th>
<th>SEM</th>
<th>SDD</th>
<th>CV%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL Squat Right</td>
<td>4.78</td>
<td>1.79</td>
<td>0.82</td>
<td>.359-.956</td>
<td>0.82</td>
<td>1.28</td>
<td>37</td>
</tr>
<tr>
<td>SL Squat Left</td>
<td>4.78</td>
<td>1.86</td>
<td>0.86</td>
<td>.491-.966</td>
<td>0.72</td>
<td>1.00</td>
<td>40</td>
</tr>
<tr>
<td>SL Landing Right</td>
<td>4.33</td>
<td>1.50</td>
<td>0.87</td>
<td>.423-.970</td>
<td>0.45</td>
<td>1.26</td>
<td>25</td>
</tr>
<tr>
<td>SL Landing Left</td>
<td>4.78</td>
<td>1.30</td>
<td>0.67</td>
<td>.025-.917</td>
<td>0.89</td>
<td>2.45</td>
<td>27</td>
</tr>
<tr>
<td>SL Squat Right</td>
<td>4.78</td>
<td>1.79</td>
<td>0.72</td>
<td>.146-.929</td>
<td>0.96</td>
<td>1.65</td>
<td>40</td>
</tr>
<tr>
<td>SL Squat Left</td>
<td>4.78</td>
<td>1.86</td>
<td>0.69</td>
<td>.068-.922</td>
<td>0.99</td>
<td>1.75</td>
<td>35</td>
</tr>
<tr>
<td>SL Landing Right</td>
<td>4.38</td>
<td>1.46</td>
<td>0.93</td>
<td>.716-.983</td>
<td>0.41</td>
<td>1.14</td>
<td>34</td>
</tr>
<tr>
<td>SL Landing Left</td>
<td>4.78</td>
<td>1.46</td>
<td>0.92</td>
<td>.393-.989</td>
<td>0.47</td>
<td>1.52</td>
<td>40</td>
</tr>
</tbody>
</table>

<p>| Table 2. Intra-Rater Reliability of Qualitative Rating Criteria (QASLS) |</p>
<table>
<thead>
<tr>
<th>Testing Occasion</th>
<th>Kappa coefficient (95%CI)</th>
<th>Percentage of Exact agreement (PEA%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R SLS</td>
<td>L SLS</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>0.85 (0.73-0.98)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

L= Left limb, R= Right limb, SLL = Single-Leg Landing, SLS = Single-Leg Squat

<p>| Table 3. Intra-Rater reliability scoring of Right SLL by individual QASLS component |</p>
<table>
<thead>
<tr>
<th>QASLS Items</th>
<th>QASLS Component</th>
<th>PEA%</th>
<th>Kappa Value (95%CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arm Strategy (Excessive arm movement to balance)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>Trunk Alignment (Leaning in any direction)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>Pelvic Plane (Loss of horizontal plane)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>Pelvic Plane (Excessive tilt or rotation)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>Thigh motion (WB thigh moves into hip adduction)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>Thigh motion (NWB thigh not held in neutral)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>Knee position – noticeable valgus (Patella pointing towards 2nd toe)</td>
<td>78</td>
<td>0.78 (0.69-0.92)</td>
</tr>
<tr>
<td>8</td>
<td>Knee position – significant valgus (Patella pointing past inside of foot)</td>
<td>78</td>
<td>0.75 (0.64-0.90)</td>
</tr>
<tr>
<td>9</td>
<td>Steady Stance (Touch down with NWB foot)</td>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>Steady Stance (Stance leg wobbles noticeably)</td>
<td>100</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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Table 4. Inter-Rater Reliability of QASLS

<table>
<thead>
<tr>
<th>Raters</th>
<th>Kappa Coefficient (95%CI)</th>
<th>Percentage of Exact Agreement (PEA%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLS</td>
<td>SLL</td>
</tr>
<tr>
<td>1 Vs 2</td>
<td>.125 (-0.18-0.43)</td>
<td>.030 (-0.30-0.63)</td>
</tr>
<tr>
<td>1 Vs 3</td>
<td>.182 (-0.16-0.52)</td>
<td>.171 (-0.18-0.52)</td>
</tr>
<tr>
<td>2 Vs 3</td>
<td>.737 (0.51-0.97)</td>
<td>.129 (-0.17-0.43)</td>
</tr>
</tbody>
</table>

SLL = Single-Leg Landing, SLS = Single-Leg Squat

Table 5. Inter-Rater PEA% and Kappa Scoring QASLS participants during SLS and SLL

<table>
<thead>
<tr>
<th>Participant</th>
<th>Rater</th>
<th>No of Agreements</th>
<th>Total Tasks</th>
<th>PEA%</th>
<th>Discrepancy between PEA</th>
<th>Kappa Coefficient (95%CI)</th>
<th>Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Leg Squat (SLS)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1 Vs 2</td>
<td>6</td>
<td>10</td>
<td>60.0</td>
<td>20</td>
<td>.310 (0.18-0.44)</td>
<td>Fair</td>
</tr>
<tr>
<td>1</td>
<td>1 Vs 3</td>
<td>6</td>
<td>10</td>
<td>60.0</td>
<td>20</td>
<td>.200 (0.07-0.33)</td>
<td>Non-slight</td>
</tr>
<tr>
<td>1</td>
<td>2 Vs 3</td>
<td>8</td>
<td>10</td>
<td>80.0</td>
<td>80</td>
<td>.600 (0.47-0.73)</td>
<td>Moderate</td>
</tr>
<tr>
<td>2</td>
<td>1 Vs 2</td>
<td>3</td>
<td>10</td>
<td>30</td>
<td>30</td>
<td>.310 (0.18-0.44)</td>
<td>Fair</td>
</tr>
<tr>
<td>2</td>
<td>1 Vs 3</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td>60</td>
<td>.000* (N/A*)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2 Vs 3</td>
<td>9</td>
<td>10</td>
<td>90</td>
<td></td>
<td>.800 (0.67-0.93)</td>
<td>Substantial</td>
</tr>
<tr>
<td>3</td>
<td>1 Vs 2</td>
<td>9</td>
<td>10</td>
<td>90</td>
<td></td>
<td>.286 (0.16-0.42)</td>
<td>Fair</td>
</tr>
<tr>
<td>3</td>
<td>1 Vs 3</td>
<td>7</td>
<td>10</td>
<td>70</td>
<td>30</td>
<td>.400 (0.27-0.53)</td>
<td>Fair</td>
</tr>
<tr>
<td>3</td>
<td>2 Vs 3</td>
<td>6</td>
<td>10</td>
<td>60</td>
<td></td>
<td>.800 (0.67-0.93)</td>
<td>Substantial</td>
</tr>
<tr>
<td><strong>Single Leg Land (SLL)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1 Vs 2</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td></td>
<td>.200 (-.36-.76)</td>
<td>Non-slight</td>
</tr>
<tr>
<td>1</td>
<td>1 Vs 3</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>10</td>
<td>.000* (N/A*)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2 Vs 3</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td></td>
<td>.087 (-.50-.68)</td>
<td>Non-slight</td>
</tr>
<tr>
<td>2</td>
<td>1 Vs 2</td>
<td>6</td>
<td>10</td>
<td>60</td>
<td></td>
<td>.310 (-0.07-0.69)</td>
<td>Fair</td>
</tr>
<tr>
<td>2</td>
<td>1 Vs 3</td>
<td>8</td>
<td>10</td>
<td>80</td>
<td>20</td>
<td>.524 (-0.05-1.0)</td>
<td>Moderate</td>
</tr>
<tr>
<td>2</td>
<td>2 Vs 3</td>
<td>6</td>
<td>10</td>
<td>60</td>
<td></td>
<td>.310 (-0.07-0.69)</td>
<td>Fair</td>
</tr>
<tr>
<td>3</td>
<td>1 Vs 2</td>
<td>4</td>
<td>10</td>
<td>40</td>
<td></td>
<td>.200 (-.41-.81)</td>
<td>Non-slight</td>
</tr>
<tr>
<td>3</td>
<td>1 Vs 3</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td>10</td>
<td>.000* (N/A*)</td>
<td></td>
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<tr>
<td>3</td>
<td>2 Vs 3</td>
<td>5</td>
<td>10</td>
<td>50</td>
<td></td>
<td>.000* (N/A*)</td>
<td></td>
</tr>
</tbody>
</table>

*Kappa values unable to be calculated due to lack of variance between 1 or both raters
tent with those reported in the above literature, 95% CI remain large and are potentially due to the variability within human movement. Despite ICCs being commonly reported in reliability studies, within qualitative research many interpretations of the ICC exist. Therefore clarification of excellent or good reliability is elusive with studies classifying broad values (from 0.40–>0.80) as excellent or fair to good.30

Intra-rater reliability was found to be excellent (PEA% 90–100%, k = 0.85-1.0) and is in agreement with other work17 (although limited to SLS) that has analyzed rater-reliability. There are believed to be no comparable papers currently available concerning the reliability of the QASLS tool and a SLL task.

Overall inter-rater compound QASLS scoring was non-substantial for SLS (k = 0.03–0.17), which is lower than previously reported reliability,17 however PEA% ranged from 43–90%. Results were comparative to other qualitative measures that have analysed SLS.2 Chmielewski et al. showed PEA of 32–48% during SLS via segmental approach and weighted kappa values of 0.00–0.55.31 Schultz et al. (2015) described inter-rater agreement via Krippendorff a (ka) as poor (k = .38) when using the FMS on female athletes.

Inter-rater reliability of each QASLS component was fair to almost perfect (k = 0.40–1.0). Regarding individual component analysis, best scores appeared to be between R2 and R3 during the SLS with 100% agreement in 8/10 categories. The three raters demonstrated differences of agreement in components 6, 7, and 8 (NWB thigh movement and knee valgus). Previous findings17 have also concluded rater disagreement of the valgus components during the scoring of SLS in university participants. The raters in this research, as with the raters in this current study received no formal training and were reliant on the operational differences presented within the tool.

The operational differences presented in components 7 and 8 of the QASLS tool are very similar in their description, which might not be concise enough for raters to deduce the difference between the terms “noticeable” and “significant”. It is unclear if the reliability results observed in this study are attributed to the level of rater training or vagueness of the operational definition of knee valgus. This might also provide an explanation for why these differences were not reflected in SLL results where the greater complexity of the task suggests valgus is easier to spot within the movement pattern.

Inter-rater reliability was unable to be calculated for some categorical components due to the lack of variance between raters and observations of movement errors, and is described as the kappa paradox.24 When conceiving this study, due to minimal research regarding the QASLS tool, important decisions regarding the interpretation of the variable generated by the QASLS tool were considered, as this would dictate the statistical approach. Unlike quantitative variables seen in 2D or 3D movement data that follow interval or ratio principles that can be parametrically analyzed, a case could be made for QASLS being classified as ordinal (due to the dichotomous element of the segmental evaluation where the outcome falls into two categories of yes or no) and interval (compound scores that run on a scale of 0–10 where the gaps are proportional, thus, how best to establish tool performance relating to reliability and agreement was open to debate. Previous visual rating methods that also use dichotomous scoring, treat data as interval.9–11 The QASLS tool has been designed as a clinical instrument to provide a score that guides practitioners in evaluation of single-leg loading patterns of the whole system, the decision was therefore made to evaluate data as an interval variable.

STUDY APPLICATIONS AND LIMITATIONS

A strength of this study was the presence of both the kappa and PEA% analysis methods, yet, neither method is without fault. PEA is a precise, interpretable and easily determined statistic but does not account for chance rater guesses.24 The kappa value eliminates any chance rater choices, but is limited in sensitivity in data prevalence that clusters very high or very low, or in homogenous populations where estimate agreement appears exclusively lowered.22

Described as the “base rate problem”32 and usually seen in a moderate to high PEA and a low kappa score, the paradox has been shown to occur in very simple cases with only two evaluators and two outcomes (similar to this papers design), at equal points of the sensitivity and specificity of the raters, or if the prevalence of one of the raters assigns one specific outcome more frequently53 as observed between R1 and R2, and R1 and R3.

Data indicated that at individual participant level, movement variability was high with different movement patterns deployed within the same movement pattern, but as an overall cohort movement patterns were consistent and therefore variability was low. It is unsurprising that this data set has high levels of homogeneity that is likely unavoidable in the analysis of a sub-elite population. Analysis of movement quality remains a key aspect of profiling and programming within the sporting environment, it is therefore likely that future research will continue to be focused within this population. It is prudent to acknowledge the limitations of this non-heterogeneous sample and the likely impact that would have on a kappa score, and establishing a truly heterogeneous elite sporting population would be difficult to achieve. The argument is therefore made that the limitation is within the statistic rather than the direct relevance of the population. Future research into other sporting populations such as injured or adolescents where a cohort could be relatively heterogeneous in their construct would be warranted.

A final limitation of the study is the level of rater training provided in using the QASLS tool. The findings of the kappa results are potentially suggestive of a redesign of the test instrument or retraining of the raters.24 Given the robustness of the intra-rater and between and within-session results, the requirement for full instrument redesign appears unlikely. Raters were provided with the same standardized instructions on how to administer the tool along with the basic component operational definitions embedded within the tool. It is possible that each rater interpreted
each section in a specific way which ultimately impacted agreement.

While training around the use and interpretations of other movement visual rating criteria is standardized by other authors, currently there are no training programs available for the QASLS tool. It was therefore decided that understanding the current interpretations, limitations, and strengths of the QASLS tool as it is currently used without training within clinical practice, was more pertinent for this study, to better guide any future recommendations around QASLS training content.

Rater training is an important component to qualitative analysis34 but rarely appears to be delivered in a standardized way.3,9,10,31,32 Providing raters with greater instruction around operational differences and providing potential examples of each observable segmental strategy (e.g. trunk dominant, hip avoidant, knee dominant) may assist raters clinically in standardizing their scoring methods. This is particularly evident around components 7 and 8 of the QASLS tool where identifying minor deviations in knee movement appeared more difficult. This is also supported by the better levels of reliability and agreement observed during SLL, where the larger deviations seen within that movement pattern are more discernible. The QASLS tool has demonstrated satisfactory within and between and intra-rater reliability for its use by practitioners. Results demonstrate that the current operational definitions within the tool are adequate for intra-rater use, further work on rater-education to include standardized examples, may maintain more consistent and objective analysis to improve agreement ratings before more widespread use.

CONCLUSION

The QASLS tool demonstrated moderate to excellent within- and between-session reliability, and excellent intra-rater reliability, and could be used as a movement quality tool to evaluate unilateral squatting and landing tasks by a single rater. PEA% was acceptable for inter-rater agreement, but results should be interpreted with caution. It would be beneficial to explore the operational definitions used within the tool, so inter-rater agreement could be elevated to more acceptable levels. A potentially homogenous population was selected, and while not unrepresentative of a healthy, elite sporting population, it is unclear how the QASLS tool may be influenced by more heterogenous samples such as injured populations or adolescent younger age groups. Future additional investigation within additional groups of athletes will provide greater understanding into the application and continuing development of the QASLS and other visual observation tools of movement quality.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

Submitted: June 27, 2022 CDT, Accepted: August 31, 2023 CDT

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REFERENCES


Concurrent Validity of The Expanded Cutting Alignment Scoring Tool (E-CAST)

Lauren Butler, Alexa Martinez, Ashley Erdman, Dai Sugimoto, Alex Loewen, Eryn Milian, Charles Wyatt, Kristin Hayden, Amie DeVerna, Kirsten Tulchin-Francis, Sophia Ulman

1 Physical Therapy, Florida International University, 2 Rehabilitation, Nicklaus Children’s Hospital, 3 Scottish Rite for Children, 4 Waseda University, 5 The Micheli Center for Sports Injury Prevention, 6 University of Miami, 7 University of Texas Southwestern Medical Center, 8 Nationwide Children’s Hospital

Keywords: Motion Analysis, Change of Direction, Sidestep Cut

https://doi.org/10.26603/001c.87633

International Journal of Sports Physical Therapy

Background
The Expanded Cutting Alignment Scoring Tool (E-CAST) has been previously shown to be reliable when assessing lower extremity alignment during a 45-degree sidestep cut, however, the validity of this tool remains unknown. The purpose of this study was to assess the concurrent validity of the E-CAST by comparing visually identified movement errors from two-dimensional (2D) video with three-dimensional (3D) biomechanical variables collected using motion capture.

Study Design
Cross Sectional

Methods
Sixty female athletes (age 14.1 ± 1.5 years) who regularly participated in cutting/pivoting sports performed a sidestep cut with 2D video and 3D motion capture simultaneously recording. One clinician scored the 2D videos for each limb using the E-CAST criteria. Joint angles and moments captured in 3D were computed for the trunk and knee. Receiver operating characteristic (ROC) curve analyses were performed to determine the accuracy of each E-CAST item and to provide cut-off points for risk factor identification.

Results
ROC analyses identified a cut-off point for all biomechanical variables with sensitivity and specificity ranging from 70-85% and 55-89%, respectively. Across items, the area under the curve ranged from 0.67 to 0.91.

Conclusion
The E-CAST performed with acceptable to outstanding area under the curve values for all variables except static knee valgus.

Level of evidence
3b
INTRODUCTION

Anterior cruciate ligament (ACL) injuries continue to be a significant concern for the young athlete with rising rates observed in both males and females. Young female athletes who participate in cutting and pivoting sports are of particular concern due to having a higher incidence of both primary ACL injury and contralateral ACL injury after ACL reconstruction surgery.

Sidestep cutting maneuvers are frequently performed in sports and account for 60–70% of non-contact ACL injuries. Previous studies have found an association between high knee abduction moments (KAM) during cutting maneuvers and increased ACL injury risk. Furthermore, high KAM during cutting and pivoting movements have been correlated with increased contralateral trunk lean away from the plant leg, elevated knee abduction angle, knee valgus, increased cutting width, decreased knee flexion, and low/reduced ankle plantar flexion. While three-dimensional (3D) motion analysis remains the gold standard method to measure KAM, it poses challenges to clinic and on-field use due to its prohibitive cost and extensive time and training requirements.

As a result of these limitations, two-dimensional (2D) screening tools to assess sidestep cutting maneuvers have been sought for broader application. The Expanded Cutting Alignment Scoring Tool (E-CAST) has been reported to have moderate inter-rater and good intra-rater reliability for the assessment of both frontal and sagittal plane trunk and LE alignment during a 45-degree sidestep cut in a group of young female athletes. However, the level of agreement between the E-CAST and 3D biomechanical variables remains unknown. The purpose of this study was to assess the concurrent validity of the E-CAST by comparing visually identified movement errors from two-dimensional (2D) video with three-dimensional (3D) biomechanical variables collected using motion capture. The hypothesis was that all items of E-CAST would perform with acceptable to outstanding sensitivity and specificity values.

MATERIALS AND METHODS

STUDY DESIGN AND PARTICIPANTS

This study utilized a cross sectional study design to validate a visual assessment tool for a cutting maneuver. Institutional review board approval was obtained prior to commencement of the study. Specifically, the study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Texas Southwestern (Protocol Number: 082010-134, Approval Date: 2 February 1993). All participants provided written informed assent, and a parent or legal guardian provided signed consent prior to initiating testing procedures. A convenience sample of female athletes were recruited from local middle school, high school, and club sport teams, and were seen for a single visit in a motion analysis laboratory at a local sports medicine treatment center. Inclusion criteria included 1) age between 12 and 17 years of age, 2) active participation in sports involving cutting and pivoting movements in the prior 12 months, and 3) a level of physical activity between 7 and 10 on the Tegner Activity Scale. The inclusion criteria were developed to provide a sample of female pre-teen and teenage athletes who were actively playing sports that involved cutting and pivoting movements. This population was chosen due to their exposure to cutting movements and their high risk of ACL injury. The following exclusion criteria were used: 1) lower extremity injury within the prior six months, 2) history of lower extremity surgery, 3) a positive response on the Physical Activity Readiness Questionnaire (PAR-Q+), or 4) history of scoliosis. Those with lower extremity injury within the prior six month and a history of lower extremity surgery were excluded to reduce compensatory movement pattens that may result from pain, range motion deficits, or strength deficits that are associated with injury recovery. The PAR-Q+ was used to determine the participant’s readiness and safety for physical activity. A positive response on the PAR-Q+ indicates the need to seek further advice from a physician prior to engaging in physical activity.

Participants with a history of scoliosis were excluded to reduce asymmetries in trunk deviations that may result from structural spinal deformity. For testing, participants were asked to wear comfortable attire and their personal athletic footwear.

DATA COLLECTION

Participants were instrumented with retroreflective markers placed on specific bony landmarks according to a modified Plug-in Gait marker set (OMG Plc, Oxford, UK). A 14-camera motion capture system (Vicon Motion Systems Ltd, Denver, CO, USA) was used to collect 3D kinematic data sampling at 240 Hz while participants performed the sidestep cut task. Kinetic data were collected using AMTI force plates (Advanced Medical Technology Inc., Watertown, MA) that were time-synchronized to the motion capture system and sampled at 2880 Hz. Simultaneously, 2D video data were captured at 60 frames per second with 1080p quality using three cameras (Sony Cyber-shot DSC-Rx10, Tokyo, Japan) adjusted to 36 inches tall. Two cameras were positioned 156 inches from either side of the stance/pivot area (sagittal view), and one camera was positioned 146 inches in front of the stance/pivot area (frontal view).

Following the procedures outlines by Butler et al., all athletes completed a 5-minute warm up on an exercise bike (Matrix Fitness, Cottage Grove, WI) prior to performing the 45-degree sidestep cut task. Participants then practiced the sidestep cut up to three times in each direction or until they felt comfortable with the maneuver. They were instructed to sprint at 80% of their maximum speed in a forward direction toward the “opponent cone” and to pivot, attempting to fake out the “opponent cone” (Figure 1).

Specifically, participants decelerated, planted on their right foot, and performed a sidestep cut, running in the left direction between cones placed along a 45-degree line of progression. Participants completed the procedure in each direction, with three “good” trials per plant leg. A trial was considered “good” if the subject’s foot landed within the stance/pivot area necessary for successful completion.
of the task. Videos in the frontal and sagittal plane were recorded as each participant performed a total of six cutting maneuvers, with one trial per side randomly selected for analysis.

All videos were slowed by 50% for visual analysis and participants’ faces were blurred using Corel VideoStudio (Corel Corporation, Ottawa, ON). In the clinic or on-field setting most practitioners record video using a smart device which allows for playback at slower speeds. The videos in this study were slowed to allow for improved visualization and identification of movement criteria and to replicate the process used by practitioners. A clinically established checklist, E-CAST, was utilized to examine the quality of trunk and lower extremity movement during a 45-degree sidestep cut task based on 2D video. The E-CAST involves a dichotomous rating system, with scoring defined as “1” when a movement fault was present and “0” when optimal movement patterns were observed. The E-CAST evaluates items in the frontal plane (trunk lean, cut width, knee valgus) as well as items in the sagittal plane (plantar flexion and knee flexion). One physical therapist with five years of experience in pediatric sports rehabilitation trained in the scoring criteria, independently scored the 2D video in both planes for each limb using the E-CAST scoring criteria (Table 1).

Three-dimensional biomechanical data were processed using Vicon Nexus software (OMG plc, Oxford, UK). A Woltring filter was applied to the marker trajectories with a predicted mean square error of 10 mm. Analog data were filtered using a 4th-order, low-pass Butterworth filter with a cutoff frequency of 16 Hz. Segment and joint angles were computed for the trunk, knee, and ankle in the frontal and sagittal planes using a custom MATLAB (MATLAB 2016a, Natick, MA, USA) model. External knee abduction moments (KAM) were calculated and normalized to the product of height (cm) and weight (kg). An automated custom MATLAB code was used to detect events during the sidestep cut at time points of interest (i.e., initial contact, load acceptance). Additionally, knee flexion and ankle plantar flexion were extracted at initial contact (IC), defined

Figure 1. 45-degree sidestep cut task.20
Table 1. Expanded Cutting Alignment Scoring Tool (E-CAST)

<table>
<thead>
<tr>
<th>Item</th>
<th>View</th>
<th>Operational Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Trunk lean to opposite direction of cut</td>
<td>Frontal</td>
<td>At the time point of initial load acceptance if the whole trunk segment appears to be deviated greater than 10 degrees from a horizontal line through the hips (ASIS to ASIS) score 1 (YES). If not, score 0 (NO).</td>
</tr>
<tr>
<td>2. Increased cut width</td>
<td>Frontal</td>
<td>At the time point of initial load acceptance, draw a line down from the lateral most aspect of the athlete’s stance leg hip, if the line appears to fall more than one shoe width medial to the foot score 1 (YES). If not, score 0 (NO).</td>
</tr>
<tr>
<td>3. Knee Valgus at initial load acceptance (Static Evaluation)</td>
<td>Frontal</td>
<td>At the time point of initial load acceptance, if the weight bearing limb demonstrates valgus (thigh adduction, genu valgum, or knee abduction) score 1 (YES). If the weight bearing limb is in neutral alignment score 0 (NO).</td>
</tr>
<tr>
<td>4. Knee Valgus throughout the cutting task (Dynamic Evaluation)</td>
<td>Frontal</td>
<td>During the cutting task if the weight bearing limb demonstrates valgus (thigh adduction, genu valgum or knee abduction) score 1 (YES). If the weight bearing limb is in neutral alignment, score 0 (NO).</td>
</tr>
<tr>
<td>5. Decreased knee flexion angle</td>
<td>Sagittal</td>
<td>At the time point of initial contact if the athlete demonstrates a stiff or extended knee position score 1 (YES). If the athlete demonstrates a flexed knee position (Approximately&gt; 30 degrees), score 0 (NO)</td>
</tr>
<tr>
<td>6. Decreased plantar flexion angle</td>
<td>Sagittal</td>
<td>At the time point of initial contact if the stance foot lands heel to toe score 1 (YES). If the stands foot lands toe to heel score 0 (NO)</td>
</tr>
</tbody>
</table>

for 3D data analysis as the time point when the vertical ground reaction force exceeded 1% of the subject’s bodyweight. Trunk lean, cut width, and knee valgus (static evaluation) variables were extracted across load acceptance, defined for 3D data analysis as the portion of the task between IC and the point of maximum knee flexion. Knee valgus (dynamic evaluation) was evaluated throughout the cutting task, from IC to foot-off of the plant leg.

STATISTICAL ANALYSIS

Mean and standard deviation values were computed for all demographic and sport participation measures. Additionally, the percent of participants identified as exhibiting each risk factor based on the E-CAST scoring criteria were determined and mean and standard deviation values were calculated for each 3D biomechanical variable corresponding to the 2D scoring items. Logistic regression analysis was used to determine whether 3D biomechanical variables were associated with the corresponding 2D scores. Specifically, receiver operating characteristic (ROC) curves were generated to determine cut points for identifying participants who exhibited each risk factor. This point is selected such that the scoring tool correctly identifies the greatest number of participants at risk (true positives, measured via sensitivity) while minimizing the number of participants incorrectly identified for exhibiting risk (false positives, measured via specificity). Subsequently, accuracy was quantified by computing the area under the ROC curve (AUC) as well as the sensitivity and specificity (IBM SPSS Statistics for Windows, version 24.0, Armonk, NY, USA). The approach used is outlined in detail by Kumar & Indrayan (2011).25

Significance level was set to α = 0.05, and the AUC was used to classify each model as outstanding (0.90-1.00), excellent (0.80-0.89), acceptable (0.70-0.79), poor (0.51-0.69), or no discrimination (0.50 or less).26,27 Due to the slightly skewed distribution of the presence of knee valgus observed on 2D video and the limited range of the 3D knee valgus angles recorded, the ROC analysis was unable to define a cut point for the knee valgus scoring items. Therefore, ROC analyses were also performed for the knee valgus scoring items using KAM variables Dynamic knee valgus has been defined as a combination of multiaxial movements, including femoral adduction and internal rotation, anterior tibial translation, external tibia rotation, ankle eversion, and knee valgus.17,28,29 While knee valgus describes the abnormal biomechanical profile that causes the knee to be in a high-risk position, knee abduction moment indicates the amount of loading acting upon the knee. These valgus forces can increase anterior tibial translation and ultimately the load placed on the ACL by several-fold.30 Furthermore, both knee valgus angle and knee abduction moment have been reported to be primary predictors of subsequent ACL injury with 78% sensitivity and 73% specificity.12 Thus, KAM was chosen as a proxy measurement for dynamic knee valgus as it takes into consideration the forces acting on the knee joint.

RESULTS

A total of 60 female athletes who regularly participated in cutting or pivoting sports were recruited for participation in the study. Two athletes were removed from the study due to poor quality videos, leaving a final total of 58 participants (age 14.1 ± 1.6 years, body mass 54.8 ± 10.6 kg, height 162.8 ± 7.7 cm). Athlete’s average level of sport participation measured with the Tegner Activity Scale was 9.2 ± 0.8. 2D visual assessment using the E-CAST scoring criteria found that the mean score was 3.9 ± 1.2 out of a maximum score of 6.0 for the 58 athletes (116 limbs). Using the knee valgus E-CAST scores, a KAM cut point of 0.78 Nm/kg was identified throughout the cutting task with 72% of the cohort exhibiting a KAM that surpassed this cut point. Knee valgus for both the static and dynamic E-CAST items were
scored visually as present in 73% and 80% of limbs, respectively. Decreased plantar flexion angle was present in 64% of limbs, and decreased knee flexion angle was present in 49% of the limbs. Increased cut width was visually identified in 85% of limbs and trunk lean to the opposite direction of the cut was identified in 42% of the cohort. The prevalence of each 2D E-CAST scoring item and the corresponding mean 3D measures are presented in Table 2. A cut point was identified for all biomechanical variables with sensitivity and specificity ranging from 70-85% and 55-89%, respectively (Figure 2, Table 2). Across scoring items, the AUC ranged from 0.67 to 0.91.

**Table 2. Prevalence of E-CAST items, mean (SD) 3D measures, and ROC curve analysis results.**

<table>
<thead>
<tr>
<th>E-CAST Item</th>
<th>2D (%)</th>
<th>3D Measure</th>
<th>Cut Point</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Lean (°)</td>
<td>42%</td>
<td>5.0 (6.8)</td>
<td>6.1</td>
<td>76%</td>
<td>67%</td>
<td>0.78</td>
</tr>
<tr>
<td>Cut Width (mm)</td>
<td>85%</td>
<td>63.5 (51.2)</td>
<td>28.4</td>
<td>83%</td>
<td>89%</td>
<td>0.91</td>
</tr>
<tr>
<td>Knee Valgus Static (Nm/kg)</td>
<td>73%</td>
<td>0.67 (0.52)</td>
<td>0.74</td>
<td>81%</td>
<td>55%</td>
<td>0.67</td>
</tr>
<tr>
<td>Knee Valgus Dynamic (Nm/kg)</td>
<td>80%</td>
<td>1.09 (0.47)</td>
<td>0.78</td>
<td>70%</td>
<td>83%</td>
<td>0.79</td>
</tr>
<tr>
<td>Knee Flexion (°)</td>
<td>49%</td>
<td>25.7 (12.1)</td>
<td>24.2</td>
<td>83%</td>
<td>81%</td>
<td>0.90</td>
</tr>
<tr>
<td>Plantar Flexion (°)</td>
<td>64%</td>
<td>7.2 (13.2)</td>
<td>8.6</td>
<td>85%</td>
<td>86%</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Note: Positive 3D trunk lean value indicates lean towards cut limb; KAM values (Nm/kg) are reported for Knee Valgus items.

**DISCUSSION**

The purpose of this study was to assess the concurrent validity of the E-CAST by comparing visually identified movement errors from 2D video using the E-CAST scoring tool with 3D biomechanical variables collected using motion capture technology. Variables of plantar flexion, knee flexion, and cut width had the highest sensitivity and specificity and thus performed with outstanding AUC values. These findings indicate that the sagittal plane items of the E-CAST scoring tool performed the best when compared to 3D biomechanical variables. Alternatively, dynamic knee valgus and trunk lean items were found to be acceptable.
(AUC = 0.79 and 0.78, respectively), while static knee valgus performed poorly as indicated by an AUC of 0.67.

Outstanding performance exhibited by plantar flexion, knee flexion, and cut width might be a result of the simplicity and explicit nature of the language used in the E-CAST definition of these items. For example, the plantar flexion definition requires the clinician to determine if the stance foot lands "heel to toe" or "toe to heel" and the knee flexion definition references a flexed knee position greater than thirty degrees to be classified as not present. Sagittal plane measures from 2D visual assessment have been found to allow for more valid interpretation of range-of-motion. This is likely a result of the larger range of motion associated with sagittal plane movements, compared to the frontal plane, which may make movement criteria identification easier as the viewer has a larger range of motion to consider. Additionally, the definition of cut width involves drawing a line down from the lateral aspect of the athlete’s hip and determining if that line is greater than one shoe width medial to the foot. This type of spatial reference in the frontal plane may be easier to visually identify compared to evaluating frontal plane joint angles across multiple joints.

Static and dynamic knee valgus items exhibited poor and acceptable performance in classifying the presence of 3D variables (AUC = 0.67 and 0.79, respectively). While static valgus performed with a sensitivity of 81%, specificity was only 55%. Thus, the current item definition performs well in classifying athletes who do not exhibit the 3D variable but fails to successfully recognize when the 3D variable of static knee valgus is present. Alternatively, dynamic knee valgus performed with greater specificity (83%) than sensitivity (70%), however, the gap between classification performance measures was smaller. Both knee valgus items use a multicomponent definition requiring the clinician to identify whether thigh adduction, genu valgum, or knee abduction are present and does not provide a reference degree. Dynamic knee valgus likely performed better than static knee valgus given that movement faults were more evident throughout the cutting task than at initial load acceptance. It is possible that using a definition that requires the viewer to consider movement at multiple joints may make visual assessment more challenging. Furthermore, knee valgus is a multilobar motion which presents additional challenges for 2D video-based assessment. Specifically, knee valgus identified via 2D methods has not been found to correlate well with 3D biomechanics during single leg squatting and landing tasks. In a study by Ulman et al., no agreement was found between 2D identification of knee valgus and 3D knee biomechanical assessment during a single leg squat or a single leg drop landing, while remaining variables, including trunk flexion and lean, were found to exhibit moderate to excellent percent agreement. This suggests the need for more explicit and comprehensive definitions of knee valgus for 2D visual assessments.

To achieve agreement for the knee valgus items, one option explored was taking into consideration the forces acting on the knee joint (i.e., kinetics). Given that the logistic regression analysis indicated agreement between 2D scores and KAM, this may suggest that visual identification of risk at the knee may still be possible when considering the loading forces acting on the knee alongside full lower extremity kinematics rather than just knee angle. A total of 72% of limbs in this study surpassed the cut point for KAM throughout the cutting task. The authors would consider this high risk for ACL injury based on the E-CAST checklist definitions. Furthermore, Dos Santos et al. found that athletes with higher scores on the CMAS (poorer cutting mechanics) demonstrated greater multilobar knee joint loads. Specifically, these athletes performed a 90-degree sidestep cut with greater knee abduction angles, lateral foot plant distances, internal foot progression angles, and lower knee flexion range of motion and with greater knee flexion, abduction, and internal rotation moments. They also found a positive relationship between the CMAS total score and peak KAM. Therefore, when screening for high knee joint loads, the cumulative effect of multiple joint movements may be more important than the assessment of one joint alone. For example, assessments of knee valgus in isolation may be less effective than assessments that include evaluation of multiple joints and positions resulting in a cumulative “risk” score.

Trunk lean performed with acceptable AUC, with sensitivity (76%) slightly greater than specificity (67%). Although the trunk lean definition includes explicit language and provides a degree reference, participants demonstrated movement variability at the trunk across multiple planes (e.g., trunk flexion, lateral flexion, and rotation) which may have made the visual identification of frontal plane trunk lean more challenging. This suggests that when assessing for movement faults at the trunk, multiple planes of motion need to be considered both individually and together in combination.

LIMITATIONS

Limitations relating to the use of 2D video-based assessments need to be acknowledged. When using 2D video, participant rotation may result in the loss of a fully perpendicular frontal plane and sagittal plane view which can lead to error during movement assessment. Furthermore, this study utilized a planned 45-degree sidestep cut. Planned cutting tasks have been shown to result in lower knee joint loads compared to unplanned cutting tasks. However, unplanned cutting tasks are more challenging to capture using 2D video, requiring more cameras and greater complexity of set up. Moreover, video assessment in this study was performed by a physical therapist. This may present concerns relating to the tool’s generalizability for use by coaching staff. Lastly, a power analysis was not performed prior to commencement of the current study.

CONCLUSION

In conclusion, the E-CAST performed with acceptable to outstanding AUC values for all variables except static knee valgus. These findings suggest that the E-CAST individual
scores have moderate to good evidence of concurrent validity with 3D variables during a 45-degree sidestep cut. Future studies should aim to improve knee valgus criteria definitions to better align with 3D kinematics and kinetics.

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DISCLOSURE STATEMENT

The authors report there are no competing interests to declare.

Submitted: January 12, 2023 CDT, Accepted: August 28, 2023 CDT
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The MyJump App is a Valid Method of Assessing and Classifying Limb Symmetry During Recovery from Anterior Cruciate Ligament Reconstruction

Isaac Whiteley\textsuperscript{a}, Vasilios Sideris\textsuperscript{a}, Roula Kotsifaki\textsuperscript{a}, Enda King\textsuperscript{a}, Rod Whiteley\textsuperscript{b}

\textsuperscript{a} Rehabilitation, Qatar Orthopaedic and Sports Medicine Hospital

Keywords: Application, Assessment, Hop, Performance, Return to sport, Video

Background

Jump testing performance and limb symmetry measures are important metrics for clinicians to monitor during rehabilitation after Anterior Cruciate Ligament (ACL) reconstruction, however they require hardware and software which is not commonly available in clinical practice. Video-based solutions may present a feasible alternative, but their veracity in classifying patients using limb-symmetry of 90% has not been established, nor have the clinimetric values for the performance measures been reported in this population.

Purpose

To describe the diagnostic accuracy (pass/fail using 90% LSI) and clinimetrics of an iPad-based app ("MyJump") compared to reference force plate analyses for limb symmetry, jump/hop height, contact time, flight time, and reactive strength index.

Study design

Prospective cohort, diagnostic accuracy

Methods

Fifty-one consecutive patients recovering from ACL reconstruction undertaking routine independent clinical evaluation of their hop and jump performance were concurrently and independently examined using force plates and the MyJump app. Diagnostic accuracy of MyJump was compared to reference force plate analyses using a criterion of 90% limb symmetry.

Results

Diagnostic accuracy of the MyJump app was very good: positive predictive value for jump height was 0.85 and 1.0 for reactive strength index, and negative predictive value was 0.95 and 1.0 for the same metrics, respectively. Of the 151 classifications made using the MyJump app, there were five false positives and three false negatives – all of these were in classification of jump height with no misclassifications of RSI. Irrespective of jump type, the MyJump app displayed excellent reliability (ICC>0.95) for both height and reactive strength index. Minimum detectable changes were approximately 1cm for height, 0.1 for reactive strength index, 0.02s for contact time, and 0.3s for flight time.

Conclusion

Where force plates are unavailable, the MyJump app is a valid and reliable substitute for criteria assessment of jump/hop height and reactive strength index in those recovering.
from ACL surgery using a 90% limb symmetry threshold. The minimum detectable changes vary by metric but are likely sufficiently accurate to detect clinical changes.

**Level Of Evidence**

**Level 3**

**INTRODUCTION**

Monitoring the progress of patients who are rehabilitating after an anterior cruciate ligament reconstruction (ACLR) is important to ensure appropriately targeted care is provided for the individual. Many patients undertaking this care ultimately aim to return to sporting activity where the ability to hop and jump are important determinants of safe and effective performance. Accordingly, once clinically indicated, it is important to monitor hop and jump performance during rehabilitation to provide feedback regarding clinical progression and thereby inform treatment choices. A variety of jump tasks are commonly employed, each assessing different components of the musculoskeletal system. A squat jump, for example, is thought to primarily be a measure of concentric force production, whereas countermovement and box (drop) jumps represent increased utilization of the stretch-shortening cycle. Achieving competence in one but not the other can inform clinical decision making in terms of the contents of rehabilitation and strength training. Patients may show competence in one type of jump but not another which would direct rehabilitation towards the incompetent jump type. To incorporate this clinical reasoning into rehabilitation, the practitioner must be able to ascertain whether the patient has achieved competence (or not) in this jump type. This requires assessment of jump performance, and ultimately determining if the jump has passed or failed some type of criteria. Typically, this assessment is scored as pass/fail using a 90% limb symmetry index, found by dividing the performance on the uninjured limb by the involved limb. For example, a jump height of 20cm on the involved limb and 16cm on the uninjured limb would equate to a LSI of 80% (16/20).

Jump height can be used as a performance measure which can be compared to an individual’s previous measures and normative population data as an indicator of rehabilitation progression. In addition to the height achieved during a jump or hop, the reactive strength index (RSI, defined as the flight time divided by the contact time) is considered an important metric assessing an athlete’s ability to cope with stretch-shortening demands and infer a range of other performance-related qualities. Importantly, in anterior cruciate ligament reconstruction (ACLR) patients, RSI has been shown to be significantly impaired in those who suffered a contralateral injury in the absence of differences in hop performance. Including this metric in clinical assessment of patients recovering from ACLR provides important additional information which can then inform rehabilitation choices. Deeper examination of the components of this metric – i.e. the contact and flight times, has been advocated to better inform athlete-specific aims of rehabilitation: rapid force generation and maximum force generation respectively. While RSI provides an overall summary of an athlete’s plyometric or reactive strength capacity it is important to analyse and understand the components of that performance (contact time and jump height) so that the athlete’s specific deficits can be targeted more precisely in rehabilitation (for example: employing lower intensity efforts focusing on shorter ground contact times vs higher intensity efforts focusing on maintaining short ground contact time with maximal efforts). Hence the ability to accurately assess and interpret these components of RSI is key to successful restoration of function after ACLR.

Between-limb movement differences during landing in those who injured their anterior cruciate ligament (ACL) and those with a past history of ACL injury suggest that there are differences in kinematics during jumping and landing many years after their injury and surgery. Measuring jump performance using only flight time cannot infer kinematics or kinetics of an individual, and flight time is dependent in part on kinematics. Accordingly, validation is required not only in healthy participants using a video-based measure of jump performance but additionally in those with ACL injury for whom it is reasonably suspected that their biomechanics could vary. Jump performance is seen to vary according to athletic ability independent of knee function. As such, estimation of knee function through jump testing needs to be validated across a range of participants representative of those presenting for rehabilitation after ACL injury: athletic to non-athletic, those skilled in and naïve to jump technique, and with varying knee strengths.

Recently, video-based applications have been promoted as an alternative to force plates for measuring jump performance and could feasibly be a cost-effective alternative, however their validity (compared to force plates) has not been documented in recovering ACLR patients who likely demonstrate differences in kinematics and kinetics compared to healthy participants during their rehabilitation.

Despite the continuous nature of jump metrics (e.g. cm, msec), clinicians and patients will often seek a dichotomized “pass/fail” result from a test, and frequently a diagnostic threshold of less than 10% limb asymmetry is used. For clinicians to implement this relatively inexpensive solution in practice, data describing the diagnostic accuracy compared to a reference standard are required. Additionally, information regarding the minimum clinically important differences for the continuous measures (i.e. jump height, contact and flight time, RSI) in a population of ACL injured participants encountered in regular clinical practice will be important to interpret between-session changes in performance in these patients. Therefore, this investigation sought to describe the diagnostic accuracy (pass/fail using 90% LSI) and clinimetrics of an iPad-based app (“MyJump”) compared to reference force
plate analyses for limb symmetry, jump/hop height, contact time, flight time, and reactive strength index. There was no a priori hypothesis regarding the veracity of the application.

METHODS

Fifty-one consecutive patients presenting for routine independent clinical assessment after ACL reconstruction from January to May 2022 were recruited for participation. There were no exclusions for any surgical comorbidities. These patients were a combination of professional and recreationally active patients presenting sequentially for care at the facility. As part of the usual rehabilitation of these patients, they agree to undertake periodic stage-appropriate subjective, clinical, and physical performance examination to inform their rehabilitation content and progression. The study was approved by the local Institutional Review Board (Ethics approval no E202009010) and was conducted in accordance with the recommendations of the STARD initiative.20

TEST PROCEDURE

Once the patient had commenced two and one leg jumps/hops as part of their rehabilitation, these tests are respectively included in the routine independent clinical examination process. Briefly, patients are assessed pre-operatively, and then from six weeks post-operative every six weeks until discharge. During each assessment (six-week interval), the patient first completed a range of subjective questionnaires, and then was physically examined (patient-reported outcomes, clinical exam including range of motion, instrumented ligamentous laxity, isokinetic knee strength, hip and ankle dynamometry, gait, etc) before performing a warm-up of at least six minutes stationary cycling along with any exercises the patient prefers so that they were ready to undertake the movement testing (Figure 2). The movement tests are performed in a standardized manner on a non-treatment day in a designated analysis area with the sequence stopping if either the patient did not feel confident to continue, or the supervising physiotherapist was not confident of a safe execution of the test after having observed the preceding tests and the sub-maximal practice trials for the current test. The complete battery of movement tests would include, in order, the following: two leg squat, unilateral step down from a 30cm box, single leg squat, two leg modified counter-movement jump, one leg modified countermovement jump, two leg drop-jump from 30cm box, one leg drop jump from a 15cm box, and finally a squat jump. Note that all the jump tests are performed in a "modified" manner compared to some definitions as arm swing was not allowed – the athlete was instructed to keep their hands on their "hips" during the test. After reviewing the results of these tests, the patient would then continue to the remaining stations.

QUANTIFICATION OF THE JUMPS

The jumps are examined for performance using two laboratory force plates (BMS600900–4K, AMTI, Watertown, MA, USA). Data were recorded with ForceDecks software (Version 2.0.8, Vald Performance, Newstead, Australia) at a frequency of 1000 Hz with concomitant kinematic examination using Inertial measurement units (Ultium Motion Sensors, Noraxon, USA) placed on the feet, shanks, thighs, and sacrum. After zeroing the plates, and weighing the athlete, each test or jump is first demonstrated, and then practiced by the participant. Note that the participant will have also been familiarized with the task as part of their normal rehabilitation prior to this testing. Once the participant has performed at least one practice jump to the satisfaction of the examiner and indicates they are ready for testing, the recording is commenced. The ForceDecks software automatically identifies jump types, along with a range of metrics. The jump-type identification is verified by the operator, along with the jump’s quality, with manual removal of any mis-identified, or poorly performed jumps (e.g. landing outside the force plates, arm swing, etc). Importantly, the athletes were instructed to jump and then keep their legs straight until landing to ensure the flight-time calculations weren’t manipulated by tucking their knees up – upon visual identification of this strategy the athlete was reminded of the jump instructions, and that jump was discarded.

CONCOMITANT VIDEO ANALYSIS OF JUMPS

Additional to the usual practice, video recording of the feet from the front of the patient performing these tasks was performed simultaneously (Figure 1) using an iPad Pro (at 240 frames per second, high-definition video resolution) for subsequent analyses using the "MyJump Lab Pro" application (Carlos Balsalobre-Fernández, version 2.1.1)

Briefly, a recording of a jump is loaded into the app then the take-off and landing frames are manually selected. Prior to the commencement of the research, standardized definitions of the start and end of the jumps were made. For take-off, the first frame where it was certain both feet were off the ground was selected – this required visual identification of a gap between the feet and the ground, accounting for any motion blur, with no deformation of the shoe. For landing, the first frame when it was certain one foot had landed was selected; this was described as the frame where there was no visible gap between the shoe and the ground, a lack of motion blur and deformation of the shoe. With these events defined, the application then calculates jump height through flight time as well as the RSI for drop-jumps. Typically, this offline analysis took approximately 12 minutes per participant depending on the number of jumps which needed to be assessed.

Statistical analysis was conducted in Excel (Office 365, Microsoft, USA), SPSS (version 24, IBM Corporation, USA), and JMP (v 16, SAS Institute Inc, USA). After initial exploratory data analysis including visualization, descriptive, veracity, and normality checks, an ICC (absolute agreement) was conducted from which the standard error of the
measure and from which the minimum detectable change was calculated. Bland-Altman plots were generated to describe agreement and bias, and using a threshold of 90% for limb symmetry, confusion matrices and then test clinimetrics were then generated.

The experimental set-up is shown in Figure 1, and the entire ACL testing sequence is outlined in Figure 2.

RESULTS

Participant demographics are presented in Table 1. All jump types demonstrated excellent reliability between repetitions (ICC>0.95) with minimum detectable change of approximately 1cm for jump height and approximately 0.1 for reactive strength index (Table 2). There was a systematic small bias across all measures suggesting that the MyJump app slightly underestimated both the jump height and reactive strength index compared to the reference force plate analysis (Table 2). Diagnostic accuracy was very good (>90%) when using a limb symmetry cut-off value of 90% for the involved (ACLR) leg compared to that individual’s uninvolved leg for both jump height, reactive strength index, flight, and contact times (Tables 3, 4, and 5).

DISCUSSION

The MyJump app performs well in correctly classifying patients using a limb symmetry index of 90% when measuring both jump height and reactive strength index. A clinician using this app will be correct approximately 90% of the time in classifying the patient as passing or failing this return to sport criterion when using the MyJump app (compared to the reference force plate analyses) using an LSI threshold of 90%. Of the 131 classifications made using the MyJump app, there were eight misclassifications - five false positives and three false negatives – all of these were in classification of jump height and there were no misclassifications of RSI.

The MyJump app is a valid method of measuring jump height and reactive strength index. Here we have consistently shown ICC values greater than 0.95 irrespective of jump type or metric. The minimum detectable differences were typically in the order of approximately 1cm for jump height, less than 0.1 for RSI, 0.07s for contact time, and 0.01s for flight time. Clinically, it can be inferred that changes in jump height, RSI, contact or flight time which exceed these values are attributable to changes in physical performance beyond measurement error.

There is greater knee work contribution during the propulsion phase (which determines performance) of vertical jumps compared to horizontal jumps. Therefore jump height better estimates knee work contribution than the easier to clinically measure jump distance. The ease of clinical use and low cost are likely primary reasons for the more widespread clinical adoption of jump distance despite it being a poor metric of knee function after ACLR. The significant price advantage of this app compared to the reference force plates and their software should increase clinical integration of this measurement and improve moni-

Figure 1. Depiction of testing procedure. Patient is performing jump testing on embedded force plates (in this case a double leg counter movement jump) while simultaneous video capture is being performed by an investigator, blinded to the results of the force plate testing. At the conclusion of the day’s testing, the video is analysed using the MyJump software to determine the metrics described.
Complimentary to the performance metrics of jump height, RSI is seen to provide additional clinically relevant information regarding the performance ability of those recovering from ACLR surgery. RSI performance has been shown to be one of the last performance qualities to recover post ACLR compared to strength, jump height, jump distance and change of direction performance.\textsuperscript{10,14,22} In addition ongoing deficits have been demonstrated post ACLR despite the recovery of other jump performance metrics.\textsuperscript{14,16,22} Reactive strength has also been demonstrated to be lower in those that went on to rupture their healthy contralateral knee post ACLR despite no differences in other jump performance measures.\textsuperscript{22} Consequently the ongoing monitoring of RSI during drop jump testing is integral to assessing the athlete’s rehabilitation progress, return-to-play readiness, and re-injury risk post ACLR. Therefore, the excellent performance of the MyJump app in correctly classifying limb symmetry for RSI suggests that this may afford an important improvement in care for the great majority of practitioners who do not have access to force plates.

The current work extends previous research conducted in healthy cohorts.\textsuperscript{13,25-31} The small systematic bias across all metrics reported here has not been previously documented, although the reliability data are essentially the same as previously reported.\textsuperscript{15,25-31} Differences in hardware, software versions as well as the reference population and the user technique are possible sources of the bias first reported here. For example, using an earlier version of the MyJump app with an iPhone capturing at 120Hz (half the capture rate of the current research) the MyJump app was reported to slightly overestimate flight time compared to force plates capturing at 2000Hz\textsuperscript{13} (bias in the opposite direction to the present data). Care was taken in the current research to standardize the definition of the frames defining the start and end of the jump. Previous research had not specifically defined these events with objective criteria. Where comparisons against reference populations are being conducted (e.g. return to sport testing, pre-competition health evaluations) these differences should be considered however they should not be an important factor for within participant testing where limb symmetry is the primary outcome.

Figure 2. Flowchart depicting the standardised testing sequence. Initially patients report a standardised subjective examination, followed by physical examination including hip strength testing, then a warm-up which is followed by the “jump testing” sequence (shaded boxes, bold font). At the conclusion of the jump testing sequence, the testing continues with gait, ankle and knee strength testing, after which patient review is conducted.
### Table 1. Demographics of the included ACLR patients

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/female</td>
<td>49/2</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>28.5 ± 8.6</td>
<td>13.8 - 51.8</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>80.7 ± 14.8</td>
<td>49 - 126</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175.4 ± 8.7</td>
<td>154.4 - 195</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>26.2 ± 4.7</td>
<td>17.8 - 40.8</td>
</tr>
<tr>
<td>Tegner score pre-injury</td>
<td>7.5 ± 1.5</td>
<td>3 - 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Procedure</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL hamstrings autograft</td>
<td>29</td>
</tr>
<tr>
<td>ACL BTB autograft</td>
<td>13</td>
</tr>
<tr>
<td>ACL Quadriceps tendon autograft</td>
<td>3</td>
</tr>
<tr>
<td>ACL allograft</td>
<td>1</td>
</tr>
<tr>
<td>Anterolateral ligament tendon graft</td>
<td>4</td>
</tr>
<tr>
<td>Lateral Tenodesis</td>
<td>12</td>
</tr>
<tr>
<td>Meniscus repair</td>
<td>14</td>
</tr>
<tr>
<td>Partial meniscectomy</td>
<td>8</td>
</tr>
<tr>
<td>Dominant leg, right/left</td>
<td>42/9</td>
</tr>
<tr>
<td>Injured leg, dom/non-dom</td>
<td>32/19</td>
</tr>
</tbody>
</table>

Abbreviations: ACL: Anterior Cruciate Ligament; BTB: bone tendon bone (patellar tendon); n: number of participants; SD: Standard Deviation

### Table 2. Descriptive and reliability statistics for the jump metrics.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Number of jumps</th>
<th>Mean (SD)</th>
<th>ICC (95%CI) p-value</th>
<th>MDC (95%CI)</th>
<th>Mean Difference (95%CI) p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump Height (all jumps, cm)</td>
<td>641</td>
<td>19.55 (-9.55)</td>
<td>0.999 (0.988 to 0.999) &lt;0.001</td>
<td>0.837 (0.609 to 2.949)</td>
<td>0.37 (0.398 to 0.341) &lt;0.001</td>
</tr>
<tr>
<td>Reactive Strength Index (all reactive jumps)</td>
<td>207</td>
<td>1.04 (-0.4)</td>
<td>0.995 (0.949 to 0.998) &lt;0.001</td>
<td>0.078 (0.043 to 0.251)</td>
<td>0.029 (0.032 to 0.025) &lt;0.001</td>
</tr>
<tr>
<td>Modified Countermovement Jump Height (cm)</td>
<td>153</td>
<td>26.38 (-8.43)</td>
<td>0.998 (0.996 to 0.999) &lt;0.001</td>
<td>1.045 (0.660 to 1.431)</td>
<td>0.234 (0.169 to 0.299) &lt;0.001</td>
</tr>
<tr>
<td>Modified Single Leg Jump Height (cm)</td>
<td>206</td>
<td>11.6 (-4.6)</td>
<td>0.993 (0.829 to 0.998) &lt;0.001</td>
<td>1.067 (0.555 to 5.276)</td>
<td>0.441 (0.395 to 0.483) &lt;0.001</td>
</tr>
<tr>
<td>Drop Jump Height (cm)</td>
<td>78</td>
<td>29.29 (-6.16)</td>
<td>0.997 (0.958 to 0.999) &lt;0.001</td>
<td>0.935 (0.488 to 3.497)</td>
<td>0.352 (0.285 to 0.418) &lt;0.001</td>
</tr>
<tr>
<td>Squat Jump Height (cm)</td>
<td>66</td>
<td>27.25 (-5.94)</td>
<td>0.994 (0.986 to 0.997) &lt;0.001</td>
<td>1.276 (0.878 to 1.948)</td>
<td>0.308 (0.170 to 0.446) &lt;0.001</td>
</tr>
<tr>
<td>Single Leg Drop Jump Height (cm)</td>
<td>138</td>
<td>14.67 (-4.85)</td>
<td>0.994 (0.757 to 0.998) &lt;0.001</td>
<td>1.041 (0.524 to 6.626)</td>
<td>0.454 (0.408 to 0.500) &lt;0.001</td>
</tr>
<tr>
<td>Drop Jump Reactive Strength Index</td>
<td>73</td>
<td>1.41 (-0.37)</td>
<td>0.993 (0.934 to 0.998) &lt;0.001</td>
<td>0.085 (0.048 to 0.261)</td>
<td>0.031 (0.024 to 0.038) &lt;0.001</td>
</tr>
<tr>
<td>Single Leg Drop Jump Reactive Strength Index</td>
<td>134</td>
<td>0.85 (-0.25)</td>
<td>0.99 (0.876 to 0.977) &lt;0.001</td>
<td>0.069 (0.040 to 0.244)</td>
<td>0.027 (0.023 to 0.031) &lt;0.001</td>
</tr>
</tbody>
</table>

Reactive Strength Index measured as flight time divided by contact time. The mean difference represents the MyJump App estimation of the parameter subtracted from the reference force plates. Abbreviations: ICC: Intraclass Coefficient; MDC: Minimum Detectable Change; CI: Confidence Interval
The MyJump App is a Valid Method of Assessing and Classifying Limb Symmetry During Recovery from Anterior Cruciate...
enhanced by either future software algorithm updates or simple end-user subtraction of these values.

LIMITATIONS

The current study was conducted on a consecutive clinical cohort in a laboratory environment on a cohort which was almost entirely male, and the footwear was self-selected. This may influence the generalizability of these data to other ACL cohorts, and indeed other injury cohorts seen in clinical practice where jump monitoring is of interest. While the accuracy described (90%, or approximately one incorrect classification per 10 tests) appears superficially good, it remains to be seen if this is clinically acceptable. The consequences of incorrect classification – perhaps earlier resumption of ‘at risk’ activities for a rehabilitating athlete and potential re-injury need to be weighed and considered by the practitioner, and more generally with future research examining the predictive ability of these tests.

Three methods are described for measuring jump height – flight time, impulse momentum, and work-energy. Each approach has its strengths and weaknesses end users should be aware of when interpreting and comparing findings. Flight time is a proxy for jump height which requires a specific jump technique to be an accurate reflection of jump height. Specifically, the athlete must not pull their legs into flexion during the landing phase (which would artificially extend the flight time) and this must be monitored during testing, as was the case in the current research. It should be noted however that this monitoring was done visually discarding any such identified trials, however it is possible that some misidentified trials may have escaped this scrutiny.

CONCLUSION

The MyJump app is a valid method to estimate and classify vertical jump height and reactive strength index in clinical practice for participants recovering from ACLR. The minimum detectable change data (approximately 1cm for jump height and 0.1 for reactive strength index, irrespective of jump/hop type) presented here suggest that clinical progression can be determined with high sensitivity. The overall diagnostic classification accuracy (using a limb symmetry threshold of 90%) was over 90% for both jump height and reactive strength index.

CONFLICTS OF INTEREST

All the authors declare no conflict of interest perceived or otherwise in the production of this paper.

Submitted: March 08, 2023 CDT, Accepted: August 29, 2023 CDT
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Original Research

Reliability of Upper Extremity Functional Performance Tests for the Non-overhead Athlete

Bryan L Riemann1, George J Davies1

1 Biodynamics and Human Performance Center, Georgia Southern University-Armstrong Campus

Keywords: shoulder, return to sports, closed kinetic chain upper extremity stability test

https://doi.org/10.26603/001c.87924

Background

While there have been reliability studies conducted on several upper extremity functional performance tests (UEFPT), there are several complicating factors that inhibit the ability to draw definitive consensus about the reliability of the tests in both females and males. Having reliability estimates for UEFPT in the same cohort facilitates direct comparison of their relative and absolute reliability.

Purpose

To establish the test-retest reliability of the closed kinetic chain upper extremity stability test (CKCUEST), seated medicine ball chest pass test (SMBCPT) and hands-release push-up test (HRPUT) in a cohort of males and females with a history of non-overhead sport participation. A secondary purpose was to examine the associations between the three UEFPT.

Study Design

Test-retest reliability, single cohort study.

Methods

Forty adults (20 females, 20 males) with a history of non-overhead sport participation completed three UEFPT during two data collection sessions three to seven days apart. Measures of systematic bias, absolute reliability and relative reliability were computed between the sessions. Additionally, correlational analyses were conducted between the three UEFPT.

Results

Only the UECKST (both sexes) demonstrated significant (p< 0.003) second session performance improvements. All three tests exhibited excellent relative reliability (intraclass correlational coefficients ≥ 0.823) and except for the HRPUT in males, coefficients of variation were all below 8.8%. Except for a significant relationship (r=.691, p=0.001) between the UECKST and SMBCPT for the females there were no other associations between the three UEFPT.

Conclusion

All three UEFPT demonstrated sufficient reliability. Thus, all three assessments can be used for serial assessments to progress a patient through rehabilitation as well as contribute to the criteria used in making return to sport decisions.

Corresponding Author:
Bryan L Riemann, PhD, ATC
Biodynamics and Human Performance Center
Georgia Southern University- Armstrong Campus
11935 Abercorn Street
Savannah, GA 31419
briemann@georgiasouthern.edu
Level of Evidence

INTRODUCTION

The kinesiological complexity of the shoulder complex, coupled with the lack of inherent anatomical static stability, predisposes the shoulder to a variety of injuries, particularly during participation in sport and physical activity.\(^1,2\)

Especially problematic are the long term sequelae that can accompany shoulder injury.\(^3\) For example, following acute traumatic shoulder injury, there is an alarmingly high rate of recurrent instability and reinjury that occurs upon return to activity.\(^4,5\) The risk for recurrent instability and reinjury appears the highest for young adult males participating in collision sports.\(^2,6\)

Following shoulder injury or surgery (or both), many athletes will go through rehabilitation programs to help them return to their sport. One contributing factor to the high reinjury rates could be the lack of agreement regarding which tests, outcome measures, or metrics should be used for making clinical decisions regarding readiness to return to sport (RTS). Consequently, many athletes could be returning to their sporting activities without adequate rehabilitation to optimize shoulder function. Therefore, following sufficient time for tissue healing constraints and patient education, it is important to establish specific tests and criteria that can be used for facilitating RTS decisions. At a minimum, the testing battery should consist of the following components: patient reported outcomes (PROs), impairment measurements (e.g., range of motion, proprioceptive measurements, etc.), measures of muscle strength, power and endurance, general upper extremity functional performance tests (UEFPT), neuro-cognitive-mechanical reactive tests, and sport specific tests.\(^7\)

Naturally, the UEFPT selected to assist with RTS decisions should relate to the patient’s type of sport. Additionally, for a test to be clinically useful as criteria for RTS, it must be reliable. For athletes participating in overhead sports, the reliability of several open kinetic chain UEFPT were recently reported.\(^8\) Regarding athletes from non-overhead sports, there have been reliability studies conducted on the closed kinetic chain upper extremity stability test (CKUEST) and seated medicine ball chest push test (SMBCPT); however, there are several complicating factors in some of the reports that inhibit the ability to draw definitive consensus about the reliability of the two tests. Although several authors have reported relative reliability for the CKUEST and SMBCPT using intraclass correlation coefficients (ICC), in some cases non-generalizable forms of the ICC were used or the ICC model was not specified. Furthermore, some investigators have conducted reliability analyses using a mixed sample of males and females\(^9\) - \(^12\) while others have conducted separate analyses for males and females\(^13,14\) or limited their study sample to one sex.\(^15 - 17\) In the case of the CKUEST, this is particularly important as different plank positions are adopted by males and females\(^18\) which prompts sex differences in the underlying biomechanics.\(^19\) Additionally, slight variations of the original test descriptions\(^17,20\) have been used in the reliability studies, such as having females assume a full push up position instead of the modified push up position during the CKUEST\(^12,21\) and specifying horizontal projection of the medicine ball\(^10,11,16\) during the SMBCPT compared to the original description of the test.\(^20\) Finally, computing reliability estimates for both tests in the same cohort has not been considered. Having reliability estimates for both tests in the same cohort will facilitate direct comparison of their relative (i.e., ICC) and absolute (i.e., coefficient of variation) reliability. Thus, the purpose of the current investigation was to establish the test-retest reliability of the closed kinetic chain upper extremity stability test (CKUEST), seated medicine ball chest pass test (SMBCPT) and hands-release push-up test (HRPUT) in a cohort of males and females with a history of non-overhead sport participation. A secondary purpose was to examine the associations between the three UEFPT. Of note, The HRPUT provides a mechanism to solely evaluate upper extremity concentric force and endurance as the release phase eliminates the augmentation provided by the eccentric stretch phase (i.e., strain energy, etc.) of a traditional push up. It was hypothesized that there would be moderate magnitude association between the CKUEST and HRPUT but no associations involving the SMBCPT.

METHODS

PARTICIPANTS

Forty healthy young adults (20 males, 20 females) with a history of non-overhead sport participation were recruited for the study. Prior to study participation, all participants completed a demographic, physical activity and injury history form, and the 2019 Physical Activity Readiness Questionnaire. A member of the investigative team reviewed all completed forms to verify each participant was appropriate for study participation. Inclusion criteria included being between 18 and 35 yrs old, meeting criteria set by the American College of Sports Medicine for being physically active,\(^22\) and participation in a non-overhead recreational or competitive sport for a minimum of one year. Participants were excluded from study participation if they had a previous history of cervical spine or upper extremity injury or surgery within a year prior to data collection, were deficient in range of motion needed to perform the tests or were unable to complete the tests as prescribed. This investigation was approved by a university institutional review board and all participants read and signed an approved informed consent form.

RESEARCH DESIGN

This study used a randomized repeated measures research design with study participation requiring completion of two data collection sessions with three to seven days of separation. The two data collection sessions were scheduled at
near identical times each day and participants were asked to avoid vigorous physical activity (e.g., upper extremity resistance or exercise training) 24 hrs prior to each session. The order of the three UEFPT tests was randomized during the first session and duplicated during the second session. Prior to data collection, all participants completed a warm-up which consisted of arm circles forwards, backwards, and arm crosses. Each warm-up activity was completed in thirty seconds, for a total of three sets. After completion of the warm-up, subjects were shown a pre-recorded demonstration video illustrating the tests to be performed. Prior to the CKCUEST and HRPUT, participants completed five to eight submaximal practice repetitions to demonstrate proficiency with the test procedures, defined as being able to repetitively perform the two tasks without hesitation between repetitions. Practice for the SMBCPT was built into the gradient warm-up described below. During all practice trials, participants received cuing as needed. Two-minute rest periods were given between each UEFPT.

TEST PROCEDURES

CLOSED KINETIC CHAIN UPPER EXTREMITY STABILITY TEST (CKCUEST)

The procedures for the CKCUEST followed the original descriptions of the test.\textsuperscript{17,18} For the starting position, males were tested in the traditional push-up position and females were tested in the modified push-up position from the knees. Participants were positioned with their hands over two pieces of athletic tape spaced placed .914m apart with the upper extremities positioned perpendicular to the floor and shoulders over the hands. On the command, “go”, the participant removed one hand from the floor and touched the opposite line and then replaced the same hand on the original line. The participant then removed the opposite hand from the floor and touched the opposite line and replaced the same hand to its original line. A single test consisted of this alternating procedure for 15 seconds. Participants performed as many touches as possible in the allotted time, and touches were recorded by researchers. A touch was defined as the hand crossing over and touching the opposite line. Prior to three maximal effort trials, participants performed a submaximal test at 50% maximum perceived exertion to facilitate test acclimation. Participants rested for 45 seconds between each testing trial. The number of touches from each testing trial were counted and averaged across the three attempts.

SEATED MEDICINE BAL CHEST PUSH TEST (SMBCPT)

The SMBCPT (Figure 1) was performed with the participants sitting with their back stabilized against a wall, legs straight, with feet hip-width apart while holding a 2.73kg medicine ball at chest level. Participants were instructed to push the medicine ball as far forward as possible while keeping their back flush against the wall, and their elbows in towards their sides during the push maneuver. Participants completed a 50% effort and 100% effort warm-up trial prior to three maximal effort trials. Three maximal throws for distance were performed and measurements were recorded in meters from the wall to where the medicine ball landed. The furthest distance achieved out of the three trials was recorded as the performance outcome.

\textbf{Figure 1. Seated Medicine Ball Chest Pass Test starting position (left) and ending position (right).}
HANDS-RELEASE PUSH-UP TEST (HRPUT)

HRPUT began in the prone position with the participants’ hands flat on the ground directly under their shoulders similar to the traditional push-up position (Figure 2-left). The males assumed a full plank position with feet together and toes on the ground, whereas the females used a modified push-up position from the knees. From the initial tripod position, participants were next instructed perform the lowering phase of a pushup until their chest, front of the hips, and thighs made contact with the ground; this served as the start position for the test. Upon the command, “go”, participants pushed their entire body as a single unit into the “up” position by fully extending their elbows. The participant’s entire body was required to remain in a straight body alignment, from head to the ankles (males) or knees (females), with no bending or flexing the knees, hips, trunk, or neck. Failure to maintain a straight alignment during a repetition resulted in that repetition not counting. After the elbows were fully extended and the subject reached the “up” position, the participants bent their elbows to lower body back to the ground as a single unit until the chest, hips, and thighs made ground contact. Without moving the head, body, or legs, the participants raised both hands from the ground simultaneously, keeping the upper arms adjacent to their trunk, so that a clear hands-ground gap was visible to ensure the participants released their hands from the ground (Figure 2-right). Their hands were then lowered to the floor directly under their shoulders. This completed one repetition. Failure to make a continuous effort to push off from the ground, resting on the ground, or lifting the feet off the ground during the test resulted in termination of the test. In addition, the test was terminated if the participant expressed that they couldn’t continue. The only authorized rest position during the test was the “up” position. Participants completed as many correct repetitions as possible in two minutes. The number of correct repetitions was counted and recorded as the performance outcome.

STATISTICAL ANALYSIS

All statistical procedures were conducted using IBM SPSS Statistics for Windows, version 27 (IBM Corp., Armonk, NY, USA) and Microsoft Excel, version 16 (Microsoft Corporation, Redmond, WA, USA). Separate statistical analyses were conducted for the males and females. Exploratory analyses were conducted on the data from each session to identify potential erroneous data entry errors. Normality of the between session difference scores was examined using Q-Q plots and Shapiro-Wilks tests. Heteroscedasticity between sessions was examined by using the Bland-Altman method. Systematic bias between testing sessions were evaluated using dependent t tests. Absolute reliability was determined by computing standard error of measurement (SEM), 24 90% minimal detectable difference (MDD90%), and coefficient of variation (CV). Relative reliability was computed using ICC2,1. Additionally, following examination of scatterplots, separate sex Pearson correlational analyses were conducted between the three UEFPT. Coefficients of variation were considered acceptable when values were below 10%. The magnitude for the ICC and correlation coefficients were interpreted as follows: less than 0.40: poor/weak, between 0.40 and 0.59: fair, between 0.60 and 0.74: good/moderate, and between 0.75 and 1.00: excellent/strong.

RESULTS

Forty healthy young adults (20 males, 20 females) with a history of participation in various non-overhead sports participated in the study. (Table 1)
Apart from the UECKCST (p=0.006) for the females, results of the exploratory analysis for normality revealed no significant (p=0.070 to 0.524) departures for the difference scores. Closer inspection of the UECKCST scores revealed one female participant to exhibit less touches (2.4 touches) during the second session. The lower score contrasted with the other 19 females who all showed improvement during the second session (i.e., more touches). When normality of the difference scores were examined without this participant included, the distribution was no longer statistically significant from normal (p=0.066). Because the non-normality was attributable to a single participant, coupled with wanting to keep the analyses as simple as possible, the UECKCST data for the females did not undergo a data transformation. Results of the heteroscedasticity analysis yielded no significant relationships with Kendall’s Tau values ranging between -.159 to .174.

Descriptive statistics for test performance across the two sessions are provided in Table 2. Only the UECKCST for both sexes (Table 3), demonstrated significant (p ≤ 0.005) improvements in performance during the second session compared to the first session. Except for the HRPUT in males, the absolute reliability expressed as CV for the remainder of the tests in both sexes were all below 8.8%. Across all three absolute reliability metrics, the results were slight better for the females compared to the males (smaller values). The ICC results demonstrated excellent relative reliability for all three tests.

Results of the correlational analyses (Figure 3) yielded only one significant relationship (r=.691, p=0.001) between UECKCST and SMBCPT for the females. Aside from the non-significant relationship between UECKCST and HRPUT for the females (r=.342, p=0.140), the remainder of the coefficients were less than .149 (p >0.530).

**DISCUSSION**

The primary purpose of this investigation was to assess the intersession reliability of three UEFPT to assist with RTS decision making in a cohort of males and females with a history of non-overhead sport participation. Based on current literature voids, paramount to the investigation was conducting comprehensive reliability analyses (i.e., systematic bias, relative reliability, absolute reliability), separately for each sex, to enable direct comparisons between the three tests. Across the three UEFPT, the relative reliability of all three UEFPT were excellent with the reliability estimates being slightly higher for females compared to males. Based upon the coefficients of variation, only the UECKCST and SMBCPT had values less than 10% across both sexes; the HRPUT coefficient of variation for the males was just beyond 10%. Thus, this investigation largely provides support for all three UEFPT and provides clinicians with the necessary information to interpret serial testing with these three tests.

The ICC, which largely represents the consistency of an individual’s rank relative to the group across the two testing sessions, for the three UEFPT across both sexes were higher than the threshold criteria of .75. Important to consider when assessing the clinical meaningfulness of ICC are the confidence interval widths, which represent the precision of the estimates (e.g. narrower indicates more precision), and the lower bounds (e.g. are they within an acceptable range). The confidence interval widths and lower bounds for the females also support the relative reliability of the three UEFPT. For the males, in addition to the ICC being slightly smaller than the females, the confidence interval precision was less (i.e., wider confidence intervals) and the lower bounds were below .7. This may be attributable to more activity level variability for the males which likely results in greater upper extremity strength and power differences in the cohort. Compared to the females, more males were involved with weight training and football, activities that both require high degrees of upper body strength; however, within those activities there was likely high degrees of proficiency variability, such as the various positions in football and player size, which likely creates more variation in the actual strength and test performance. As described previously, mixed sex samples, slight method-
Table 3. Results of the systematic bias (difference between the two assessment sessions), absolute reliability, and relative reliability analysis conducted on the functional performance tests. The units associated with CKCUEST are touches, the units associated with HRPUT are push ups, and the units for the SMBCPT are meters.

<table>
<thead>
<tr>
<th>Test</th>
<th>Sex</th>
<th>Systematic Bias</th>
<th>Absolute Reliability</th>
<th>Relative Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SD</td>
<td>p-value</td>
<td>SEM</td>
</tr>
<tr>
<td>UECKCST</td>
<td>F</td>
<td>1.8 ± 1.4</td>
<td>&lt;0.001*</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1.5 ± 2.0</td>
<td>0.003*</td>
<td>1.4</td>
</tr>
<tr>
<td>HRPUT</td>
<td>F</td>
<td>1.1 ± 3.9</td>
<td>0.217</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>-1.5 ± 4.6</td>
<td>0.175</td>
<td>3.3</td>
</tr>
<tr>
<td>SMBCPT</td>
<td>F</td>
<td>.05 ± .27</td>
<td>0.383</td>
<td>.19</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>.13 ± .41</td>
<td>0.160</td>
<td>.29</td>
</tr>
</tbody>
</table>

*statistically significant systematic bias (p<.05)

UECKCST: upper extremity closed kinetic chain stability test, HRPUT: hands release push up test; SMBCPT: seated medicine ball chest pass test; SD: standard deviation; SEM: standard error of the measurement; CV: coefficient of variation; MDD 90%: 90% minimal detectable difference; ICC: intraclass correlation coefficient; CI: confidence interval; D: dominant; ND: non-dominant; F: female; M: male

The SEM reported for the UECKCST across two testing sessions ranges 1.5 to 2.8 touches for healthy females and 1.2 to 2.0 touches for healthy males. The females in the current study demonstrated a lower SEM than the previous literature, while the males were within the range of the previous reports. Interestingly, the females in the current study demonstrated a smaller SEM (i.e., better absolute reliability) than the males, whereas in the previous reports the males demonstrated smaller SEM than the females. These slight differences are likely attributable to inclusion/exclusion criteria differences. The current investigation focused upon non-overhead athletes. In contrast, the previous literature using healthy participants focused on sedentary, upper extremity upper extremity sport-specific recreational athletes, or just physically active.

Only two previous investigations have reported SEM for the SMBCPT in a cohort of young adult females and mixed cohort of overhead athletes. While our SEM for the females is within ~0.06m of the previously reported female cohort, our male participants exhibited SEM that exceeds the previous mixed sample report by ~0.19m. One explanation may be that both previous investigations specified a strict horizontal throw be used. In contrast, and similar to a previous report examining the association between SMBCPT and bench press throw performance, we did not limit the maneuver to a strict horizontal projection.

Table 3 and Figure 5.
Gillespie and Keenum\textsuperscript{27} compared chest pass throw performance while seated in a chair under controlled and uncontrolled projection angle conditions and reported \(-0.30\text{m}\) greater throw distance for the uncontrolled projection angle condition. Thus, because we did not restrict projection angle, it is likely that our throw distances are greater than the two previous SMBCPT reports\textsuperscript{11,16} and associated with the greater throw distances are SEM increases.

As a unitless measure, the CV provides a means to directly compare the absolute reliability of the three UEFPT. Across both sexes, slightly smaller CV (better absolute reliability) were identified for the SMBCPT than the UECKCST, with the HRPUT demonstrating the largest CV. It is also important to note that the HRPUT CV for the males was slightly larger than the 10% acceptability threshold. The larger CV for the HRPUT is likely a function of the test duration being up to two minutes. Despite the larger CV, in light of the MDD\textsubscript{90\%}, being 6.4 (females) and 7.6 (males) push-ups for the two-minute effort the HRPUT can likely play an integral role in RTS decision making following upper extremity injury or surgery.

In the current study, only the UECKCST exhibited a statistically significant improvement across the two testing sessions. The two previous studies that considered systematic bias for the UECKCST also reported statistically significant improvements with repeated testing.\textsuperscript{9,13} Although the previous literature does not provide full descriptive statistics regarding the significant session improvements, estimation from the graphs presented suggest improvements between 1.5 to 2.4 touches; the significant mean improvements in the current study (1.8 touches for females, 1.5 touches for males) are both within this range. Closer inspection of our data yielded 85\% (17/20) of the females and 75\% (15/20) of the males to show greater touches during the second assessment. Further investigation yielded 75\% (15/20) of the females and 45\% (9/20) of the males demonstrating touch improvements that exceeded the standard of error measurement (i.e., typical error) threshold. As a result, practitioners should expect, on average, a one to two touch improvement when interpreting UECKCST scores from a second test administration. Thus, to be reasonably certain improvement in test performance exceeds that attributable to repeated exposure and measurement error, practitioners should seek an increase in touches that exceed the systematic bias and 90\% minimal detectable difference. Those thresholds, based on systematic bias plus minimal detectable differences, are \(-4\) and \(5\) touches for females and males, respectively. There was only one previous report,\textsuperscript{10} which used a radar gun to measure ball velocity instead of measuring distance, that examined and reported no systematic changes in SMBCPT performance.

The void of research examining the HRPUT prohibits comparing the current results to previous results. Since the collection of the data for the current study, a slightly different HRPUT version has been incorporated into some military performance tests in place of the traditional push-up test. In contrast to the hands being lifted with upper arms remaining adjacent to the trunk within the current study, the military version incorporates the hands being moved outward from shoulders until full shoulder abduction position is reached. A traditional push-up is technically an upper extremity stretch-shortening movement because of the eccentric stretch created with the downward movement followed by the concentric power production push-up phase. Therefore, to solely evaluate the concentric power of the upper extremity musculature, the release phase of the HRPUT eliminates the eccentric stretch and attenuates the stretch-shortening augmentation to performance. Therefore, the HRPUT may be best suited to evaluate true concentric power press capacity of the upper extremity muscles, similar to upper extremity movements in sport that occur without the stretch-shorten sequence (e.g., wrestling, jujutsu, gymnastics, etc.). Our results, except for the CV for the males being 2.5\% greater than the acceptable threshold, provide initial supportive insight into the test-retest reliability of the HRPUT.

In contrast to the authors’ hypotheses, there were no significant relationships between the UECKCST and HRPUT for either the females or males. Despite similar testing positions, the authors’ speculate that large discrepancy in test duration (UECKCST=15s, HRPUT=2 min) relies upon different muscle performance characteristics. Specifically, it is likely that the HRPUT draws more upon muscle endurance whereas the UECKCST relies upon a blend of muscle performance and power to execute the frontal plane upper extremity movements. Additionally, while HRPUT solely involves moving the head-torso vertically, the UECKCST requires a degree of eye-hand coordination to sequentially touch the targets. Based upon previous research reporting a weak relationship between UECKCST and SMBCPT,\textsuperscript{16} the significant moderate strength association between the UECKCST and SMBCPT for the females in the current study was unexpected. The SMBCPT, being a single maximal effort maneuver, is a bilateral upper extremity muscle power assessment that has been previously demonstrated to associate with ballistic bench press performance.\textsuperscript{15} The relative short UECKCST test duration (15s) coupled with the modified push-up position used by the females to perform the UECKCST not requiring high levels of muscle endurance to maintain the position while executing alternating touches likely explains the statistically significant association.

Overall, except for the relationship between the UECKCST and SMBCPT for the females, the lack of associations between tests suggests they are assessing different aspects of upper extremity functional performance and thus can be used along a continuum. Specifically, as progression hierarchy, the authors recommend first assessing a patient with the SMBCPT, followed by the UECKCST and then the HRPUT. Unlike the UEFPT for overhead sport activities that are completed unilaterally,\textsuperscript{9} all three of the UPFPT in the current investigation are bilateral assessments. Consequently, practitioners should be cognizant that the healthy (uninjured) side may be able to partially compensate for deficiencies in the injured limb. As a result, practitioners may want to follow up bilateral UEFPT with unilateral UEFPT and examination of limb symmetry indices.\textsuperscript{28}
Finally, it is important to recognize that this study sample included both recreational and competitive athletes across a variety of specific non-overhead sports. This study population was chosen to provide practitioners with initial reliability estimates regarding these three UEFPT across a broad population of non-overhead athletes. As test performance may differ between participation level and sports, future research should explore the reliability of the three UEFPT in other varied populations.

CONCLUSION

The results of the current study provide support for all three UEFPT and offer clinicians the necessary information to interpret serial testing with using these three tests. With the exception of the moderate relationship between UECKST and SMBCPT for the females, the lack of strong associations between performance of the three tests implies that they are reflecting different aspect of upper extremity functional performance.

ACKNOWLEDGEMENTS

We would like to thank Nicole Ebel, Morgan Taylor, Ben DeLoach and Luke Thayer for their assistance with participant recruitment and data collection.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

Submitted: June 05, 2023 CDT, Accepted: August 31, 2023 CDT
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Original Research

Reliability and Concurrent Validity of a Markerless, Single Camera, Portable 3D Motion Capture System for Assessment of Glenohumeral Mobility.

Ofra Pottorf1, Daniel Vapne2, Jamie Ghigiarelli1, Kaitlyn Haase
1 Allied Health and Kinesiology, Hofstra University, 2 PT Solutions Physical Therapy

Keywords: “3D motion”, “glenohumeral joint”, “goniometry”, “range of motion”, “reliability”, “validity”

https://doi.org/10.26603/001c.88003

International Journal of Sports Physical Therapy

Introduction
Recent technological advancements have enabled medical, sport, and fitness professionals to utilize digital tools that assist with conducting movement examinations and screenings. One such advancement has been the implementation of a single camera, markerless, and portable 3D motion capture system designed to obtain ROM measurements for multiple body parts simultaneously. However, the reliability and validity of a markerless 3D motion capture system that uses a single camera has not been established.

Purpose
The purpose of this study was to investigate the reliability and concurrent validity of this 3D motion capture system compared to a goniometer in assessing ROM of the glenohumeral joint.

Study Design
Quasi-experimental reliability, convenience sampling.

Methods/materials
Forty healthy volunteers (mean ± SD, age 27.4 ± 12.4 years, height 173.4 ± 11.1 cm, weight 72.1 ± 16.2 kg) participated in this study. Intrarater reliability was analyzed by ICC(2,k) with a 95% CI using two repeated trials for each shoulder movement (flexion, abduction, external rotation, internal rotation) that were recorded simultaneously via two methods: a standard goniometer and a 3D motion capture system. Concurrent validity was analyzed using Pearson Correlation Coefficient (r).

Results
The intrarater reliability between the two instruments for glenohumeral motions yielded an overall ICC of 0.82 (95% CI: 0.74-0.88) indicating good reliability for both instruments. The 3D motion capture system demonstrated strong correlations with goniometry for shoulder flexion (r = 0.67), abduction (r = 0.65), and external rotation (r = 0.76), and very strong correlation for shoulder internal rotation (r = 0.84).
Conclusion

Results from this study indicated that a markerless, single camera, portable 3D motion capture system can be a reliable and valid tool to assess glenohumeral joint ROM in comparison to a standard goniometer.

Level of Evidence

INTRODUCTION

Range of motion (ROM) assessments are commonly performed by healthcare professionals including physical therapists, occupational therapists, chiropractors, physicians, and other medical professionals when the focus of rehabilitation is related to the musculoskeletal and neuromuscular systems. Range of motion measurements assist healthcare professionals in monitoring progress during the rehabilitation process. These assessments are also important for establishing baselines, functional limitations, or dysfunction in ROM due to injury or disease. They are also often used in sports performance evaluations for athletes who want to increase strength and joint mobility, regardless of injury status. Prior authors have reported that adequate ROM is fundamental to perform functional activities of daily living and meet vocational demands. Thus, it is important for healthcare providers to assess and reassess ROM during the physical rehabilitation process to ensure sufficient progress towards return to function.

Physical therapists and other healthcare professionals use various methodologies and tools to assess ROM. Some healthcare professionals utilize standardized objective tools such as a goniometer, inclinometer, or a smartphone while other healthcare professionals implement more subjective techniques such as a visual estimation or by observing functional movement patterns. The goniometer is a gold standard tool commonly used by healthcare professionals to assess joint ROM, and also is a primary instrument used in higher education to teach future healthcare professionals how to assess joint ROM. Goniometry has been used widely due to its portability and low cost. However, a limitation of goniometry is that it requires the clinician to use both hands, making stabilization of the extremity difficult, and thus increasing the risk of error in reading the instrument.

In recent years, digital tools ranging from electrogoniometers with simple flex sensors, to more complex machine learning-based systems are becoming more widely utilized in clinical practice. Motion capture systems are a subset of these digital tools that have shown great promise for accurate and timely measurements in the domain of human movement analysis, including ROM assessment. Two-dimensional (2D) motion capture systems such as smartphones utilize readily accessible technology but are limited in their ability to assess ROM, when a picture or video is captured it does not account for depth and the perceived angles of the objects, thus the frame is largely dependent on the perspective of the lens. This is referred to as parallax error. Therefore, if a person is not positioned precisely in front of the camera their joint angle measurements may be skewed.

Three-dimensional (3D) motion capture systems that implement Light Detection and Ranging (LiDAR) technology use light emitted from a pulsed laser to measure distance. LiDAR and other depth sensing technology afford clinicians high fidelity data models and more accurate spatiotemporal representations of body movements, which result in greater reliability and validity of ROM assessments when compared to 2D motion capture tools. Unfortunately, many 3D motion analysis systems are complex to set up, require multiple cameras, are costly, and not portable, making them inaccessible to healthcare providers.

With recent advancements in technology, new digital tools have been introduced that assist medical, sport, and fitness professionals in performing examinations and screenings. One recent advancement introduced was a 3D motion capture system that uses a single camera, is markerless, and portable (Kinotek, Inc., Portland ME). This system was designed to obtain ROM measurements for multiple body parts simultaneously. The system is capable of measuring 64 distinct movements and 750 data points per visual analysis using 50fps. For each analysis, the software outputs objective data on ROM, asymmetries present between right and left, and a quality movement graph that provides metric analysis for motion tracking for the entirety of the movement (Figure 1A-C). The software provides pre- and post-movement comparisons, progress charts, and other data that can be easily translated to written documentation. In addition, this system generates an avatar of the individual for 3D visuals which can rotate 360° enabling the user to focus on specific areas during motion tracking for optimal visualization. This system uses Microsoft’s Azure Kinect camera, which is commercially available, and relatively inexpensive compared to other 3D motion capture systems on the market. The setup is simple and can be completed by a single user without assistance. The system is portable, cost effective, and works via a WiFi connection to any compatible device, such as a laptop. However, the reliability and validity of a markerless 3D motion capture system that uses a single camera has not been established. The purpose of this study was to investigate the reliability and concurrent validity of a markerless, single camera, portable 3D motion capture system compared to goniometer in assessing ROM of the glenohumeral joint.
had active pain or tingling/numbness during the time of data collection, or were not able to provide consent.

ETHICAL APPROVAL

Ethical approval for this study was granted by Hofstra University Institutional Review Board. Prior to data collection, participants reviewed and signed an informed consent.

INSTRUMENTS

The instruments utilized for data collection are represented in Figure 2 (A-B), which included one (A) Full-circle standard 12-inch plastic goniometer and (B) 3D motion capture system (Kinotek Inc., Portland ME). The goniometer is as a commonly used tool by healthcare providers for assessing joint ROM and identifying body asymmetries, and previous studies reported this tool to be a reliable and valid option for measuring ROM in various joints of the body.\textsuperscript{3,12,20–24} Thus, for data collection the goniometer was used in this study to compare measurements between the 3D motion capture system and a standard tool commonly utilized by healthcare professionals.

TESTER SELECTION AND PROCEDURE

The tester selected for this study was a licensed physical therapist with 15 years of clinical experience that commonly uses a goniometer in clinical practice. In addition, the tester had experience as an educator in a class that taught goniometry to physical therapy students. To assess the reliability of the tester, five repeated goniometric measures were taken by the tester and statistically analyzed for intrarater reliability. For data collection, the same tester took all measurements with the goniometer. The tester was blinded to the displayed readings while positioning the goniometer on the participant and a second person recorded the readings. For this study, active ROM of the gleno-humeral joint was measured (abduction, flexion, external rotation, internal rotation). Each of the movements were performed with the participant positioned in a standing position and seven feet from the camera, as demonstrated in Figure 3. The room was set up with the floor marked at seven feet from the center of the camera, forward facing towards the camera. The camera was positioned with a 6º tilt upwards at a height aligned to the mid-pelvic region. Each participant was given a verbal cue to start active ROM for each of the shoulder movements while the camera was recording, and instructed to stop at the end of the available range and hold the position while the testers recorded the goniometric measurement. Verbal instructions were standardized so that all participants received the same verbal cueing. Prior to each movement, participants were shown a visual demonstration of the movement and were also instructed on potential body substitutions with each movement. Then, one practice trial was performed. After the trial, the tester provided feedback to the participant to mitigate any further extraneous variables that were identified pertaining to the movement such as body substitutions and speed of movement. Two additional trials for each move-
ment were then recorded that were used for data analysis, following the procedure described above.

STATISTICAL ANALYSIS

Data were analyzed using SPSS Statistics v28 (Armonk, NY). Intrarater reliability was determined using the Intraclass Correlation Coefficient (ICC2,k) with a 95% Confidence Interval. Descriptive statistical analysis was also performed to analyze the demographic information collected from the sample of participants. Concurrent validity was determined using the Pearson Correlation Coefficient (r) by comparison of the averaged readings from the two trials using both instruments.

RESULTS

The total sample size of participants meeting inclusion criteria was 40; 29 who identified as female and 11 who identified as male. The average age for participants was 27.4 ± 12.4 years with age ranging from 18 to 62 years old. The average height and weight for participants was 173.4 ± 11.1 cm and 72.1 ± 16.2 kg, with a range of 152.4 to 193.0 cm and
DISCUSSION

The purpose of this study was to investigate the reliability and concurrent validity of a markerless, single camera, portable 3D motion capture system compared to a goniometer in assessing active ROM of the glenohumeral joint. While other studies have investigated the reliability and validity of multi-camera 3D motion capture systems, the reliability and validity of a markerless 3D motion capture system that uses a single camera has not been established.

Reliability and validity are important to establish for tools and technologies, especially when being used by healthcare or sports professionals. Portney and Watkins25(27) describe that “usefulness of a measurement and decision-making depends on the extent of its reliability and validity, where reliability refers to the extent of consistency in repeated measures and validity refers to the extent of accuracy or if the tool is measuring what it is intended to measure”. They conclude that reliability and validity are fundamental to all aspects of a measurement, because without it one cannot have confidence in the data collected nor draw sound conclusions from those data. The current study found, for concurrent validity measurements with the 3D motion capture system were comparable to those taken with the standard 12-inch plastic goniometer with correlation values ranging from 0.65 - 0.84 indicating high to very high correlation between the instruments, where 0 < r ≤ 0.19 = very low correlation, 0.2 ≤ r ≤ 0.39 = low correlation, 0.4 ≤ r ≤ 0.59 = moderate correlation, 0.6 ≤ r ≤ 0.79 = high correlation, and 0.80 ≤ r ≤ 1.0 = very high correlation.26,27 The measurements obtained using both instruments yielded intrarater reliability in the range of 'good' overall.28 These results are comparable to previous research that reported good intrarater reliability when utilizing similar measurement procedures.11-14,29 Macedo and Magee28 reported on passive ROM of peripheral joints, which included the shoulder joint, on healthy adult females. They reported the SEM for the goniometer to be 3.5° while the Minimal Detectable Change (MDC) at a 95% CI ranged from 4° to 21° with a mean of 9.6°. Results from the current study reported results consistent with those previously reported.

Range of motion assessments are important for evaluating the effectiveness of treatment over time, establishing baselines, limitations, or dysfunction in ROM due to injury or disease, and monitoring progress during the rehabilitation process.1,30,31 Advancements in technology have introduced new digital tools that assist medical, sport,

Table 1. Mean and Standard Deviation for Glenohumeral Motion using the Goniometer and 3D Motion Capture System.

<table>
<thead>
<tr>
<th></th>
<th>Abduction</th>
<th>Flexion</th>
<th>ER</th>
<th>IR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean° (SD)</td>
<td>Mean° (SD)</td>
<td>Mean° (SD)</td>
<td>Mean° (SD)</td>
</tr>
<tr>
<td>Goniometer</td>
<td>171.03 (7.09)</td>
<td>152.38 (8.29)</td>
<td>84.03 (15.60)</td>
<td>40.92 (14.37)</td>
</tr>
<tr>
<td>Kinotek</td>
<td>170.95 (6.06)</td>
<td>158.39 (9.90)</td>
<td>75.56 (12.78)</td>
<td>47.44 (14.21)</td>
</tr>
</tbody>
</table>

SD=Standard Deviation; ER=External Rotation; IR=Internal Rotation
Table 2. Intrarater Reliability of measurements taken with the goniometer and 3D Motion Capture System.

<table>
<thead>
<tr>
<th></th>
<th>Abduction</th>
<th>Flexion</th>
<th>External Rotation</th>
<th>Internal Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goniometer ICC</td>
<td>ICC = 0.76 (0.64-0.84) SEM = 0.71</td>
<td>ICC = 0.83 (0.75-0.89) SEM = 0.90</td>
<td>ICC = 0.94 (0.91-0.96) SEM = 1.74</td>
<td>ICC = 0.90 (0.85-0.94) SEM = 1.55</td>
</tr>
<tr>
<td>Kinotek ICC</td>
<td>ICC = 0.64 (0.49-0.75) SEM = 0.68</td>
<td>ICC = 0.89 (0.83-0.93) SEM = 1.08</td>
<td>ICC = 0.92 (0.88-0.95) SEM = 1.41</td>
<td>ICC = 0.68 (0.54-0.79) SEM = 1.501</td>
</tr>
</tbody>
</table>

ICC = Intraclass Coefficient; SEM = Standard Error of Measurement; CI = Confidence Interval

Figure 4A. Relationship between measures from the standard goniometer and 3D motion capture for shoulder abduction on the standard goniometer and 3D motion capture.

and fitness professionals in performing examinations and screenings. Results from this study demonstrated a strong positive correlation between Kinotek and the goniometer. There are several benefits of incorporating 3D motion analysis for ROM assessment. First, 3D motion capture provides motion tracking throughout the entirety of the active ROM, which allows greater insight to the quality of the movement while also allotting the operator to stop the movement at any point during the movement. Another benefit is that this 3D motion capture software generates an avatar of the individual being recorded. The avatar can be rotated and viewed in the frontal, sagittal, and transverse plane allowing the operator to view the individual’s movement at any angle (Figure 1B). However, a standard goniometer costs significantly less than a 3D motion capture system, has greater portability, and is still widely utilized by postsecondary institutions to teach joint ROM assessment.

This research study had limitations in that the data collected were on healthy individuals. It would be advantageous in future studies to consider a sample with mobility impairments or conditions or of different populations such as those with musculoskeletal and neuromuscular disorders, as active ROM of the glenohumeral joint in healthy individuals may not correlate with those who have shoulder pathology. A power analysis was conducted prior to data collection to determine the approximate sample size needed to produce a meaningful effect size, and although 40 participants (80 shoulders) met these criteria, a larger sample size would also be beneficial in future studies to further strengthen the generalizability of any conclusions. While this study found promising results for reliability and validity of glenohumeral active ROM, it is recommended that future studies investigate other joints using this 3D motion capture system to investigate the reliability and validity of this newer technology. Despite these limitations, this study provides a promising future for physical therapists and other healthcare professionals who focus on rehabilitation and sports performance evaluations, as the 3D motion capture system can be a reliable and valid alternative to the goniometer in assessing joint ROM.
CONCLUSIONS

This study found acceptable reliability and validity of the 3D motion capture system in comparison to standard goniometric measurements when assessing glenohumeral joint active ROM. Three-dimension motion capture systems are valuable in rehabilitation related to the musculoskeletal and neuromuscular systems. However, they have not been widely used by healthcare and sports professionals due to its limited portability, large size, use of multiple cameras, high cost, and complexity of operation. A 3D motion capture system that is portable, markerless, and uses a single camera can offer physical therapists and other healthcare
Figure 4D. Relationship between measures from the standard goniometer and 3D motion capture for shoulder internal rotation on the standard goniometer 3D motion capture.

professionals alternate time efficient methods to assess mobility of multiple joints simultaneously and provide objective time series data of movement patterns.

CONFLICT OF INTERESTS
Ofra Pottorf is an Independent Consultant and Advisor for Kinotek, Inc.
Kaitlyn Haase is an employee of Kinotek, Inc.

Submitted: May 10, 2023 CDT, Accepted: August 30, 2023 CDT
REFERENCES


Original Research

Perceptions of Physical Therapy and The Role of Physical Therapists in Injury Prevention Among Professional Basketball Players: A Qualitative Study

Alison Marks¹, Carol A. Courtney¹,², William E. Healey²

¹ Physical Therapy and Human Movement Science, Northwestern University, ² Physical Therapy and Human Movement Sciences, Northwestern University

Keywords: elite athletes, physical therapy, injury prevention, qualitative

International Journal of Sports Physical Therapy

Background
Injury prevention is critical in competitive professional sports, however, the role of physical therapists in this aspect of healthcare is not fully understood.

Purpose
The purpose of this study was to describe professional basketball players’ perceptions of physical therapy (PT) and physical therapists’ role in injury prevention.

Study Design
Qualitative, semi-structured interview

Methods
Thirty-five professional basketball players (mean age 23.1 years ± 3.9; 42% female; 72% African American; 90% college graduates) from over 20 teams participated. Athletes participated in semi-structured interviews that focused on injury prevention and utilization of PT services. Two researchers coded the transcripts, organized the findings into general categories, and created major themes. Data saturation was reached when no new information emerged.

Results
Over half (62.9%) stated that PT mainly addressed post-injury and return-to-sport rehabilitation. An overwhelming majority of players highlighted the use of an athletic trainer (AT) over physical therapists in injury prevention due to perceived expertise and trust.

Conclusion
While PTs are educated in preventive care and acute injury management, professional basketball players viewed their role primarily for return-to-sport rehabilitation. The organizational structure of healthcare in professional basketball may promote closer professional relationships with ATs while limiting those with physical therapists. The result is that elite athletes may miss out on treatment specific to the PT profession.
Level of Evidence

Level 4

BACKGROUND

There is a growing concern regarding injury rates in elite athletes, specifically professional basketball players, with concrete evidence demonstrating that lower-extremity injuries are a major source of missed games. Reduction of these injuries is a major objective of professional sports teams as any injury can result in significant time lost in training and competition. Overuse injuries are common in professional basketball. Researchers have identified risk factors for injury and overuse in professional basketball, including history of injury in the last 12 months and player schedules with back-to-back games. It is clear that injuries, including overuse injuries, are prevalent in professional basketball and a paradigm shift may be needed for adequate medical management to take place. Team medical personnel including physicians, athletic trainers, strength and conditioning coaches, and physical therapists understand that injury prevention is critical to the long-term success of the professional athlete, yet prevention guidelines are not explicit.

Recent authors have suggested that best outcomes occur when the patient participates in the clinical decision-making process regarding their care. Accordingly, a patient's health beliefs and their knowledge of healthcare play a major role in optimal holistic patient care. More specifically for the professional athlete, knowledge of factors that may predispose them to injury, and identifying the appropriate health care professional from whom to seek care may be critical. Determining knowledge and beliefs regarding injury prevention in professional basketball players is needed to provide valuable, individualized services for these athletes.

To investigate risks and prevention factors in professional basketball, a previous study characterized the opinions of physical therapists, physicians, and athletic trainers who worked with elite athletes. Study investigators used a qualitative approach to conduct interviews and identify themes about injury risk and prevention factors and found that inadequate sport technique, nutrition, and overtraining were causative factors. Factors to prevent injuries included categories of training interventions/physical therapy (PT), psychological features, and behavioral strategies. Determining the knowledge level of professional basketball players on injury prevention may help to guide management and provide specific protocols to ensure appropriate interventions. While the Saragiotto study provided valuable input from medical professionals associated with professional teams, the perspectives from athletes were not investigated.

Knowledge of beliefs related to prevention of injuries may contribute to the planning and implementation of more adequate strategies than those presently used. A new framework concluded that adherence to injury prevention programs improved with understanding and believing in the program. In addition, the relationship between a player and the provider may enhance their own prevention program. The purpose of this study was to describe professional basketball players' perceptions of PT and physical therapists' role in injury prevention.

METHODS

This was a qualitative research study using semi-structured interviews questions, which were initially piloted with retired professional and collegiate basketball players (APENDIX). The study interviews were performed over a four-month period. One of the authors had extensive qualitative research experience.

PARTICIPANTS

A convenience sample of professional basketball players currently on the active roster of a National Basketball Association (NBA), Women's National Basketball Association (WNBA), or NBA Growth League (G-League) team who were >18 years old were invited by email to participate in this study. Northwestern University Institutional Review Board approved this study. Participants were assigned a numerical subject identification to promote confidentiality and anonymity.

DATA COLLECTION

Semi-structured interviews were used to investigate participants' understanding of injury prevention and their knowledge and use of PT services. Team-related personnel were identified through public websites, such as NBATA.com, Realgamed.com, NBA.com, WNBA.com, gleague.nba.com. Prior to each interview, participants provided consent and the researchers used an audio recording device to capture the content. A participant responded by telephone at a mutually-agreed upon time between him/herself and the research investigator (APM). Each recording was transcribed verbatim. Interviews lasted approximately 10-15 minutes.

Follow-up interviews were scheduled after coding analysis for member checking to enhance trustworthiness and to explore the credibility of results. Ten participants (four NBA players, three WNBA, three G-League) were contacted and verified their statements and findings.

DATA ANALYSIS

Based on the comparative qualitative analysis process, two of the authors created a codebook to develop categories and themes (Figure 1). During open coding, all ideas and phrases were examined and given a label. Transcriptions were coded separately by the two researchers and then differences were discussed and modified to reach consensus.

Codes with commonalities were grouped together to create categories for analysis (See example in Table 1). Inves-
Figure 1. Comparative Qualitative Analysis

Three primary themes emerged from the coded data that described the perceptions of these professional basketball players regarding PT and the role of physical therapists overall and specifically in injury prevention. The themes were: 1) these athletes reported a general knowledge of PT centered around post-injury rehabilitation; 2) when asked, they perceived physical therapists’ role in injury prevention to include strengthening and flexibility exercises, and individualized educational approaches; and 3) to prevent injuries, athletes chose a team healthcare provider they trusted, and this was most commonly the team athletic trainer. Below three themes are presented with exemplary supporting quotes.

RESULTS

A total of 35 professional basketball players (age 23.1 years ± 3.9; 42% female; 90% college graduates) from over 20 teams participated in the study (Table 2), with 15 individuals from the WNBA, 10 from the NBA, and 10 from the NBA G-League. Almost 90% of study players reported a previous injury that caused them to miss out on practice or games. An online review of the organization’s medical staff revealed that 29 of 30 NBA teams, three of 12 WNBA, and three of 29 G-League teams had a team physical therapist listed.

The three research questions, associated interview guide questions, and participant responses are found in Table 3. Percentages based on count of players’ responses were calculated for each interview guide question and included in Table 3.
Table 1. Example of Codebook

<table>
<thead>
<tr>
<th>Interview Question</th>
<th>Codes</th>
<th>Definitions</th>
<th>Quotations from Transcripts</th>
</tr>
</thead>
<tbody>
<tr>
<td>What do you think</td>
<td>Ill prepared</td>
<td>Any discussion about lack of preparation, including strength training,</td>
<td>&quot;I think a lot of injuries happen from the lack of</td>
</tr>
<tr>
<td>can cause injuries</td>
<td></td>
<td>flexibility, mobility. This includes types of training, such as lifting</td>
<td>almost prevention, things</td>
</tr>
<tr>
<td>in athletes</td>
<td></td>
<td>weights, prevention/maintenance programs.</td>
<td>that you do before ever</td>
</tr>
<tr>
<td>participating in</td>
<td></td>
<td></td>
<td>stepping on a court or</td>
</tr>
<tr>
<td>your sport?</td>
<td></td>
<td></td>
<td>before practice starts or</td>
</tr>
<tr>
<td></td>
<td>Overuse</td>
<td>Any mention of overuse, wear &amp; tear, increased fatigue due to duration of</td>
<td>&quot;Constant pounding on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sport activity, or length of season.</td>
<td>dudes’ knees when they</td>
</tr>
<tr>
<td></td>
<td>Lack of</td>
<td>Includes inadequate sleep, lack of time or ability to recover throughout the year.</td>
<td>No proper rest</td>
</tr>
<tr>
<td></td>
<td>proper rest</td>
<td></td>
<td>No sleep</td>
</tr>
<tr>
<td></td>
<td>and recovery</td>
<td></td>
<td>No time to recover</td>
</tr>
</tbody>
</table>

THEME 1: ALMOST ALL PARTICIPANTS HAD A GENERAL KNOWLEDGE ABOUT PT, WHICH EMPHASIZED POST-INJURY REHABILITATION IN ORDER TO RETURN TO THEIR SPORT

When asked to describe PT, the majority (65%) of professional basketball players in this study connected PT with post-injury rehabilitation. Post-injury rehabilitation was defined by the interviewer as, "any mention of an injury or source of discomfort to rehabilitate. Any factor contributing to recovery for the purpose of returning to game play". The following players described physical therapists’ role in recovery after an injury.

I think they help you recover from injury and you do the steps necessary to make sure that you’re able to carry on with regular life ... or in athletics being able to get back on the field or court or whatever you’re doing. (NBA #33)

I think of them as the person for rehab. Once you actually have an injury, I guess is what I think of physical therapist is doing. (WNBA #24)

I think a physical therapist works on whatever is injured or whatever you broke or injured, and they get it back up to speed and even stronger so you are able to perform and do whatever you were doing before you injured whatever it was. (G-League #5)

Several athletes described PT as only one part of their rehabilitation and that they followed the team physician’s or athletic trainer’s recommendations, as exemplified by this athlete’s comment, "Personally, [I go to PT] probably when the trainer recommends it." The following player described how PT was one of several team providers who contributed to her rehabilitation.

To kind of jumpstart the recovery rehabilitation process, and once I got to a certain point with the PT, and they would allow me to go where I need to go, then it would be to the next person." (WNBA #19)

Only one participant struggled with uncertainty and lack of knowledge on the role of a physical therapist. Without experience of a previous injury at the time of the interview, he was less knowledgeable on this topic. He provided more generalized statements about PT; however, his response still mentioned PT being a last resource following an injury.

What does a physical therapist do? I feel like this would be an easy question, but ... I don’t know. I’ve never ever been to one, to be honest with you, but if it really got to that point, I don’t know, I guess I can’t really answer that one. (G-League #16)

THEME 2: PHYSICAL THERAPISTS’ ROLE IN INJURY PREVENTION INCLUDED STRENGTHENING AND FLEXIBILITY EXERCISE AND INDIVIDUALIZED EDUCATIONAL APPROACHES

The vast majority of participants did not recognize a role for physical therapists in injury prevention. However, when probed, the athletes mentioned physical therapists’ ability to improve strength and flexibility (54.3%), provide individualized plans of care (42.9%), and education (42.9%). Prevention methods and assessments were consistently discussed during each interview, which ranked second to post-injury rehabilitation. While injury prevention was mentioned as a role of physical therapists, none of the participants admitted to using a physical therapist for this healthcare need unless it was part of a post-injury rehabilitation.

"I broke my ankle about two years ago. So I had to use a physical therapist because I was coming back and trying to get back ready to play. But once I was cleared I didn’t really use them ... So I’ll say during an injury or coming off an injury." (G-League #5)

If I have like a very serious injury or I have to gain strength back in a certain part of my body, so that’ll probably be like the only time I’ll use the physical therapist. (NBA #15)
Participants frequently mentioned that a physical therapist would provide exercise programs focused on their weaknesses. It was perceived that player education and physical assessments will improve a player’s outcome. Participants had positive comments regarding a physical therapist’s ability to provide education, which emphasized prevention. The following player described this individualized treatment plan.

Probably the most important thing is they give you a workout plan specifically to your needs, whatever your injury or whatever your prevention wants to be. They can give you a routine that can help you either solve your problem or prevent your problem. (WNBA #17)

Athletes believed injuries were caused by being ill-prepared (54.3%), overuse (45.7%), accidents (37.1%), lack of proper rest and recovery (34.3%), nutrition (25.7%), and improper biomechanics (20%). To prevent injuries, players reported they would strengthen (77.1%), stretch (54.3%), use therapeutic modalities (45.7%), maintain healthy behaviors (28.6%), and visit a healthcare provider (22.8%). A large majority of WNBA players mentioned playing for multiple leagues during a calendar year. After concluding the WNBA season, they would continue their career overseas, before returning to start the next season. The women believed their care is affected by the constant playing without a true offseason.

I don’t think we get the right treatment because each trainer wants to get us through the season without thinking about the one right after. So, I feel like the main thing is just people trying to find the quickest solution versus trying to find a solution that will help us long term. (WNBA #10)

Some athletes, however, reported the benefits of using a physical therapist for proactive or preventive care.

I think that more athletes can work with physical therapists before injury. I think for a long time it’s kind of been something that if you get injured, it’s a result to go see a physical therapist. But I like the thought of it being more proactive and working with them beforehand. (WNBA #24)

[Would see a PT] Usually only once I’ve injured something or if I’m coming off of an injury. But actually, well since this injury … I’m planning on continuing meeting up with a physical therapist throughout the season. Maybe not as vigorous as if I was still injured, but maybe once or twice a week or maybe once every couple of weeks just to continue doing stuff that will strengthen up my foot. But even other parts of my body so that way I can make sure that I’m doing all that I can to prevent future injury. (WNBA #12)

**THEME 3: TO PREVENT INJURIES, ATHLETES CHOSE A TEAM HEALTHCARE PROVIDER BASED ON TRUST AND THE PERSON’S EXPERTISE, AND THIS WAS MOST COMMONLY THE TEAM ATHLETIC TRAINER**

An overwhelming majority (82.8%) of study participants mentioned an athletic trainer as the healthcare provider to perform injury prevention, followed by strength coach (40%), physical therapist (14.3%), physician (8.6%), and chiropractor (5.7%). Reasoning for using these healthcare providers for injury prevention included expertise (62.9%), trust (40%), comfort (34.3%), treatment modalities (14.3%), and other factors (5.7%).

Expertise was operationally defined as “any discussion of knowledge or expertise in their field, which includes experience or education”. Study participants verbalized that they strived to have the best care during their prevention and rehabilitation of injuries. Since PT was associated with rehabilitation after injuries have occurred, the players discussed physical therapists as being the experts for that specific role. Athletic trainers (AT) and strength coaches were associated with expertise in preventing injuries from happening based on their perceived knowledge and skills.

Just because they [AT] usually have the best expertise on how the body works, and symptoms, and things like that. Usually, they’re the best at knowing those things. (NBA #11)

That’s their field of expertise. The trainer, that’s what he studies, so he just... That’s really what he does, is just tries to prevent an injury from happening. (G-League #22)

A trusting relationship with the team provider was a positive factor that was repeated throughout many interviews, and exemplified with the following player’s comment:

Especially in this league, … try to find people they trust. Everybody knows it’s a business, but you got to find people that you trust, because you don’t want your information going everywhere. (NBA #9)

Other factors associated with trust included the close relationships with and confidence in the provider, as well as previous history between the player and provider, which made them feel comfortable in their care. The players with providers who were with them from the start had more detailed reviews of their care. In some instances, these clinicians would be retained for care outside of team responsibilities, as noted by the following two athletes.

Just because of the relationship I had with him [strength coach]. I know him for seven, eight years now, been working with them for six or seven of those years. I’m just comfortable with him. (NBA #6)

I have someone who’s worked with me since I was 16 after my ankle injuries. No matter if I’m in Europe or in WNBA, I still use his [strength coach] programs because I know that he knows my body best and I just trust him the most. (WNBA #10)

As mentioned earlier, feeling comfortable with the team provider was identified as another key component in injury prevention, and time together helped build these feelings of trust and comfort.

We spend the most time with them [AT], too, so we have a good rapport and I’m comfortable speaking with them about stuff. (NBA #30)
DISCUSSION

This is the first study to explore the perspectives of professional basketball players' knowledge and use of PT, specific to injury prevention methods. Based on the responses of the participants, our results revealed that professional athletes valued general PT services to recover from a serious injury; however, the role of physical therapists in injury prevention was perceived to be limited mostly to post-injury rehabilitation. Once recovered, employment of the physical therapist services was rare. Athletes emphasized the benefit of PT, but participants highlighted the preference to use their individual athletic trainers for prevention of injury due to perceived expertise and trust. When discussing the use of PT, the majority of athletes were unsure if their team had a physical therapist on staff although 49% of all teams had one based on the results of a general search online.

In discussions about the use of PT services, it may be beneficial for athletes to be educated on the various roles physical therapists may perform beyond post injury. Moreover, it was apparent from the data that athletic trainers had significantly greater contact with the athlete, which may play a key role in promoting communication between members of the sports medicine team, the coach, and athlete.19 High levels of trust and comfort were conveyed to the team athletic trainer due to constant exposure and access to this member of the healthcare team. A possible strategy for expansion of the physical therapists' role may begin with improved interdisciplinary communication. Specifically, increased presence of physical therapists within the professional team organization and interaction with team players, staff and leadership may build trust and increase understanding and utilization of PT services.

Previous rehabilitation literature has provided clinicians with a vast library of resources regarding the common injuries sustained with each sport. Prior to this current study, there was a lack of research highlighting the athletes' knowledge and beliefs about the psychological or functional risk factors for potential injuries. The players' interviews strengthened previous research by attesting that risk factors, such as overuse injuries and highly demanding schedules,20 can contribute to future injuries. Moreover, psychological, physical, and behavioral beliefs of the athlete can influence injury prevention.10,11 These beliefs may affect the use of PT due to the perceived negative connotation for injuries.

Strategies to increase utilization of PT within professional sports include increasing time present in the training room with the purpose to increase collaboration with the team staff. Multiple study participants clarified their perspective of PT to be influenced by the lack of presence in the training room. This finding aligns with previous research, which stated main themes perceived to influence patient-therapist interactions included interpersonal skills, practical skills, individualized patient-centered care, and environmental factors.21 An example of an effective strategy to build positive relationships with the players include taking time to learn their backgrounds and personalities, which enabled players to view their relationship with the clinician as positive.22 Moreover, the same study confirmed that participants reported a positive recovery when they were actively involved in the rehabilitation process. It was viewed as beneficial to increase their knowledge about the injury, overall increasing the participants' sense of control.22

In a recent editorial,23 Strack et al. cited the emergence of the Doctor of Physical Therapy degree, direct access in physical therapist practice and sport specialization as factors that have provided new opportunities for physical therapists, and specifically sport physical therapists, on professional sports medicine staffs. While the prospects for sport physical therapists to work at the professional level have clearly improved, it is possible that athletes may lack understanding of their role in their healthcare and overall injury prevention. With sports physical therapists taking on leadership positions within the healthcare team,23 this may aid in rectifying this apparent lack of understanding.

Research has lacked the viewpoint of the athlete, which has restricted the holistic treatment physical therapists can provide to their players. This study identifies the potential beliefs of the players and provides an opportunity for the therapist to address them. In the future, physical therapists can collaborate with the training staff and athletes to provide continuous education, promote autonomy, and work towards a standardization of care. As established by the participants, the physical therapist needs to be visible and accessible to build trust for a lasting relationship. Physical therapists working with elite athletes require thoughtful, deliberate strategies for creating a niche within professional sports.

LIMITATIONS

The study sample represented only a small sample of the total population of professional basketball players in the United States and therefore may not represent the views of all professional players. However, saturation was reached after 35 participant interviews, supporting the major themes identified in this study.

CONCLUSION

Previous research has characterized the opinions of physical therapists, physicians, and athletic trainers on their roles when working with elite athletes, however the perceptions of the role of physical therapists in professional sports by the athletes themselves had not been studied. Based on the viewpoint of the athletes in this study, physical therapists were employed primarily for post-injury and return-to-sport rehabilitation. Results of this study suggested that professional basketball players engaged with...
athletic trainers for injury prevention because of their level of trust and comfort with these healthcare providers. The organizational structure of healthcare in professional basketball may promote closer professional relationships with athletic trainers while limiting those with physical therapists. The result is that elite athletes may miss out on treatment specific to the PT profession. To address this, increased education and the expansion of physical therapists’ role on interprofessional healthcare teams may allow for more comprehensive care. Expansion of the physical therapist’s role on interprofessional healthcare teams may allow for more comprehensive and holistic care and potentially diminish injury rates among basketball players.

ACKNOWLEDGEMENTS

The authors would like to thank the professional basketball players who participated in this study.

CONFLICT OF INTEREST

No potential conflict of interest declared

Submitted: April 04, 2023 CDT, Accepted: August 27, 2023 CDT
REFERENCES


Appendix 1

Higher Levels of Income and Education are Associated with More Specialized Sport Participation Behaviors: Results from a Representative Sample of Youth Sport Parents from the United States

Eric G Post, Matthew J. Rivera, Darleesa Doss, Lindsey E. Eberman

Department of Applied Medicine and Rehabilitation, Indiana State University, College for Public Health and Social Justice, Saint Louis University

Keywords: youth sport, parent, socioeconomic status

https://doi.org/10.26603/001c.86127

Original Research

Background
While previous studies have examined the impact of family socioeconomic characteristics on a child’s sport specialization behaviors, this research has been limited to affluent communities with limited sociodemographic diversity.

Hypothesis/Purpose
The purpose of this study was to examine associations of parent income and education with child sport specialization behaviors among a nationally representative sample of youth sport parents in the United States.

Study Design
Cross-sectional.

Methods
Parents of youth athletes in the United States (n=256, age: 39.2±8.1 years, 57.2% female) were recruited to complete an online questionnaire by Qualtrics Online Samples (Qualtrics, Provo, UT) using a combination of actively managed, double-opt-in market research panels. The questionnaire used for this study consisted of: 1) parent demographics (including parent age, race/ethnicity, biological sex, gender identity, household income, and educational status), and 2) child sport participation characteristics and sport specialization behaviors.

Results
Parents who reported an annual household income of $75,001 or more were more likely than parents making less than $75,000 to report that their child participated on an organized club team (OR [95%CI]: 1.94 [1.15-3.27]), participated on multiple organized teams at the same time (OR [95%CI]: 1.85 [1.10-3.11]), or specialized in a single sport (OR [95%CI]: 2.45 [1.45-4.14]). Parents who reported receiving a Bachelor’s degree or higher were more likely than parents who did not to report that their child participated on an organized club team (OR [95%CI]: 3.04 [1.78-5.18]), participated on multiple organized teams at the same time (OR [95%CI]: 2.42 [1.43-4.10]), or specialized in a single sport (OR [95%CI]: 1.94 [1.15-3.26]).

Conclusions
These results suggest that in the modern youth sport culture, family resources may serve as a major determining factor in the type of experiences available for a youth athlete.

Corresponding Author:
Eric G. Post, PhD, ATC, 567 N 5th Street, Indiana State University, Terre Haute, IN, USA, 47809
eric.post@indstate.edu
812-237-8336.
Level of Evidence

INTRODUCTION

Participation in youth sports has a wide range of benefits for a child, including increased physical activity, the development of motor and social skills, and most importantly, having fun and making friends. Increasingly, youth sports are also viewed as an avenue for obtaining a college scholarship, which has led to the increasing professionalization of youth sports and the push towards increasingly specialized youth sport behaviors. For example, a recent survey found that approximately one-in-three Little League baseball players between the ages of 7 and 12 have received private coaching in the previous year in an effort to improve their skills. Another survey found that over half of youth basketball athletes had traveled overnight at least once a month in the past year for basketball competitions or showcases. As a result of this shift towards highly professionalized youth sports, the ability of a child to participate is increasingly not only a matter of a child's interests, but also the ability of the child's family to access these environments.

Several previous studies have examined the impact of family socioeconomic characteristics on a child's sport specialization behaviors. One survey of parents of club athletes in Wisconsin found that as the income category of a household increased, their children were more likely to specialize in a single sport or played a sport year-round. A similar study of high school baseball parents in southern California reported that children from high-income families were more likely to participate on a club team, specialize in baseball, and play baseball year-round. However, these previous studies were limited due to the non-representativeness of their study populations, with the majority of participants in each study consisting of white, highly-educated, and affluent individuals. To the authors' knowledge, only one study to date has examined the impact of family socioeconomic characteristics on sport specialization behaviors in a sample of parents that was nationally-representative with regard to parent race/ethnicity. This study found that the children of high-income parents were more likely to participate in a variety of highly specialized behaviors. However, this study only surveyed parents of youth basketball athletes, limiting the ability to draw more general conclusions about youth sport parents in the United States.

Therefore, the purpose of this paper was to examine associations of parent income and education with child sport specialization behaviors among a nationally representative sample of youth sport parents. It was hypothesized that parents with higher household incomes or levels of educational attainment would be more likely to report that their children participated in a variety of specialized sport behaviors.

MATERIALS AND METHODS

PARTICIPANTS

This cross-sectional study was declared exempt by the Institutional Review Board at Indiana State University. A national sample of youth sport parents from across the United States completed an online questionnaire administered via Qualtrics Online Samples (Qualtrics, Provo, UT). Qualtrics Online Samples recruited participants for this study using a combination of actively managed, double-opt-in market research panels. The "opt-in for market research" process requires respondents to submit an initial registration form requesting to participate in market research studies. These respondents are used by Qualtrics for corporate and academic research only. Potential respondents build their profile from a standardized list of questions. The panels then use the profiles to randomly select respondents for surveys where the respondents are likely to qualify. Potential respondents were sent an e-mail invitation from Qualtrics Online Samples informing them that the survey was for academic research purposes only and how long the survey was expected to take. To avoid self-selection bias, the e-mail invitation did not include specific details about the contents of the survey. Within the e-mail invitation was a link to the questionnaire, which was completed through Qualtrics (Qualtrics). Participants first completed screening questions that determined whether they qualified for the study.

Participants were recruited via Qualtrics Online Samples due to the improved ability to recruit racial and ethnic minorities compared to traditional survey recruitment methods that typically results in largely White/Caucasian samples. The sample recruited was nationally-representative with regards to race/ethnicity in the United States (White/Caucasian 66.1%; African American/Black 12.3%; Hispanic/Latino of any race 11.0%; Asian 5.5%; 2+ races 2.5%; Native American/Alaskan Native 1.7%, Other 0.9%).

To qualify for this study, participants had to be a parent of a child between 7 and 17 years old and the child had to have participated on an organized youth sports team in the previous year. If participants qualified, they were presented with an information page describing the study, and then proceeded to the rest of the questionnaire. Data collection took place over a one-week period in May 2021.

QUESTIONNAIRE

The questionnaire for this study was developed by a panel of content-area experts as part of a more extensive mixed-methods study focusing on youth sport participation behaviors during and after the COVID-19 pandemic. The specific sections of the questionnaire used for this study consisted of: 1) parent demographics (including parent age, race/ethnicity, biological sex, gender identity, household income, and educational status), and 2) child sport participation characteristics and sport specialization behaviors.
The parent education categories consisted of: Less than High School, High School diploma or GED, Some college, Associate or two-year college degree, Bachelor or 4-year college degree, Professional degree, and Doctorate degree. The parent household income categories were measured in United States dollars (USD) and consisted of: Less than $35,000, $35,001 to $50,000, $50,001 to $75,000, $75,001 to $100,000, $100,001 to $150,000, and more than $150,000. These categories were dichotomized as described in the statistical analysis section for final analysis.

In section two of the questionnaire, parents were asked how many months in the previous year their child participated in organized sports, how much money they had spent on their children’s sport participation in the previous year, and whether their children participated on school, recreational, or club teams in the previous year. For sport specialization behaviors, parents were asked whether their child participated on multiple different sports teams at the same time, received private coaching outside of their organized teams, or traveled overnight at least once per month for sport competitions during the past year. Parents were asked whether their child met the definition of a specialized athlete (“participation in a single sport for more than 8 months of the year and at the exclusion of playing other sports”). Finally, parents were asked whether their child had suffered an injury in the previous 12 months while playing sports that required them to seek medical care.

Prior to collecting data, the questionnaire was pilot tested in a sample of eleven youth sport parents who met the study inclusion criteria to establish face and construct validity and internal consistency. An acceptable level of internal consistency was found, with a Cronbach’s Alpha value of 0.805 (minimum alpha level of 0.80 needed).

**RESULTS**

Participant demographic data is presented in Table 1. A total of 236 youth sport parents (mean age: 39.2±8.1 years old, 57.2% female) fully completed the questionnaire and were included in the analysis. Just over half (N=122, 51.7%) of participants reported a bachelor’s degree or higher level of educational attainment, while just under half (N=117, 49.6%) of participants reported an annual household income of $75,001 or more. The sport participation characteristics of participants’ children over the previous 12 months is presented in Table 2. Parents reported spending a median of $1,548 [IQR: $574-$3,754] on their children’s sport participation in the previous 12 months. Just under half (N=111, 47.0%) of all participants reported that their child specialized in a single sport, with a similar proportion of parents (N=107, 45.3%) reporting that their child participated on multiple organized teams at the same time. Slightly fewer parents (N=100, 42.4%) reported that their child received private coaching for their sport outside of their organized team or traveled overnight for their sport at least once in the previous year (N=86, 36.4%). Approximately one-fourth of participants (N=62, 26.3%) reported that their child suffered an injury while playing sports in the previous 12 months that required them to seek medical care.

Differences in child sport participation based on parent income are provided in Table 3. Parents who reported an annual household income of $75,001 or more were more likely than parents making less than $75,000 to report that their child participated on an organized club team (OR [95%CI]: 1.94 [1.15-3.27]), participated on multiple different organized sports teams at the same time (OR [95%CI]: 1.85 [1.10-3.11]), or specialized in a single sport (OR [95%CI]: 2.45 [1.45-4.14]). There were no significant differences based on parent income category in the likelihood of a child receiving private coaching (p=0.07), traveling overnight for their sport at least once (p=0.44), or sustaining an injury that required medical care (p=0.05). Parents with a household income of $75,001 or more reported spending more money on their child’s sport in the previous year compared to parents making less than $75,000 (median [IQR]: $2,115 [$984-$5,008] vs. $1,050 [$407-$2,640], p<0.001) (Figure 1).

Differences in child sport participation based on parent education category are provided in Table 4. Similar to the findings for parent income, parents who reported receiving a bachelor’s degree or higher were more likely than parents who did not to report that their child participated on an organized club team (OR [95%CI]: 3.04 [1.78-5.18]), participated on multiple organized teams at the same time (OR [95%CI]: 2.42 [1.45-4.10]), or specialized in a single sport (OR [95%CI]: 1.94 [1.15-3.26]). Additionally, parents who reported receiving a bachelor’s degree or higher were also more likely to report that their child received private coaching outside of their organized team (OR [95%CI]: 1.92 [1.14-3.25]) or suffered a sports injury that required them to seek medical care (OR [95%CI]: 2.04 [1.12-3.71]). There were no significant differences based on parent education.
Table 1. Parent Demographics (N=256)

<table>
<thead>
<tr>
<th>Variable</th>
<th>N (%)</th>
<th>Mean (SD), or Median [IQR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent Age</td>
<td>39.2</td>
<td>(8.1)</td>
</tr>
<tr>
<td>Parent Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>101 (42.8%)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>134 (56.8%)</td>
<td></td>
</tr>
<tr>
<td>Gender non-conforming</td>
<td>1 (0.4%)</td>
<td></td>
</tr>
<tr>
<td>Parent Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>101 (42.8%)</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>135 (57.2%)</td>
<td></td>
</tr>
<tr>
<td>Parent Race/Ethnicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>13 (5.5%)</td>
<td></td>
</tr>
<tr>
<td>African American/Black</td>
<td>29 (12.3%)</td>
<td></td>
</tr>
<tr>
<td>Native American/Alaskan Native</td>
<td>4 (1.7%)</td>
<td></td>
</tr>
<tr>
<td>Hispanic/Latino of any race</td>
<td>26 (11.0%)</td>
<td></td>
</tr>
<tr>
<td>Native Hawaiian/other Pacific Islander</td>
<td>0 (0.0%)</td>
<td></td>
</tr>
<tr>
<td>White/Caucasian</td>
<td>156 (66.1%)</td>
<td></td>
</tr>
<tr>
<td>Two or more races</td>
<td>6 (2.5%)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>2 (0.9%)</td>
<td></td>
</tr>
<tr>
<td>Parent Education</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than High School</td>
<td>3 (1.3%)</td>
<td></td>
</tr>
<tr>
<td>High school diploma or GED</td>
<td>36 (15.3%)</td>
<td></td>
</tr>
<tr>
<td>Some college</td>
<td>45 (19.1%)</td>
<td></td>
</tr>
<tr>
<td>Associate or 2-year college degree</td>
<td>30 (12.7%)</td>
<td></td>
</tr>
<tr>
<td>Bachelor or 4-year college degree</td>
<td>67 (28.4%)</td>
<td></td>
</tr>
<tr>
<td>Professional degree</td>
<td>50 (21.2%)</td>
<td></td>
</tr>
<tr>
<td>Doctorate degree</td>
<td>5 (2.1%)</td>
<td></td>
</tr>
<tr>
<td>Parent Household Income Category (USD)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than $35,000</td>
<td>33 (14.0%)</td>
<td></td>
</tr>
<tr>
<td>$35,001 to $50,000</td>
<td>45 (19.1%)</td>
<td></td>
</tr>
<tr>
<td>$50,001 to $75,000</td>
<td>41 (17.4%)</td>
<td></td>
</tr>
<tr>
<td>$75,001 to $100,000</td>
<td>42 (17.8%)</td>
<td></td>
</tr>
<tr>
<td>$100,001 to $150,000</td>
<td>43 (18.2%)</td>
<td></td>
</tr>
<tr>
<td>More than $150,000</td>
<td>32 (13.6%)</td>
<td></td>
</tr>
</tbody>
</table>

category in the likelihood of a child traveling overnight for their sport at least once in the previous 12 months (p=0.17). Parents with a reported education level of a bachelor’s degree or above reported spending more money on their child’s sport in the previous year compared to parents with less than a bachelor’s degree (median [IQR]: $2,108 [$984–$5,256] vs. $1,070 [$89–$2,545], p<0.001) (Figure 2).

DISCUSSION

To the authors’ knowledge, this is the first study to examine associations of parent income and education with child sport specialization behaviors among a sample of various youth sport parents that is nationally-representative with regard to race/ethnicity. Parents in the higher income and education categories were more likely to report that their child specialized in a single sport, participated on a club team, or participated on multiple different sports teams at the same time. Additionally, parents in the higher educational attainment category were more likely to report a child receiving private coaching for their sport or suffering an injury in sport that required them to seek medical care.

These findings are in general agreement with several previous studies of youth sport parents. Surveys of parents of club sport athletes, Little League and high school baseball athletes, and youth basketball athletes have all reported that parents who report higher family incomes or greater educational attainment are more likely to have a child who specializes in a single sport or participates in a wide variety of sport specialization behaviors, such as participation on a club team or receiving instruction from a private coach.²⁻⁵ Unsurprisingly, several of these studies
also reported that parents in the higher-income categories also reported spending significantly more money on their child’s sport participation compared to parents in the lower-income categories.\textsuperscript{2,3,5} Similarly, we found that parents in the higher income or education categories spent approximately twice as much money on their children’s sport activities compared to parents in the lower-income or education categories.

The current findings, and the results of the previous studies cited above, are part of a larger trend towards disparities in access and resources among modern families. For example, Doeke et al. reported that in 1970, there were no differences in the amount of time parents spent with their child based on parent education, but by 2012 parents with higher levels of education reported spending three more hours with their children per day compared to parents with less educational attainment.\textsuperscript{9} Additionally, the amount of time that high-education parents spend assisting with their child’s schoolwork has increased over this time period from three hours per week to eight hours per week.\textsuperscript{9} The authors theorize that these differences are not truly due to a lack of educational attainment among these parents, but likely result from a lack of financial resources and time due to the need to be working beyond full-time or working multiple jobs with variable schedules compared to parents with higher levels of education.\textsuperscript{9} Similarly, Ramey et al. reported that from 1995 to 2008, parents with higher education have re-allocated over nine hours per week from independent child leisure-time towards direct childcare, compared to a re-allocation of four hours per week among parents with lower educational attainment.\textsuperscript{10} The authors report that this shift has occurred alongside an environment of increasingly competitive college admissions, which the authors describe as the “rug-rat race”.\textsuperscript{10} In an environment of increasing economic uncertainty and with increasing material returns to college education, Wilkinson and Pickett suggest that parents with sufficient resources may respond to the anxieties caused by this environment by becoming increasingly involved and invested in their child’s success.\textsuperscript{11} In fact, a recent meta-analysis reported that parent expectations of their children have increased over the past 30 years, and these changes in parent expectations are larger in countries with greater income inequality.\textsuperscript{12}

The results of the current study also make sense within the lens of the so-called “rug-rat race” towards college admissions. Youth sport success is increasingly viewed as an

<table>
<thead>
<tr>
<th>Variable</th>
<th>N (%)</th>
<th>Mean (SD), or Median [IQR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months of Organized Sport Participation</td>
<td>3 [1-6]</td>
<td></td>
</tr>
<tr>
<td>Money Spent on Children’s Sports in Past 12 Months (USD)</td>
<td>1,548 [578-3,754]</td>
<td></td>
</tr>
<tr>
<td>Any children participate on organized school team?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>180 (76.3%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>56 (23.7%)</td>
<td></td>
</tr>
<tr>
<td>Any children participate on community recreational team?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>148 (62.7%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>88 (37.3%)</td>
<td></td>
</tr>
<tr>
<td>Any children participate on organized club team?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>132 (55.9%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>104 (44.1%)</td>
<td></td>
</tr>
<tr>
<td>Any children participate on multiple organized teams at same time?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>107 (45.3%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>129 (54.7%)</td>
<td></td>
</tr>
<tr>
<td>Any children receive private coaching outside of organized teams?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>100 (42.4%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>136 (57.6%)</td>
<td></td>
</tr>
<tr>
<td>Any children travel overnight for sport at least once?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>86 (36.4%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>150 (63.6%)</td>
<td></td>
</tr>
<tr>
<td>Any children participate in single sport for more than 8 months at the exclusion of other sports?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>111 (47.0%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>125 (53.0%)</td>
<td></td>
</tr>
<tr>
<td>Any children suffer an injury while playing sports that required them to seek medical care?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>62 (26.3%)</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>174 (73.7%)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Differences in child sport participation based on parent income category.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Less than $75,000</th>
<th>$75,001 or more</th>
<th>X²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any children participate on organized club team?</td>
<td></td>
<td></td>
<td>5.6</td>
<td>0.02</td>
</tr>
<tr>
<td>Yes</td>
<td>57 (47.9%)</td>
<td>75 (64.1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>62 (52.1%)</td>
<td>42 (35.9%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children participate on multiple organized teams at same time?</td>
<td></td>
<td></td>
<td>4.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Yes</td>
<td>45 (37.8%)</td>
<td>62 (53.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>74 (62.2%)</td>
<td>55 (47.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children receive private coaching outside of organized teams?</td>
<td></td>
<td></td>
<td>3.3</td>
<td>0.07</td>
</tr>
<tr>
<td>Yes</td>
<td>43 (36.1%)</td>
<td>57 (48.7%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>76 (63.9%)</td>
<td>60 (51.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children travel overnight for sport at least once?</td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.44</td>
</tr>
<tr>
<td>Yes</td>
<td>40 (33.6%)</td>
<td>46 (39.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>79 (66.4%)</td>
<td>71 (60.7%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children specialized in single sport?</td>
<td></td>
<td></td>
<td>10.6</td>
<td>0.001</td>
</tr>
<tr>
<td>Yes</td>
<td>43 (36.1%)</td>
<td>68 (58.1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>76 (63.9%)</td>
<td>49 (41.9%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children suffer an injury while playing sports that required them to seek medical care?</td>
<td></td>
<td></td>
<td>4.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Yes</td>
<td>24 (20.2%)</td>
<td>38 (32.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>95 (79.8%)</td>
<td>79 (67.5%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

avenue for college admissions or scholarships, and early sport specialization is widely believed among parents to increase the chances of their child improving at their sport and eventually receiving a college scholarship. However, the increasing time and financial resources needed to support a child’s participation in the highly specialized modern youth sport culture serves as a significant barrier to many families. In series of qualitative interviews with parents from low socioeconomic status families, Hernandez et al. reported that parents overwhelmingly described wanting their children to participate in sport both due to the benefits for their child’s health, but also because sport participation developed skills that aligned with their family’s values, such as teamwork, discipline, hard work, and socialization. Several of these parents also expressed a belief in the ability of youth sports to help "break the socioeconomic cycle" for their families, by developing skills that may lead to future opportunities or help their children stay out of trouble. However, these parents also reported that the increasing cost and time burden of youth sports, as well as the current youth sport culture of specialization and participation on selective club teams were significant barriers for their child’s sport participation.

A novel aspect of the current findings is the recruitment of a sample of youth sport parents that is nationally-representative with regard to the parent’s race/ethnicity. While this study focused specifically on the associations of parent income or education with child sport participation and specialization behaviors, it is also important to further understand the influence of various cultural backgrounds on participation in the current youth sport culture. For example, in a qualitative investigation of Hispanic/Latinx parent-child dyads, the participants reported a variety of strategies unique to their cultural background that they used to navigate the youth sport environment. These included selecting organizations that aligned with their cultural values and relying on extended family members as resources for navigating youth sports. However, the participants also reported negative consequences due to the interaction of their cultural background and the youth sport environment, such as not feeling like they belong in certain settings or dropping out from sport participation altogether. Therefore, it is important to consider the multi-dimensional nature of socioeconomic status, as there are existing disparities in education and income based on race/ethnicity, which in turn contribute and intersect with the disparities in access to youth sports that have been demonstrated in this study and others.

This study has several important limitations to consider. First, the sample was limited to 236 parents, which resulted in small numbers of parents in certain race/ethnicity categories, despite recruiting a sample that was proportionally representative regarding race/ethnicity. Second, because the authors chose to recruit the sample to be nationally representative for race/ethnicity, our sample is not necessarily nationally-representative regarding parent education or income categories. This decision was made due to the limited research in samples of parents that are diverse regarding race/ethnicity, and the difficulty/cost required to recruit samples that are nationally representative across
multiple demographic categories. However, as a result there were not sufficient counts within each income or education categories and dichotomized these variables instead to meet the assumptions for all our Chi-square analyses. Future research in this area should aim to recruit samples of participants that are nationally-representative not only in race/ethnicity, but also in household income and educational attainment, in order to perform more robust statistical analysis that is able to determine associations across more specific categories of income and education. Due to the potential overlap between education and income, future research should also attempt to isolate the potential effects of each of these variables. Finally, we chose to define specialization as a dichotomous (yes/no) variable using the most recent consensus definition of sport specialization,\textsuperscript{16} as opposed to using other measures that have been used in this area of the literature, such as the 3-point scale.\textsuperscript{17} As a result, it is difficult to make comparisons between the relatively high prevalence of specialization (47%) observed in the current study with previous research. The on-going difficulties in scientific definitions of early sport specialization highlights the need for development of a valid and reliable measure of specialization in youth sports.\textsuperscript{18}

CONCLUSION

In a nationally representative sample of youth sport parents, it was found that increased parent income and education were both associated with their children participating in a variety of specialized sport behaviors, such as specializing in a single sport or participating on multiple teams at the same time. These results suggest that in the modern youth sport culture, family resources may serve as a major determining factor in the type of experiences available for a youth athlete. As a result, many youth are currently excluded from participating in sports as a result of the modern year-round, specialized youth sport culture.

ACKNOWLEDGEMENTS

This study was funded by an internal grant from the University Research Committee at Indiana State University.

DISCLOSURES

The authors have no conflicts or disclosures to report.

Submitted: January 12, 2023 CDT, Accepted: July 16, 2023 CDT

Figure 1. Comparison of money spent in past year on child’s sport activities between parent income categories. Presented as a notched box plot, with box representing interquartile range (IQR), whiskers representing range of 1.5 times the IQR, line indicating median, notch displaying 95% confidence interval of the median, and individual data points for each parent.
Table 4. Differences in child sport participation based on parent education category.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Less than Bachelor’s degree</th>
<th>Bachelor’s degree or above</th>
<th>X²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any children participate on organized club team?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>48 (42.1%)</td>
<td>84 (68.9%)</td>
<td>16.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>No</td>
<td>66 (57.9%)</td>
<td>38 (31.1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children participate on multiple organized teams at same time?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>39 (34.2%)</td>
<td>68 (55.7%)</td>
<td>10.2</td>
<td>0.001</td>
</tr>
<tr>
<td>No</td>
<td>75 (65.8%)</td>
<td>54 (44.3%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children receive private coaching outside of organized teams?</td>
<td></td>
<td></td>
<td>5.4</td>
<td>0.02</td>
</tr>
<tr>
<td>Yes</td>
<td>39 (34.2%)</td>
<td>61 (50.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>75 (65.8%)</td>
<td>61 (50.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children travel overnight for sport at least once?</td>
<td></td>
<td></td>
<td>1.9</td>
<td>0.17</td>
</tr>
<tr>
<td>Yes</td>
<td>36 (31.6%)</td>
<td>50 (41.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>78 (68.4%)</td>
<td>72 (59.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children specialized in single sport?</td>
<td></td>
<td></td>
<td>5.7</td>
<td>0.02</td>
</tr>
<tr>
<td>Yes</td>
<td>44 (38.6%)</td>
<td>67 (54.9%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>70 (61.4%)</td>
<td>55 (45.1%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Any children suffer an injury while playing sports that required them to seek medical care?</td>
<td></td>
<td></td>
<td>4.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Yes</td>
<td>22 (19.3%)</td>
<td>40 (32.8%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>92 (80.7%)</td>
<td>82 (67.2%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Comparison of money spent in past year on child’s basketball activities between parent education categories.

Presented as a notched box plot, with box representing interquartile range (IQR), whiskers representing range of 1.5 times the IQR, line indicating median, notch displaying 95% confidence interval of the median, and individual data points for each parent.
REFERENCES


Clinical Commentary/Current Concept Review

The Use of Elastic Resistance Bands to Reduce Dynamic Knee Valgus in Squat-Based Movements: A Narrative Review

Davis A Forman, Shahab Alizadeh, Duane C Button, Michael WR Holmes

1 Department of Kinesiology, Trent University, 2 School of Human Kinetics and Recreation, Memorial University of Newfoundland, 3 Faculty of Applied Health Sciences, Brock University

Keywords: Electromyography, muscle activity, kinematics, knee alignment, lower limb

International Journal of Sports Physical Therapy

An elastic band wrapped around the distal thighs has recently been proposed as a method for reducing dynamic knee valgus (medial movement of the knee joint in the frontal/coronal plane) while performing squats. The rationale behind this technique is that, by using an external force to pull the knees into further knee valgus, the band both exaggerates the pre-existing movement and provides additional local proprioceptive input, cueing individuals to adjust their knee alignment. If these mechanisms are true, then elastic bands might indeed reduce dynamic knee valgus, which could be promising for use in injury prevention as excessive knee valgus may be associated with a greater risk of sustaining an ACL rupture and/or other knee injuries. Due to this possibility, certain athletic populations have already adopted the use of elastic bands for training and/or rehab, despite a limited number of studies showing beneficial findings. The purpose of this narrative review is to examine current literature that has assessed lower limb muscle activity and/or lower limb kinematics performance on squat-based movements with or without an elastic band(s). Importantly, this paper will also discuss the key limitations that exist in this area, propose suggestions for future research directions, and provide recommendations for training implementations.

Level of Evidence

5

INTRODUCTION

When performing physical activities that include some element of a squat movement, such as barbell squats, deadlifts, or lunges, conventional wisdom dictates that the knee should remain aligned with the hips, ankles, and feet. That is, the knees should make minimal medial or lateral movement in either the descent or ascent phase of the exercise. However, medial displacement of the knee in the frontal plane, known interchangeably as medial knee collapse or knee valgus, has been historically considered one of the most common movement faults when performing squat-based exercises. This is potentially a problem for long-term knee health; considerable evidence has shown that greater knee valgus increases the risk of suffering a knee injury, namely anterior cruciate ligament (ACL) ruptures.1-5 Due to this risk, trainers, clinicians, and researchers have been motivated to find effective ways of correcting this movement pattern when it presents.6

It has been proposed that the use of an elastic band wrapped around the distal thighs might be such a method.5,6 It was argued that, by pushing the knees into further medial knee collapse (valgus), and providing the individual with enhanced proprioceptive input at the distal thigh, an elastic band might encourage greater muscle activation of the hip external rotators, which in turn assist in returning the knees back into a more neutral alignment. An elastic band would also hold the distinct advantage over other corrective options in that minimal instruction or feedback would be needed from a trainer or clinician. If the trainee is responding to the elastic band, and pushing their knees

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*Corresponding Author:
Davis A. Forman, PhD
Assistant Professor
Department of Kinesiology
1600 W Bank Dr, Peterborough, ON K9L 0G2
Phone: 705-748-1011 x6259
Email: davisforman@trentu.ca
outwards against the external force, individuals could theoretically make corrective improvements in their technique with no additional supervision.

A number of investigations have reported seemingly conflicting findings on the usefulness of elastic bands during squat training, making it difficult to propose best practices for exercise prescription. On one hand, elastic bands wrapped around the thighs have become common within the fitness/strength training community in recent years for their perceived benefits, despite a lack of scientific findings showing clear and promising results. On the other hand, certain members of the research community have opposed the use of elastic bands in correcting medial knee collapse,\(^{9,10}\) given that some findings show elastic bands might actually increase knee valgus while performing squat-based movements.\(^{7-9,11,12}\) For example, Reece and colleagues\(^{9(p1)}\) recently claimed, “Squatting with resistance bands is likely to increase the risk of knee injury. Coaches and clinicians who already implement this technique are advised to remove resistance band squats from training and rehabilitation programmes,” which is also unsupported (at least without considerable context) by current research.

Thus, the purpose of this narrative review is to examine current literature that has assessed lower limb muscle activity and/or lower limb kinematics performance on squat-based movements with or without an elastic band(s). The risks of medial knee collapse will be briefly discussed, as will the rationale for employing elastic bands as a corrective intervention. Most of this review’s attention will be directed to those studies which have directly examined the influence that elastic bands have on the lower limbs while performing squat-based movements, focusing primarily on measures of lower limb muscle activity and kinematics and the possible benefits and risks that utilizing elastic bands might have. Finally, recommendations for trainers/clinicians regarding elastic band usage and suggestions for future research directions will be discussed.

THE PROBLEM: DYNAMIC MEDIAL KNEE COLLAPSE

Dynamic medial knee collapse (knee valgus) occurs when an individual’s knee(s) move towards their body’s mid-line in the frontal plane\(^{13-15}\) (Figure 1B). In such an event, the knees are no longer aligned with the hips, ankles, and feet. This can place increased compression loads on the lateral compartment of the knee, and increased distraction loads on the medial compartment of the knee\(^{4,5,16}\) which may increase the risk of developing lower extremity injuries, including anterior cruciate ligament (ACL) ruptures\(^{2,17}\), patellofemoral pain\(^{18-20}\), knee osteoarthritis\(^{21}\), and knee cartilage and meniscus damage.\(^{14,22}\) For example, in a study that pre-screened 205 female athletes ahead of their competitive season by quantifying knee valgus angles while performing drop jumps, those who sustained ACL ruptures exhibited significantly larger knee valgus angles than those who were uninjured.\(^{2}\) Research has also demonstrated that preventative training measures, aimed at reducing knee valgus moments in individuals who exhibit poor knee alignment, can lower the risk of an ACL injury.\(^{1,23-25}\) Collectively, this research has led to the notion that knee abduction is an undesirable movement pattern and should be corrected if observed.\(^{5,26}\)

Conversely, there is some evidence illustrating that medial knee collapse may not be a risk factor for knee injuries. Regarding ACL injuries specifically, Cronström and colleagues\(^{27}\) performed a meta-analysis of longitudinal studies that had performed various baseline knee kinematic and/or kinetic assessments during weight-bearing activities; injury metrics were collected from participants at a later date. Contrary to current clinical opinions, no kinematic or kinetic measure accurately predicted future ACL injury.\(^{27}\) However, the authors point out that this may in fact be the result of reduced prevalence of medial knee collapse in today’s young athletic populations. Following the work of Hewett and colleagues,\(^{2}\) in addition to earlier findings on cadaver knees that examined valgus torques on ACL loading,\(^{28-30}\) preventative training measures were rapidly adopted by sporting organizations\(^{3,31}\) and incorporated into clinical guidelines,\(^{32}\) well before a large body of literature on this topic could be properly generated. As a result, most of the studies in this meta-analysis\(^{27}\) reported very low knee abduction angles in their baseline measurements. For example, Hewett and colleagues\(^{3}\) reported peak knee abduction angles as high as 9°, while all subsequent work has been around 2°.\(^{33-35}\) One study even reported that approximately 40% of included study participants had already adopted some form of preventative ACL injury training prior to their involvement in the study.\(^{34}\) Therefore, the results of this meta-analysis\(^{27}\) may not be that medial knee collapse is not correlated with an increased risk of ACL injury, but rather, recent preventative training measures have been largely successful at reducing this risk. It is also worth noting that there is currently no agreed upon consensus on which medial knee collapse magnitudes are acceptable and which are undesirable, making it difficult to know when preventative training measures should and should not be prescribed. For instance, of the limited normative data available, a peak of 2° knee abduction reported in recent studies is well within the typical range seen at initial contact following a vertical drop jump (8.71 ± 9.1°),\(^{36}\)

Most importantly for this review, however, is that whether medial knee collapse increases the risk of knee injury or not, many coaches, trainers, clinicians, and rehabilitation specialists continue to screen for and correct this movement pattern whenever it is present. This review will focus on how effective one such corrective method (elastic bands) is at addressing this potential problem.

THE PROPOSED SOLUTION: ELASTIC BANDS ENCOURAGE PROPER KNEE ALIGNMENT

The idea of using elastic bands to correct medial knee collapse is essentially a modern-day form of Reactive Neuromuscular Training (RNT). First proposed by Michael L. Voight in the 90s,\(^{37}\) RNT is a rehabilitation technique that heavily utilizes reactive exercises (exercises that provide the individual with some sort of external cue to respond to
while they strive to achieve a simple movement or goal),
thus limiting the need for verbal and/or visual instruction 
from a therapist or trainer.

One way in which RNT is utilized today, and the most 
important as it relates to this review, is to take an individual 
who presents with an undesirable movement/posture and 
exaggerate said movement/posture using external force. 
For example, if an individual presents with dynamic knee 
valgus while squatting, it is possible that verbal and/or vi-
sual instruction from a trainer or coach may be ineffective 
at fully changing the movement. However, if an elastic band 
wrapped around the individual’s distal thighs were to pull 
them into even further knee valgus, the individual might 
then be forced into reacting to the larger displacement. If 
utilized chronically, RNT may change the movement pat-
tern, as has been shown in other applications of RNT.38–42

To the authors’ knowledge, Gooyers and colleagues8 
were the first to examine elastic bands wrapped around the 
distal thighs for the purpose of correcting medial knee col-
lapse. In their paper, the authors suggested that, because 
lower extremity joint motions are coupled during closed- 

![Figure 1. A) Depiction of what has traditionally been considered proper knee alignment while performing a squat-based movement. B) Depiction of medial knee collapse, or medial knee movement in the frontal plane while performing a bodyweight squat. C) Example of the typical location that elastic bands are placed (denoted by the two arrows) while performing squat movements. This location is normally on the distal thighs just proximal to the patella. D) Example of an elastic band, and its location on the distal thighs, being used during a bodyweight squat.](image-url)
THE EVIDENCE: ELASTIC BANDS ON MUSCLE ACTIVITY AND KNEE ALIGNMENT

To the best of the authors’ knowledge, a total of nine original studies have examined the use of elastic bands wrapped around the distal thigh and their effects on either hip external rotator muscle activity, lower limb kinematics, or both while performing squat movements. These studies, along with their key methods and outcomes, are summarized in Table 1. Although many of these investigations have been performed exclusively on barbell back squats,9,12,47,48 the literature as a whole has assessed a considerable range of exercises with elastic bands, including bodyweight squats,7,8,49 overhead barbell squats,11 countermovement jumps,8 squat jumps,8 and drop jumps.50 The intensity at which these exercises were performed at varied widely, from as low as bodyweight to as high as 85% of IRM. The abovementioned studies were performed on participants who were at least recreationally active, while most were performed on chronically resistance trained individuals; Foley and colleagues48 remain the only researchers to have examined inexperienced participants. Although the literature slightly favors males in terms of recruitment, five of the nine studies were conducted on both male and female participants. The resistance imposed by the elastic bands is perhaps the most inconsistent variable across these studies, and, unfortunately, the units of resistance differ from study to study. For instance, the most common elastic bands utilized in this body of work are those sold by TheraBand®, which communicates resistance based on the strength (in kg) needed to stretch the band to 100% elongation (twice the band’s resting length). Of the studies that have used TheraBand®, resistance at 100% elongation ranged from 1.7 to 6.5 kg. Of the remaining work, most reported the resistance of their bands based on the mostly linear relationship between applied force and band stretch, with resistance ranging from 0.6 to 6.8 N/cm.

MUSCLE ACTIVITY

According to the hypothesis put forward by Gooyers and colleagues,8 an increase in hip external rotator muscle activity should lead to improvements in knee alignment. Of the nine studies summarized in Table 1, all but one8 included measures of muscle activity in their experimental design, and of these eight, all but one11 showed that the use of an elastic band increased muscle activity in at least one lower limb muscle. Although not all studies collected EMG from the same muscles, an increase in gluteus maximus muscle activity was reported by five different studies,7,9,47–49 lending support to the notion that band usage may indeed promote external rotation of the hip (Figure 2). The only studies that did not find an increase in gluteus maximus activity were Dai and colleagues,50 who exclusively examined gluteus medius in their investigation, and the aforementioned work by Forman and colleagues11 and Alizadeh and colleagues.12

Regarding the work by Forman and colleagues,11 the use of an elastic band wrapped around the distal thighs had no effect on muscle activity while squatting for any of the muscles examined, including the gluteus maximus, gluteus medius, planter flexors, and the knee extensors. This finding can likely be explained by one, or both, of the following reasons: 1) The exercise used in this study was an overhead barbell squat, which is the most technically-challenging movement examined thus far in this body of work. While participants were chronically resistance trained, none had extensive experience performing overhead barbell squats, and thus, the novelty of the movement may have overshadowed the novelty of using an elastic band. 2) It was also reported that band usage significantly decreased peak knee flexion angle, indicating that overall squat range of motion may have been reduced. Since repetition cadence was controlled in this study,11 a squat performed with a shorter range of motion is a squat performed more slowly, which may have reduced muscle activity51–54 and offset any potential increase induced by the use of an elastic band.

The work of Alizadeh and colleagues12 on the other hand, is perhaps the most inconsistent with comparative literature. In this study, males and females performed barbell back squats either without the use of an elastic band or while using one of three elastic bands of varying resistance. A total of three repetitions were performed for each experimental condition at 85% of IRM. Although gluteus medius muscle activity did increase with increasing band resistance, gluteus maximus activity was not significantly different between the band conditions. One possibility for this lack of change could be the intensity these squats were performed at; at 85% of IRM, this is the heaviest workload of all studies in this narrative review. However, this intensity is not substantially higher than those used by similar work. Of the four studies that showed gluteus maximus muscle activity to increase with band usage, three also used barbell back squats, and all three utilized an intensity of ~80% of IRM in at least some portion of their protocol.

Despite a lack of statistical significance, the results of the work performed by Alizadeh and colleagues12 were trending towards an increase in gluteus maximus muscle activity with increasing band resistance. Considered alongside the other work presented in this narrative review, it is likely that elastic bands do promote increased external rotation of the hip while performing squat movements, which is not particularly surprising. For most studies, participants were repeatedly given verbal instruction to actively resist the external force provided by the elastic band and to keep the band tight throughout the entire exercise/movement. This forces participants to produce an additional external hip rotation moment on top of the exercise they are already performing, and assuming other aspects of the movement are not sacrificed in the process (such as a loss of knee range of motion11), the overall workload of the exercise is increased. This may explain why other lower limb muscles also exhibit greater muscle activity while using an elastic band. Both gluteus medius (shown in five of eight studies9,12,47–49 and biceps femoris (shown in two of six studies)48,49 muscle activity increased with band usage. Interestingly, three investigations reported a decrease in vastus lateralis muscle activity with band usage during at least one
Table 1. Key study details.

<table>
<thead>
<tr>
<th>Study</th>
<th>Sex (M/F)</th>
<th>Age (Years)</th>
<th>Training Experience</th>
<th>Exercise</th>
<th>Intensity/Workload</th>
<th>Elastic Band Resistance</th>
<th>Muscle Activity</th>
<th>Kinematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alizadeh et al.</td>
<td>M &amp; F</td>
<td>22.6 ± 2.6</td>
<td>Resistance-trained</td>
<td>Barbell back squat</td>
<td>85% of 1RM</td>
<td>1.68 kg (Red CLX)</td>
<td>1) Gluteus medius increased</td>
<td>1) KWI decreased with band strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.31 kg (Black CLX)</td>
<td>2) Vastus medialis decreased</td>
<td>2) No change in knee flexion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.44 kg (Gold CLX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martins et al.</td>
<td>M &amp; F</td>
<td>25 ± 4 (M)</td>
<td>Resistance-trained</td>
<td>BW squat</td>
<td>BW</td>
<td>0.6 N/cm</td>
<td>Increased with increasing band strength</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26 ± 5 (F)</td>
<td>and band experience</td>
<td></td>
<td></td>
<td>1.0 N/cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forman et al.</td>
<td>M</td>
<td>23.9 ± 2.4</td>
<td>Experienced</td>
<td>Overhead barbell squat</td>
<td>25% of BW</td>
<td>6.5 kg (Gold CLX, Theraband)</td>
<td>No change</td>
<td>1) Peak knee flexion decreased</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2) KWI decreased</td>
</tr>
<tr>
<td>Reece et al.</td>
<td>M &amp; F</td>
<td>18+</td>
<td>6+ months squat</td>
<td>Barbell back squat</td>
<td>80% of 1RM &amp; 40%</td>
<td>Light (2.1 N/cm)</td>
<td>1) Gluteus maximus increased</td>
<td>Peak knee valgus increased</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>experience</td>
<td></td>
<td>of 1RM</td>
<td>Heavy (6.8 N/cm)</td>
<td>2) Vastus lateralis decreased</td>
<td></td>
</tr>
<tr>
<td>Foley et al.</td>
<td>M</td>
<td>25.4 ± 4.4</td>
<td>Experienced &amp; Untrained</td>
<td>Barbell back squat</td>
<td>3 RM &amp; BW</td>
<td>1.7 kg (Red Band Loop, Theraband)</td>
<td>Increased</td>
<td>KWI unchanged</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.9 ± 2.4</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Spracklin et al.</td>
<td>M</td>
<td>23.7 ± 3.5</td>
<td>Experienced</td>
<td>Barbell back squat</td>
<td>80% of 1 RM &amp; 60%</td>
<td>2.6 kg (Blue Band Loop, Theraband)</td>
<td>Increased (gluteus medius and maximus)</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>of 1RM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dai et al.</td>
<td>M &amp; F</td>
<td>21.1 ± 2.4</td>
<td>Recreationally active</td>
<td>Drop Jump</td>
<td>BW</td>
<td>43.3 ± 18.0 N (pre-landing) &amp; 41.0 ± 17.2 N (landing)</td>
<td>Increased (gluteus medius)</td>
<td>1) Knee abduction unchanged</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2) Hip abduction decreased</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3) Knee flexion decreased</td>
</tr>
<tr>
<td>Gooyers et al.</td>
<td>M &amp; F</td>
<td>(University</td>
<td>Recreationally active</td>
<td>BW squat</td>
<td>BW</td>
<td>Light (1.5 N/cm)</td>
<td>N/A</td>
<td>1) KWI decreased (BW squat and CM jump)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>students</td>
<td></td>
<td>CMJ SJ</td>
<td></td>
<td>Medium (2.0 N/m)</td>
<td></td>
<td>2) Medium band larger KWI decrease</td>
</tr>
<tr>
<td>Lubahn et al.</td>
<td>F</td>
<td>22.3 ± 2.3</td>
<td>No sport-specific inclusion criteria</td>
<td>BW squat</td>
<td>BW</td>
<td>2.1 kg (Green, Theraband)</td>
<td>Gluteus maximus increased (BW squat)</td>
<td>Knee valgus increased</td>
</tr>
</tbody>
</table>

M = males, F = females, BW = bodyweight, CMJ = countermovement jump, SJ = squat jump, 1RM = 1 repetition maximum, KWI = knee width index, N/A = not applicable (study did not collect this metric).
portion of the squat movement, although one study had an increase in vastus lateralis activity, and two had a similar decrease in vastus medialis activity. Considered collectively, this evidence suggests that elastic bands may not just promote external rotation of the hip, but they may also encourage greater utilization of the hip extensors (shown by increases in gluteus maximus, gluteus medius, and biceps femoris muscle activity), and reduce reliance of the knee extensors (shown by decreases in vastus medialis and vastus lateralis muscle activity) while performing squat-based movements. If so, elastic band usage may represent a promising tool for trainers and rehabilitation specialists in targeting hip musculature and/or offloading the knee, depending on the needs of their athletes.

KINEMATICS

Given the discussed findings that elastic bands likely promote activation of the hip external rotators, intuition would suggest that elastic bands may also reduce medial knee collapse. Current evidence, however, does not seem to support this (Figure 5). Of the nine studies summarized in this review, seven included at least one or more lower limb kinematic measure(s) in their investigation. These measures include knee-width-index (KWI), knee flexion angle, knee abduction (or valgus) angle, hip abduction angle, and hip flexion angle. The most utilized of these measures is KWI, which is a unitless ratio of the net distance between the right and left distal thigh (or lateral epicondyles) divided by the net distance between the right and left distal shank (or lateral malleoli). Written mathematically, this gives:

\[
\text{KWI} = \frac{\text{Bilateral Distal Thigh Distance}}{\text{Bilateral Distal Shank Distance}}
\]

A KWI of 1.0 would indicate that the distance between the knees and the distance between the ankles are approximately equal, which is frequently interpreted as meaning the knees are in-line with the rest of the lower limb and exhibiting no knee valgus. A value of less than 1.0 suggests that the knees are closer together than the ankles, which in turn points to medial movement in the anterior plane (medial knee collapse has occurred). These conclusions, however, may not be accurate. For instance, if an individual is performing a squat with a very wide stance, their feet, and ankles, are already further apart than their knees even before they have descended into a squat. Their knees could very well be properly aligned with the rest of their lower limb, with no knee valgus occurring, but because of their wide stance, their KWI would be less than 1.0. For this reason, the KWI should be viewed as a limited, surrogate measure of knee valgus.

With that in mind, the first study to utilize KWI was also the first study to propose the use of elastic bands in correcting medial knee collapse. In this study, lower limb kinematics were captured while participants performed one of three exercises: countermovement jumps, bodyweight squats, and squat jumps. All exercises were performed without a band or with a light (1.5 N/cm) or medium (2.0 N/cm) tension elastic band. Although band usage had no

Figure 2. Mean differences in gluteus maximus muscle activity while performing squat-based movements with an elastic band compared to baseline (no-band) trials. Bars are shaded purely to help visibly differentiate studies from one another. Heavy, Moderate, Light = relative elastic band resistance utilized in that study, IRM = 1 repetition maximum, ECC = eccentric contraction, CON = concentric contraction, BW = bodyweight, Trained/Untrained = training status of participants.
Figure 3. Mean differences in A) knee valgus angle and B) knee width index (KWI) while performing squat-based movements with an elastic band compared to baseline (no-band) trials. Bars are shaded purely to help visibly differentiate studies from one another. Heavy, Moderate, Light = relative elastic band resistance utilized in that study, 1RM = 1 repetition maximum, ECC = eccentric contraction, CON = concentric contraction, BW = bodyweight, Trained/Untrained = training status of participants.

effect on KWI during squat jumps, KWI significantly decreased for both countermovement jumps and bodyweight squats while using elastic bands. Similar findings have been reproduced during overhead barbell squats, whereby peak and mean KWI decreased with band usage in both the eccentric and concentric phases, and during barbell back squats. The only other study which has utilized this measure found no differences in KWI when performing barbell back squats with or without an elastic band. Beyond KWI, knee valgus angles have also been directly quantified in participants performing bodyweight squats, drop jumps, and barbell back squats. While no change in knee valgus angle was observed when performing drop jumps with or without an elastic band, band usage significantly increased knee valgus angle during bodyweight squats and barbell back squats.

Considered collectively, these findings suggest that the use of an elastic band while performing squat-based movements does not acutely reduce knee valgus. In fact, it either has no effect, or it may actually increase knee valgus. This may seem at odds with the previously discussed increases in gluteal muscle activity, which should have led to an increase in hip external rotation. What may be happening is that, while elastic bands do successfully promote activation of the hip external rotators, the ensuing increase in external rotation torque is either equal to or less than the external force provided by the bands themselves, resulting in either no change in knee alignment or an increase in knee valgus.

On a surface level, an elastic band-induced increase in knee valgus may seem like a problem. In fact, some researchers have interpreted this finding as a clear warning that elastic band usage may increase injury risk during squat-based activities and have recommended trainers and clinicians to immediately remove them from training programs. In reality, though, the risk is likely minimal. While five studies have shown knee valgus to increase with band usage (or assumed an increase based on KWI interpretations), these increases have all been very small and may not be clinically significant. For instance, when squatting with an elastic band, knee valgus angle increased from 4.1° to 6.2° and from to 3.01° to 3.92°. KWI has also been shown to decrease by -0.02, -0.03, and ~4%, all while using the strongest bands utilized in these studies. Again, there is currently no agreed upon consensus on which medial knee collapse magnitudes, if any, represent an increased injury risk, and of the available normative data, the knee valgus angles shown by both Lubahn and colleagues and Reece and colleagues, both with and without a band, are well within these ranges. Based on these findings, it is unlikely the small increases in knee valgus due to elastic bands will increase the risk of lower limb injury.

While most of the present literature has exclusively focused on quantifying medial knee collapse, a few investigations have examined other kinematic measures that are likely important to consider. For example, maximum knee flexion angle and maximum hip flexion angle have been shown to decrease while using an elastic band. Although Alizadeh et al. observed no change in peak knee flexion angle in their own study, these collective findings suggest that elastic bands might reduce range of motion when used. However, band usage may not be directly responsible for this reduction. Rather, the process of adapting to the novel use of an elastic band (none of the above studies collected from participants with previous band experience) may have resulted in a decreased range of motion. This explanation is currently speculative but should be considered in future investigations seeking to examine chronic elastic band usage.

**IMPORTANCE OF BAND RESISTANCE DOSAGE**

If elastic bands are to be prescribed for the sake of correcting medial knee collapse, then the resistance of the band chosen is likely of major importance. This is primarily because greater band resistance may increase knee valgus. On the other hand, elastic bands of even light resistance seem
capable of increasing lower limb muscle activity. To elaborate, in the work by Goovers and colleagues, while the light resistance elastic band of 1.5 N/cm did decrease KWI at various portions of countermovement jumps, reductions in KWI occurred more frequently with the medium resistance band of 2.0 N/cm. Similar findings have been noted between studies utilizing elastic bands of only one resistance level. Using one of the lightest bands offered by TheraBand©, specifically 1.7 kg of resistance at 100% elongation, muscle activity from multiple muscles of the lower limb increased, all while KWI remained unchanged between conditions. In contrast, the strongest band of 6.5 kg has been shown to decrease KWI, with no subsequent changes in lower limb muscle activity.

Given these findings, some of the most recent literature on this topic has made a point of specifically focusing on elastic band resistance in their investigations, and the findings across these studies have been largely consistent. In the muscles that demonstrated an effect of elastic band usage, the relationship between muscle activity and elastic band resistance was almost linear, with muscle activity highest while performing squats with the strongest elastic bands. Similarly, medial knee collapse (measured indirectly with KWI and directly with knee valgus joint angles) increased with increasing band resistance. Thus, while stronger bands likely yield greater levels of lower limb muscle activity, which may be beneficial in training the external rotators of the hip for squat-based movements, they also result in greater medial knee collapse. Perhaps the obvious application of these findings is that trainees should simply use the lightest elastic band possible if attempting to reduce knee valgus. This will be discussed at greater length in the following sections.

CURRENT RESEARCH GAPS AND LIMITATIONS

The primary reason for conducting this review was to help provide context on a topic that is relatively poorly studied and one with sometimes contradictory findings. For those in the fitness world, it is often unclear why or for what purpose athletes are using elastic bands while performing squat-based movements, while in the academic world, there are some research circles that strongly recommend against the use of these bands over injury risk concerns. However, even now, neither the benefits nor the risks of elastic band usage are well understood. Not only is the topic limited by a small number of studies (only nine), there are also limitations in the research.

PARTICIPANT SCREENING FOR MEDIAL KNEE COLLAPSE

To date, no studies have first pre-screened their participants for medial knee collapse. To illustrate this problem, Forman and colleagues reported KWI group averages of approximately 0.99 and 1.0 in the concentric and eccentric phases, respectively, while squatting without an elastic band. This may indicate that knee alignment was already close to perfect at study onset, meaning that it is impossible to conclude that elastic band usage is ineffective at reducing medial knee collapse, given that medial knee collapse was not likely present to begin with.

CHRONIC ELASTIC BAND USAGE

It is crucial to understand that elastic band usage throughout this literature has only been examined acutely (single session studies). Thus, even if participants throughout the literature had presented with medial knee collapse at study onset (which they likely did not, as per the previous paragraph), the possible effects of elastic band usage were only quantified within a single acute session. To properly assess the validity of this potentially corrective training aid, elastic bands and their effect on medial knee collapse should be examined after chronic elastic band usage.

RNT EXAGGERATES MOVEMENT ERRORS

Researchers pursuing this topic should be reminded that the very nature of RNT is not to have trainees performing the exercise correctly while the external force is being applied (which should be exaggerating the undesirable movement pattern), but to see improvements in their technique after the external force has been removed. The findings that elastic bands increase knee valgus may actually be a promising outcome from the perspective of RNT as it means elastic bands are capable of exaggerating medial knee collapse.

INFLUENCE OF SEX ON BAND USAGE

Although research has demonstrated that females tend to exhibit greater knee valgus than males, the possibility that elastic band usage may influence either hip external rotator muscle activity, knee alignment, or both uniquely based on sex has been infrequently explored in current literature. For effective prescription, it is vitally important for future research to account for sex differences in their study design and statistical analyses.

FUTURE RESEARCH DIRECTIONS

If understanding of both the benefits and the risks of elastic band usage during squat-based movements (specifically for the purpose of correcting medial knee collapse) is to be improved, it is essential for future research to address the aforementioned limitations. First, studies should shift focus away from individuals with extensive training experience, or those with adequate knee alignment, and instead intervene with individuals who exhibit clear signs of medial knee collapse. Only by assessing this demographic can researchers make stronger conclusions regarding the effectiveness, or lack thereof, of elastic bands as corrective aids. Second, for those who do present with medial knee collapse, it is unlikely that a single session of elastic band usage will lead to noticeable improvements. It is even less likely that a single session will fully correct the problem. For elastic band usage to be fairly assessed, researchers should consider longitudinal investigations, where participants presenting with medial knee collapse utilize elastic
bands chronically over multiple sessions and weeks. Such investigations would more accurately reflect both how elastic bands are applied in practice and the length of time it might take for the technique error to improve. Lastly, if elastic bands are to be an effective RNT aid, researchers may anticipate a temporary worsening of knee valgus during elastic band usage which subsides once the bands are removed. The success or failure of elastic bands should also be assessed not during their direct usage, but while participants perform squat-based movement free of elastic bands after a prolonged period of chronic elastic band training.

RECOMMENDATIONS AND CONCLUSION

Of the evidence that is presently available, elastic band usage while performing squat-based movements appears capable of enhancing hip external rotator muscle activity, which may be of benefit to individuals who exhibit medial knee collapse as a result of insufficient hip external rotation. Over time, chronic elastic band usage could potentially strengthen this musculature and/or lead to permanent neuromuscular adaptations, which would result in improved knee alignment. This, however, is currently speculative; no longitudinal studies, focused primarily on individuals who clearly demonstrate medial knee collapse, have yet to be conducted. It is also clear that the use of elastic bands does not acutely reduce knee valgus. They either have no effect, in the case of low resistance elastic bands, or increase knee valgus, in the case of high resistance bands.

For coaches, trainers, and rehabilitation specialists considering the use of this technique either for athlete training or patient treatment, the substantial limitations present throughout the current literature make best practice recommendations difficult. If an individual chooses to use this technique, they may wish to utilize a lighter resistance elastic band. Even light elastic bands have shown the capacity to enhance hip external rotation muscle activity, and the chances of inducing a potentially undesirable increase in medial knee collapse are reduced. Even if utilizing light elastic bands, careful monitoring of a trainee’s knee alignment throughout the entire squat-based movement is indicated, and if a noticeable increase in knee valgus is observed, switch to a lighter band. Only by addressing the gaps that exist in current research can more confident conclusions be offered about the benefits and risks of using elastic bands to correct medial knee collapse during squat-based movements.

CONFLICTS OF INTEREST

The authors report there are no competing interests to declare.

DISCLOSURE OF FUNDING

No funding sources were utilized in the preparation of this manuscript.

Submitted: March 01, 2023 CDT, Accepted: August 17, 2023 CDT

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REFERENCES


Clinical Commentary: A Criteria-Based Testing Protocol for Return to Sport Post Hip Arthroscopy for Impingement

Gabriella Hugenberg, Jason Stallons, Chad Smith, Kathryn Brockhoff, Matthew Gingras, Darryl Yardley, Olufemi Ayeni, Mahmoud Almasri

1 Physical Therapy, Mercy Health. 2 Physiotherapy, McMaster University. 3 Orthopedic Surgery, McMaster University. 4 Orthopedic Surgery, Mercy Health. 5 Cincinnati Sports Medicine Research & Educational Foundation

Keywords: hip arthroscopy, hip impingement, femoroacetabular impingement, return to sport, return to play, hip functional testing

https://doi.org/10.26603/001c.87629

INTRODUCTION

Femoroacetabular impingement (FAI) is a common cause of hip pain in the adolescent and adult populations; this pain can impair daily function and ultimately impact athletic participation. The prevalence of FAI is unclear within current literature, but a recent meta-analysis found that the prevalence of FAI in young athletes with non-arthritis hip pain is 61.3%. Conservative and surgical management of FAI are both common means of treatment with evidence to support the efficacy of either option. There is, however, conflicting evidence regarding the superiority of one option over the other. Several studies have shown that surgical intervention may provide superior outcomes to physical therapy. However, the magnitude of success from surgical intervention may be somewhat limited. Palmer et al. showed that only 51% of those treated surgically saw a statistically significant improvement in functional outcomes with the extent of difference between the two treatment options varying based on which functional outcome measure...
was assessed.\textsuperscript{2,3} Additionally, several recent meta-analyses have shown similar results, but the quality of their methodology have been called into question.\textsuperscript{5-10} Saueressig et al. re-analyzed the data used in these meta-analyses and found no statistically significant difference in outcomes between surgical intervention and physical therapy.\textsuperscript{11} Other studies have shown that physical therapy may yield superior results to intra-articular injections in relation to pain and function, however the generalizability of these results is limited by short-term follow up.\textsuperscript{12,13}

Despite conflicting evidence, when patients do not respond to conservative methods of treatment, they will often seek surgical intervention. The process of returning to sport after hip arthroscopy is important for athletes, surgeons, and rehabilitation providers. For athletes undergoing hip arthroscopy for FAI, there is not a standardized return to sport testing protocol within the literature.

According to a cross-sectional cohort study by Iskoui et al. nearly 84%-87% of athletes will return to sport following hip arthroscopy; however, only 57% of athletes return to their preinjury level with only 16.9% of them reporting their sport performance to be optimal.\textsuperscript{14} There is ambiguity in appropriate return to sport time frames which ranges in the available literature from 5 to 12 months, with the most common time to return being 7.4 months.\textsuperscript{15,16} This discrepancy is due to a lack of consistency within the definition of return to sport following surgical intervention, as well as a lack of standardization within return to sport criteria and testing protocols. There have been several publications within the rehabilitation literature suggesting future studies adopt more concise descriptors within the umbrella term "return to play" or "return to sport" in order to provide an accurate assessment of the athlete’s outcome after surgery regarding their achieved level of play within their desired sport.\textsuperscript{17,18} To help provide clear descriptors, the authors will use the terminology "return to sport" provided by Ardern et al.\textsuperscript{12} For this clinical commentary, the term "return to sport" most accurately depicts the desired level of activity achieved within the stated criteria-based testing protocol.

A 2018 systematic review of 22 studies on return to sport after hip arthroscopy found that 54.5% did not provide guidance on return to sport duration or testing protocols after surgery. Of the studies that did provide a return to sport timeframe, 36.4% recommended four months. Only three studies provided information on reproducible testing and only two studies met the author’s four measures on return to sport criteria.\textsuperscript{15}

The need for a standardized criteria-based testing protocol was also supported by a 2021 systematic review by Davey et al. that assessed the current state of return to sport following hip arthroscopy. The authors found the overall return to sport rate was 84.5% and most athletes returned to sport in 6.6 months. The most common criterion used to determine readiness to return to their previous sport was time, with no standard objective criterion present in the literature. Unfortunately, most of the studies included by Davey et al. reported generic or vague criteria on return to sport (pain free, full strength, full range of motion, and have completed functional testing) and about one fourth of the included studies did not report any criteria on return to sport guidelines.\textsuperscript{19} The authors of this commentary believe that a safely guided return to sport testing protocol should include criteria-based objective measures with consideration of biological healing time.

A higher rate of return to sport has been reported among professional athletes compared to lower-level athletes.\textsuperscript{20} There was also a higher return to sport in the pediatric population and those with a short duration of pre-operative symptoms.\textsuperscript{16} Despite the high rate of return to sport following hip arthroscopy in these two populations, there are athletes who will fail to return to their preinjury level of sport. Weber et al. found that 12% of athletes will not return to sport. Of those 12%, 74.3% will not return due to hip related issues with 47.3% reporting persistent pain as their main reason.\textsuperscript{21} Unfortunately, these statistics lack generalizability as only two of the 20 articles included in this systematic review reported the age of the athletes who did not return to their sport.\textsuperscript{21}

The primary limitations in the return to sport literature related to the hip can be attributed to low quality evidence, lack of consistency within the definition of return to sport, wide variety in surgeon preferences, and wide variety in rehabilitation protocols. Currently, a comprehensive, criteria-based, return to sport testing protocol that utilizes objective measures to ensure athletes are safe for return to sport does not exist. The goal of the authors was to develop a criteria-based testing protocol following hip arthroscopy utilizing parameters best supported in the literature. It is the authors’ hope that this new criteria-based testing protocol will create consistency across care, decrease re-injury rates and increase the percentage of athletes successfully returning to sport. Therefore, the purpose of this clinical commentary is to propose a criteria-based testing protocol following a hip arthroscopy for impingement to be continually assessed from early rehabilitation through return to sport.

**CRITERIA OF PROPOSED RETURN TO SPORT TESTING PROTOCOL**

The following five criteria were identified through literature review as key parameters of a return to sport testing protocol: range of motion, strength, functional testing, psychological readiness, and time. These criteria are then further divided into specific testing components which are described in detail in individual sections below. All passing criteria recommended by the authors of this commentary are in accordance with previously published literature on each individual testing component. The full testing protocol which includes each criteria category, test components and passing criteria is outlined in Table 1.

**CRITERIA 1: RANGE OF MOTION**

To date, there are no published data on expected range of motion of the hip following surgery to correct FAI. It has
been shown that the pathology of FAI causes a significant difference in hip range of motion in the planes of flexion, abduction, extension, external rotation (ER) and internal rotation (IR). Clinicians should consider contralateral hip FAI morphology or range of motion limitations when clearing an athlete in this category.

The recommended passing criteria is pain-free active and passive range of motion within five degrees of the contralateral hip in all planes with consideration to any contralateral hip morphology. In this situation, clinicians can reference previously established normative ranges of motion for the hip joint bearing in mind the influences of factors such as age, gender, and race.

**CRITERIA 2: STRENGTH**

Strength is an often-included criteria as a part of return to sport testing following injury or surgery. The hip is unique in that it has movements in all three planes: sagittal (flexion/extension), frontal (abduction/adduction) and transverse (internal/external rotation). The authors suggest that using manual muscle testing (MMT) alone is not sufficient in determining the full extent of an individual’s strength across these three planes as it is an isometric test and subjective in nature. As an initial test, using a grade of 5 out of 5 MMT may be an indicator that the athlete is ready to progress to a more advanced stage of their rehabilita-

<table>
<thead>
<tr>
<th>Criteria Category</th>
<th>Test Component</th>
<th>Passing Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Range of Motion</td>
<td>Hip flexion, extension, abduction, adduction, external rotation, internal rotation</td>
<td>All hip ranges within 5 degrees of contralateral side and pain-free</td>
</tr>
<tr>
<td>2. Strength Testing</td>
<td>Hand Held Dynamometry</td>
<td>≥90% limb symmetry index in all planes of motion</td>
</tr>
<tr>
<td></td>
<td>Bunkie Tests</td>
<td>PSL, LSL, PPL, APL: 40 seconds, MPL: 20-30 seconds</td>
</tr>
<tr>
<td></td>
<td>Single Leg Bridge Test</td>
<td>Ability to maintain lumbopelvic neutral, neutral pelvic rotation, achieve hip extension to 0 degrees and show good gluteal activation AND ≥90% limb symmetry index</td>
</tr>
<tr>
<td></td>
<td>Isokinetic Testing: Hip Abduction/Adduction, Hip Flexion/Extension, Hip Internal/External rotation</td>
<td>≥90% limb symmetry index for peak torque, Tested at 60°/sec and 120°/sec</td>
</tr>
<tr>
<td>3. Functional Testing</td>
<td>Step Down Test</td>
<td>4 out of 5 criteria must be negative for deviation in at least 2 of the 3 trials</td>
</tr>
<tr>
<td></td>
<td>Y Balance Test</td>
<td>&gt;94% symmetry and &lt;4cm difference in reach distance between sides</td>
</tr>
<tr>
<td></td>
<td>Hop Testing for Distance: Triple, Medial, Lateral</td>
<td>≥90% limb symmetry index</td>
</tr>
<tr>
<td>4. Self-Reported Function and Psychological Readiness</td>
<td>iHot 12, HOS-Sport Subscale, Hip RSI</td>
<td>All ≥ 90% ability</td>
</tr>
<tr>
<td>5. Time</td>
<td>Athlete must be at least 5-6 months post-surgery and have passed all of the above listed criteria. If a testing component is not passed it will be retested every 7-14 days until it is passed. Isokinetic testing will be repeated every 6 weeks until passing scores are achieved.</td>
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The authors of this commentary recommend more objective testing of an athlete's strength when determining readiness to return to sport which is described in detail below.

**HAND-HELD DYNAMOMETRY**

Hand-Held Dynamometry (HHD) has been well established and validated as an objective method of testing strength in individuals. When possible, the device should be fixed against a stable base to avoid any error in measurement from clinician pressure or losing joint position during isometric testing. Not only should the clinician look at the amount of force produced but also the quality of muscle contraction as well as any compensatory movements or patterns noted during the test. Proper setup for HHD strength testing of the hip has been previously described using a belt with an emphasis on a fixed and stable base. The authors encourage using HHD to test all six motions across three planes.

The recommended passing criteria is a limb symmetry index (LSI) of > 90%.

**SINGLE LEG BRIDGE TEST**

The Single Leg Bridge Test (SLBT) has been documented to assess hamstring performance in high level athletes. The test is described with the athlete positioned supine,
the leg being tested on a box 60 cm high and knee flexed to 20 degrees. Once in the proper test position, the athlete performs as many reps as possible on both sides. The test is stopped by the clinician at their discretion for improper technique. The authors of this commentary recommend this test to be done in two ways. First, early in the rehabilitation process as a screen to assess the athlete’s pelvic control and general quality of movement. The athlete is subjectively graded “pass” or “fail” on glute activation, maintaining lumbopelvic neutral, maintaining neutral pelvic rotation, and achieving full excursion of hip extension. Second, as the athlete continues through their rehabilitation program, it should be performed as described by Freckleton et al. to identify any deficits in posterior chain endurance. It is the author’s intent that the results of this test will aid in determining the athlete’s readiness to progress into more advanced limb control tasks during their rehabilitation.

Although the above test has been shown to be predictive of hamstring injuries, the authors suggest utilizing it as a way to screen gluteus maximus performance in the early stages of the rehabilitation process. A systematic review by Macadam et al. demonstrated that performing a bridge recruits the gluteus maximus muscle albeit in different amounts based on setup. Performing a single leg bridge has been shown to provide high EMG of the hamstring muscle group as well as the gluteus maximus. Performing a single leg bridge with the knee fully flexed at 135 degrees, foot flat on table, and contralateral leg held in neutral with the knee straight was found to have the highest EMG activity of the gluteus maximus while minimizing EMG activity of the hamstrings. This position was also found to have a moderate amount of gluteus medius activity. The authors suggest modifying the SLBT testing position to have the knee flexed to 135 degrees to better bias the glutes maximus. However, it is important to note that this adaptation has not been formally studied to date.

The recommended passing criteria is a LSI of >90%.

THE BUNKIE TEST

Core strength and endurance is a key component of rehabilitation following hip arthroscopy; however, there is currently no gold standard for core assessment within return to sport testing. For this return to sport testing protocol, the authors recommend using the Bunkie Test as it is a comprehensive series of movements that assess an individual’s core strength and stability in the frontal and sagittal planes. It is a series of five tests that can also be utilized as exercises for athletes if weaknesses are identified and it incorporates static muscle function, static muscle length, postural alignment, and spinal stability. The test positions are shown in Figure 1 and an in-depth description of the setup for each test can be found by referencing the prior work by Ronai.

The Bunkie Test has been shown to be a reliable measure of core endurance in a healthy patient population but more in-depth reliability and validity studies are needed to assess efficacy in an injured patient population, and specifically for patients with hip pathology, for purposes of this return to sport testing protocol. Brumitt demonstrated effectiveness of the Bunkie Test in identifying core and hip weakness in a female distance runner with unilateral back pain in a case report. Therapeutic exercise interventions were prescribed based on the results and then the Bunkie Test was readministered, resulting in the improved isometric hold times and a resolution of the subject’s back pain.

The recommended passing criteria is a pain-free, isometric hold of 40 seconds for the anterior power line, posterior power line, posterior stabilizing line and lateral stabilizing and 20-30 seconds for the medial stabilizing line. Otherwise, muscle imbalance may be present, in accordance with normative data reported by Ronai.

ISOKINETIC TESTING

For objective testing of muscle strength, isokinetic dynamometers are the gold standard. In addition to providing a patient’s peak torque to compare their uninvolved to involved limb, isokinetic assessments allow us to normalize peak torque to body weight for comparison to other individuals as well as to establish agonist/antagonist ratios through different angular velocities. Isokinetic dynamometers are also considered effective for use during rehabilitation to address muscle function. A great deal of research has been generated in the field of rehabilitation and sports performance with regard to isokinetic testing with the knee joint being the most studied and to a lesser extent the hip. Although less studied, isokinetic testing of hip musculature does appear to be reliable and valid in individuals with FAI. Meyer et al. showed good to excellent reliability for isokinetic testing of the hip in the directions of hip flexion/extension and abduction/adduction. Casartelli showed that patients with FAI have significantly lower maximum voluntary contraction (MVC) strength than controls for hip abduction (28%), flexion (26%), external rotation (18%) and abduction (11%). The authors recommend testing in the directions of flexion/extension, abduction/adduction and IR/ER. Meyer showed that testing at velocities of 60 degrees/second for 5 reps and 120 degrees/second for 5 reps is very reliable, therefore the authors recommend testing using these parameters. The testing directions are depicted in Figure 2.

The recommended passing criteria is a peak torque LSI > 90% for each testing direction.

CRITERIA 3: FUNCTIONAL TESTING

THE STEP-DOWN TEST

The step-down test is a common functional performance test used in the clinical setting to assess basic dynamic movement patterns of the trunk and lower extremity. Previous authors have shown the test to be a reliable and valid functional performance test in the evaluation of physical function for patients with nonarthritic hip pain. It should be noted that those who pass the step-down test report less pain and greater function during sports related activities as assessed by a Visual Analog Scale and the Hip Outcome Score-Sports Subscale.
The testing procedure is carried out in the manner outlined by McGovern et al. A single evaluator assesses the overall test performance of the individual’s affected side; this is determined by the individual’s balance, balance or acceleration provided by heel contact, gross arm deviation, and their ability to perform the test. Each repetition is then graded as “positive” or “negative” based on five criteria: trunk movement (forward lean, lateral rotation, lateral flexion, thoracic rotation), posture of the pelvis (tilt or rotation), posture of the hip joint (adduction or internal rotation), posture of the knee (knee valgus or tremor) and depth of squat (inability to contact heel to ground).

The authors recommend following the test parameters outlined by McGovern et al, which means that for an individual to pass, the evaluator must first grade the overall impression of test performance as passing. Second, a total of four out of the five specific criteria must be negative for deviation. Third, a passing grade of at least one out of the three tests is required.

Y-BALANCE TEST
The Y-Balance test (YBT) is a functional test developed from the Star excursion balance test (SEBT) to improve reliability and field expediency of the SEBT. The YBT was simplified to use only the most reliable three reach directions of the SEBT (anterior, posteromedial, posterolateral). The test is intended to assess dynamic postural control and has been shown to be predictive of lower extremity injuries in young, athletic populations. There is also evidence that demonstrates a correlation between reach distance in both the posterior-medial and posterior-lateral direction and hip extension and abduction strength. The authors recommend using The YBT instrument (FunctionalMovement.com, Danville, VA) for more reliable and valid testing. To score the YBT, first calculate the average reach distance in each direction in centimeters, by taking the average of three trials for each direction. Then, calculate the distance in each direction as a percentage by taking the average distance in each direction, divided by the patient’s leg length, multiplied by 100.
The recommended passing criteria is $>94\%$ symmetry and $<4\text{cm}$ difference in reach difference between the involved and uninvolved extremity.\(^38\)

**HOP TESTING**

Functional performance tests have been commonly used to identify impairments related to ankle or knee injuries and determine the readiness of an athlete to return to sport after injury.\(^39,41-44\) Multiple authors have determined hop testing to be reliable, correlating with lower extremity strength as well as functional performance.\(^39,45-50\) There may also be a correlation between functional testing and injury prevention. In ACL rehabilitation, passing a battery of tests which include hop testing has been shown to reduce the odds of an ipsilateral ACL graft rupture by $78-84\%$.\(^51-53\) Evidence of their validity in the rehabilitation of hip pathology is scarcer. Therefore, the development of a testing protocol that bases progression of performance on functional tests that inform hip rehabilitation should be prioritized.

The authors recommend utilizing three functional hop tests to determine readiness for progression to higher level activities. These are the triple hop for distance, medial triple hop for distance, and lateral triple hop for distance, these are depicted in Figure 3. The triple hop for distance test is well established in rehabilitation of knee conditions. Although less established in rehabilitation for the hip, triple hop work seems to correlate with hip strength.\(^54\) Kollock et al. showed that triple hop work was a strong to very strong indicator of max strength and rate of force development of the hip abductors, adductors, and flexors. The medial and lateral triple hop for distance tests are less established; however, have been shown to be valid and reliable in individuals with hip pathology.\(^54\) Kivlan et al. showed that both tests were reliable (ICC: medial hop 0.96; lateral hop 0.93) with the medial hop test showing a significant difference in hop distance between the involved and uninvolved sides in dancers with hip pathology.\(^55\) These tests are intended to evaluate the individual's performance both qualitatively and quantitatively. The individual begins by standing on the uninvolved limb. They hop three times consecutively for distance in the predetermined direction.
and hold the last hop for five seconds. The assessor measures the distance hopped on each trial in centimeters and the best of the three trials is used for assessment. The procedure is then performed on the involved limb. The best trial of each extremity is compared. Each trial of the test is also graded qualitatively by the assessor. Each performance is scored through observation as "good", "fair" or "poor." A grade of "poor" is considered a "fail" and is not considered for assessment.

The recommended passing criteria is a LSI of > 90% for distance hopped and qualitative rating of "good" for each of the three hop tests.44

**CRITERIA 4: SELF-REPORTED FUNCTION AND PSYCHOLOGICAL READINESS**

**SELF-REPORTED FUNCTION (PATIENT-REPORTED OUTCOMES)**

Self-reported functional questionnaires were designed with the intent of assessing a patient’s ability to return to an active lifestyle through obtaining subjective measures of symptoms and function, as well as emotional and social health status. Unfortunately, many questionnaires assessing the function of patients with hip pathology were designed with a focus on lower-level activities with little consideration for the requirements of a younger, more athletic population. The International Hip Outcome Tool (iHOT-12) is a good example of such a tool. It has been shown to be valid, reliable, and responsive to change in young adults with various hip conditions.56 It was designed to assess Activities of Daily Living in an active population, however, has limitations in assessing athletes who participate in higher level sports-related activities. The Hip Outcome Score (HOS) is another validated functional scale that consists of an ADL subscale and Sports subscale. Martin et al. have shown the HOS to be a valid assessment tool for individuals with the diagnosis of a labral tear as well as for those who have undergone hip arthroscopy. Martin et al. also found that the HOS was able to differentiate between functional abilities of individuals, depending on their current activity level, surgical outcome, and age at a follow-up assessment performed more than three years after surgery on average.57 The authors propose that the iHOT-12 be used for assessment in the initial phases of rehabilitation, as it is a good tool for monitoring ADL progress. The authors then recommend transitioning to the Hip Outcome Score - Sports Subscale (HOS-Sports) in the later phases of rehabilitation to monitor self-reported function as it relates to sport specific tasks.

The recommended passing criteria is a score of >90% ability (or <10% disability) on these questionnaires, with a higher score indicating better function.

**PSYCHOLOGICAL READINESS**

A key factor in returning any athlete back to sport is psychological readiness. Fear of re-injury and loss of confidence has been shown to significantly affect an athlete's readiness for returning to sport, regardless of their physical state.58 Fear of re-injury has been studied in athletes returning after Anterior Cruciate Ligament (ACL) surgery but data are sparse in athletes returning to sport after FAI surgery. Assessing the psychological milestones of an athlete is imperative in the clinician’s efforts to ensure successful return to sport. The Hip Return to Sport After Injury Scale (Hip-RSI) was adapted from the ACL-RSI and is an easily administered scale that is intended to be used along-
side functional tests and measures and other patient-reported outcomes to determine readiness for successful return to sport. The Hip-RSI has been found to be both reliable and valid for assessing psychological readiness for return to sport following hip arthroscopy.59

The recommended passing criteria is a score of >90% ability (or <10% disability), with a higher score indicating a greater level of psychological readiness.

**CRITERIA 5: TIME**

There is no current evidence to support the appropriate time frame to initiate return to sport testing following hip arthroscopy. It is the author's suggestion that the Criteria 1-4 are assessed throughout the athlete's rehabilitation to identify specific deficits, impairments and performance limitations to ensure the patient is progressing appropriately toward return to sport goals. Taking biological healing times and rehabilitation protocol progressions into account the following time frames are suggested for initiation of return to sport testing.

Clinicians should begin testing the single leg bridge test and step-down test no sooner than eight weeks post-op, after these movements have already been introduced to the exercise program.60 Additionally, testing of the YBT and Bunkie test should occur no sooner than 12 weeks post-op, also after these movements have been added to the exercise program. Athletes should meet all ROM criteria by 12 weeks post-op.60 Strength testing via HHD can occur throughout the patient’s rehabilitation, with the expectation that 90% LSI is achieved by 16 weeks, prior to hop testing. Hop testing is initiated no sooner than 16-20 weeks post-op. Isokinetic testing is completed no sooner than 20-24 weeks post-op once all other previous measures have been achieved to ensure safe testing with proper motion, strength, and in accordance with biological healing of the involved structure.19,61,62

Athletes must be at least five to six months post-surgery (as this is the average time to return to sport reported in the literature19) and have passed all the above outlined criteria before being cleared for return to sport. If a testing component is not passed it should be retested every 7-14 days until a passing criteria/score is achieved. Isokinetic testing is repeated every six weeks until passing scores are achieved.

**CONCLUSION**

Currently there is no validated return to sport testing protocol following hip arthroscopy, in part due to inconsistencies between physician preferences, rehabilitation protocols, and a lack of high-quality research. After an extensive literature review, the authors have identified the best available tests and measures to be used in return to sport decision making for athletes post hip arthroscopy as a result of pathologic hip impingement and propose a comprehensive criteria-based testing protocol to make informed decisions regarding whether athletes are ready to return to sport. Moving forward, the authors intend to validate the use of this testing protocol as a part of a comprehensive rehabilitation program following hip arthroscopy with the hope that a higher percentage of athletes will be able to return to sport.

**CONFLICTS OF INTEREST**

The authors report no conflicts of interest.

Submitted: April 27, 2023 CDT, Accepted: August 09, 2023 CDT

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Clinical Commentary/Current Concept Review

On Putting an End to the Backlash Against Electrophysical Agents

Alain-Yvan Belanger1, David M. Selkowitz2, Daryl Lawson3

1 Rehabilitation, Université Laval, 2 MGH Institute of Health Professions, 3 Western Michigan University

Keywords: backlash, call to action, bashing rhetoric, modalities, biophysical agents, electrophysical agents

https://doi.org/10.26603/001c.87813

International Journal of Sports Physical Therapy

Electrophysical agents (EPAs) are core therapeutic interventions in academic physical therapy curricula around the world. They are used concomitantly with several other therapeutic interventions such as exercise, manual therapy techniques, medications, and surgery for the management of a wide variety of soft tissue disorders. Over the past decade, the practice of EPAs has been the subject of intense scrutiny in the U.S. This has been colored by some physical therapists publicly engaging in bashing rhetoric that has yet to be officially and publicly addressed by the guiding organizations which, together, regulate the practice of physical therapy in this country. Published in world renowned public media are unsubstantiated mocking remarks against the practice of EPAs and unethical allegations against its stakeholders. This rhetoric suggests that EPA interventions are “magical” treatments and that those practitioners who include them in their plans of care may be committing fraud. Such bashing rhetoric is in striking contradiction to the APTA’s Guide to Physical Therapist Practice 4.0, which lists EPAs as one of its categories of interventions, the CAPTE’s program accreditation policy, and the FSBPT’s national licensing exam. The purpose of this commentary is to expose the extent of this discourse and to call to action the APTA, CAPTE, and FSBPT organizations, as well as physical therapists, with the aim at putting an end to this rhetoric.

BACKGROUND

The authors read with great interest the recent clinical viewpoint article by Dr. Phil Page entitled "Making the Case for Modalities: The Need for Critical Thinking in Practice".1 Dr. Page discusses several elements that have contributed to the backlash against therapeutic modalities, also known as physical agents, biophysical agents, and electrophysical agents (EPAs). In this article, we use the term electrophysical agent (EPA) because it best reflects the electrical and physical types or forms of energy delivered by these agents to soft tissues. In making his case, Dr. Page rightfully singles out the conflicting and ironic messages coming from the American Physical Therapy Association (APTA), the Commission on Accreditation in Physical Therapy (CAPTE), and the Federation of State Boards of Physical Therapy (FSBPT) with regard to their official positions or policies towards EPAs in physical therapy in the U.S. The author concludes that it’s time for physical therapists to stop bashing the field of EPAs in social media.

The purpose of this commentary is to expose the extent of this discourse and to call to action the APTA, CAPTE, and FSBPT organizations, as well as physical therapists, with the aim of putting an end to this rhetoric. It is the authors’ conviction that this situation cannot continue because it may unfairly tarnish the reputation of the physical therapy profession and all its stakeholders - defined as clinicians, educators, researchers, third-party payers, manufacturers, distributors, APTA, CAPTE, FSBPT - and undermines the therapeutic value of EPAs in physical therapy practice.

HISTORY BEHIND THE RHETORIC

Words matter. They can be uplifting and inspiring. Words, especially in repeated verbal and written instances, can also be devastating and extremely harmful for the recipients. Of all the categories of therapeutic interventions listed in the

a Corresponding Author:
Alain-Yvan Belanger, PhD, PT
From the Department of Rehabilitation
Faculty of Medicine
Laval University
Quebec City,
Canada
e-mail: alainybelanger@gmail.com
Website: alainyvanbelanger.com
APTA's Guide to Physical Therapist Practice 4.0, the EPAs category appears to be the only one under the investigative microscope. No other category of interventions, to the best of the authors' knowledge, has been submitted to such intense scrutiny by the APTA, and to such persecution, by some physical therapists, in the public media.

BACKLASH, BELIEF, PREJUDICE, ALLEGATION, AND STEREOTYPE

The backlash against EPAs is a mixture of beliefs, prejudices, allegations, and stereotypes. How do dictionaries define these words? A backlash is a “strong and adverse reaction to something” by a group of individuals, which is precisely the case here. A belief is an “acceptance that something is true”. It is a personal conviction that has nothing to do with logic, evidence, or fact and, consequently, cannot be tested or disproved rationally. Unlike a belief, prejudice is “a preconceived or - half-baked - opinion based on insufficient or unexamined evidence”. Prejudices, unlike beliefs, are testable. They can be contested and disproved based on facts. A fact is verifiable, and its validity is determined by researching the evidence. Often individuals form or accept prejudices without testing their truth. Allegations are “claims or assertions, often made without proof, that someone has done something illegal or wrong”. Finally, a stereotype is a “widely held but fixed and oversimplified image of a particular type of person or thing”. Together, these constructs provide the foundation for the following examples of derogatory rhetoric toward EPAs.

ONE: “THERE IS LITTLE TO NO RESEARCH-BASED EVIDENCE”

A first long-held belief and/or prejudice is that there is little to no research-based evidence behind the practice of EPAs. Why should physical therapists use therapeutic interventions for which there is no scientific evidence? It makes perfect sense, doesn’t it! However, is it true that there is little to no research-based evidence behind the usage of EPAs? Convinced that it is true, some physical therapists have ridiculed the practice of EPAs in public newspapers. Their take-home message to the journalists was that EPAs are nothing but "voodoo treatments". For example, "Treat Me, but No Tricks Please", referring to the use of EPAs, is the title of an article published a few years ago in the influential New York Times (NYT) newspaper. In this article, a physical therapist is quoted to say, "More common are the voodoo treatments...and what might those be...none other than ice and heat and ultrasound...and laser". Such a description is both factually incorrect and culturally insensitive. Recently, more physical therapists have continued the mockery, leading another NYT journalist to write an article entitled "What to Look for in a Physical Therapist: Not all P.T.s are created equal. Find a professional who values evidence over anecdote", again referring to the "magical" nature of EPAs.

Is there research-based evidence behind the practice of EPAs? The answer is a resounding "yes"! Listed in databases like PubMed and PEDro are tens of thousands of peer-reviewed articles in the field of EPAs, written in the form of randomized controlled trials, systematic reviews, and meta-analyses that clinicians and scientists can consult and use for clinical and research purposes. For example, Bjordal et al., in 2015, reported that there were, in the PEDro database alone, over 3200 randomized controlled EPA trials and that 57% of them were published after 2004. In 2021, Page 1 reported the results of an informal PubMed search in which over 220,000 papers on electrotherapy and ultrasound were found, as opposed to only 160,000 on therapeutic exercises and 26,000 on manual therapy techniques. Research-based evidence can also be found in several academic textbooks dedicated to the field of EPAs.

Now, what about the therapeutic efficacy of EPAs? Before answering this important question, one must first keep in mind that the field of EPAs is primarily defined as the extracorporeal application of four types of energy (thermal, mechanical, electrical, and electromagnetic), using a variety of equipment, to human soft tissues for modulating signs and symptoms, as well as promoting tissue healing and body function. Secondly, one must take into consideration that EPAs are therapeutic interventions used concomitantly with a broad range of other interventions such as, but not limited to, therapeutic exercises, manual therapy techniques, medications and surgical techniques, to manage a wide array of osteo-musculoskeletal, neurological, dermatological and cardio-respiratory disorders. Some are EPAs used as a monotherapy. The use of EPAs, combined with therapeutic exercises and manual therapy techniques, represents the core foundation of physical therapy interventions.

Are EPAs efficacious therapeutic interventions? The answer is "yes". Search results from databases reveal many randomized controlled trials, systematic reviews and meta-analyses demonstrating the efficacy of EPAs for a wide range of body disorders. For example, well-established is the efficacy of transcutaneous electrical nerve stimulation (TENS) for pain, neuromuscular electrical stimulation (NMES) for quadriceps function following knee reconstruction, low-intensity pulsed ultrasound (LIPUS) for bone fracture repair, shockwave therapy for musculoskeletal disorders, and electrical stimulation for tissue repair and wound management. There is also evidence of therapeutic efficacy for other EPAs, for example, mechanical traction for lumbar disorders, cryotherapy for pain and swelling, and ultraviolet B therapy for dermatoses, and low-level laser therapy for osteoarthritis.

It is, of course, beyond the scope of this short commentary to list all the thousands of research-based articles related to the field of EPAs, and to critically appraise each of them for therapeutic efficacy. Note that the evidence for efficacy listed above rests, in most cases, on the results of extensive systematic reviews and meta-analyses. As is the case with the use of manual therapy techniques, therapeutic exercises and medications, EPAs provide short-lasting therapeutic effects (up to a few hours) only and need to be re-applied several times over days and weeks in order to achieve a cumulative effect and therapeutic efficacy.
short, the above sampling of the evidence shows that EPAs are efficacious interventions. For physical therapists to continue to proclaim in public media that there is little to no research-based evidence, and no efficacy, behind the practice of EPAs is preposterous. Now is the time to dispel this message.

TWO: “THE BODY OF RESEARCH-BASED EVIDENCE IS OF POOR QUALITY”

A second belief and/or prejudice to further bash the field of EPAs is that its body of research-based evidence is of poor scientific quality when compared to other physiotherapy interventions and disciplines and, therefore, not credible enough to establish a scientific foundation behind the field of EPAs. In 2014, Moseley and colleagues investigated the quality of published randomized controlled trials, listed in the PEDro database, between subdisciplines in physiotherapy. Their results showed that the PEDro scores were higher when trial reports were more recent, published in English, and investigated EPAs. Nowhere in the scientific peer-reviewed literature can the authors find articles demonstrating that the quality of research articles in the field of EPAs is lower than that found in other subjects or disciplines in physical therapy. To continue to harbor and spread this message in public media is fallacious and unwarrantedly damaging to the field and its stakeholders. Now is also the time to dismiss such messages.

THREE: “THE PASSIVE DELIVERY NATURE OF EPAS MAY BE HARMFUL TO PATIENTS”

A third prejudice put forward to single out and undermine the practice of EPAs is that these agents, because passively delivered, may be harmful to patients. This assertion triggered a vigorous rebuttal, in the form of letters to the editor of Physical Therapy, from international stakeholders. The main rebuttal argument is that if the passive delivery nature of a therapeutic intervention may be harmful to patients, then what to make, for example, of the practice of manual therapy techniques in physical therapy, and of the usage of medications and surgical techniques in medicine? The relevant factor is delivering the most appropriate and necessary interventions at the proper time during the course of the patient’s disorder, regardless of whether these interventions are passively or actively delivered. There is absolutely nothing wrong with the passive delivery of therapeutic interventions per se as long as the treating physical therapist, physician or surgeon provides key instructions to his/her patient as to what to do and not to do at home, and until the next treatment, in order to maximize the therapeutic effectiveness of their passive treatments. However, it is wrong to deliver a therapeutic intervention, regardless of what it may be, without giving a clear set of instructions to patients to follow in order to ensure that he or she will take an active part in the whole therapeutic process. The bottom line is that the question of harm and benefit to the patient has nothing to do with the way a therapeutic intervention is delivered, i.e., passively, or actively, and much to do about the clinician’s responsibility to provide proper instructions aimed at maximizing the therapeutic intervention’s efficacy received by the patient. To claim that EPAs may be harmful to patients because they are passively delivered is prejudicial and as such must also be dismissed from the conversation.

FOUR: “PRACTITIONERS OF EPAS MAY BE COMMITTING FRAUD”

Despite the existence of substantial and high-quality research-based evidence behind the field of EPAs, some physical therapists have taken their bashing rhetoric to the next level. The target is no longer the electrophysical agents themselves. The target has expanded to include those tens of thousands of physical therapists and physical therapist assistants who dare to include EPAs in their plans of care. The discourse escalated from belief and prejudice to allegation and stereotype. For example, there is evidence to show that one day after the public release of the APTA’s Choosing Wisely list of Five Things Physical Therapists and Patients Should Question, the Workgroup Chair for the publication asserted, in an interview published on the reputable U.S. National Public Radio’s (NPR) website, “The evidence for any beneficial effect is nil. When I graduated with my physical therapy degree in 1979, these physical agents were a large part of practice. We’ve had a hard time getting rid of them. One reason why is that insurers continue to pay for passive physical agents. I know my insurer did”. The Workgroup Chair further commented, “The continuous passive motion machines were thought to prevent stiff knees in people who had knee replacements, but studies have found that they don’t help. It turned out to be a very expensive device that was not adding any quality. But people make money on the machines”. Another physical therapist later commented in the NYT article written by Smith “There is very little, if any, evidence that ultrasound does anything at all. But PTs are using it, and they are charging for it, and they’re getting reimbursed for it – basically for a technique that’s not effective. Is that fraud? I don’t know”.

CROSSING THE LINE

By insinuating in renowned and influential public media that physical therapists who include EPAs in their plans of care are committing fraud, without providing irrefutable evidence to support their remarks, have some of our colleagues "crossed the line"? The authors strongly believe that they did. Stereotyping and alleging that physical therapists and other health care professionals who use EPAs are unscrupulous and corrupt individuals is outrageous and unethical. Expressing personal opinions and feelings can be valid and healthy, but not when it unjustly hurts the reputation of others. There is simply no place for such abusive rhetoric.

CALLS TO ACTION

Stakeholders in the field of EPAs have endured enough mockery and denigration. The authors believe that it is
time for action. We share Dr. Page's viewpoint that there is an apparent conflicting and ironic messaging coming from the APTA, CAPTE, and FSBPT organizations regarding the practice of EPAs in the U.S.\textsuperscript{1} To the best of the authors' knowledge, the long-standing bashing rhetoric against EPAs remains unanswered by these three professional organizations. Logic dictates that when an official position is under attack (e.g., EPAs are voodoo interventions), it is only reasonable to expect that it be defended. Here is the irony. In remaining silent, it appears that these professional organizations have chosen to ignore the problem or to let the bashing rhetoric continue between physical therapists, and among physical therapists, journalists, and the public. The authors consider that the silence coming from these organizations may be perceived by some physical therapists as support for more abusive and denigrating rhetoric. The public often forges opinions about health professions based on what they read in renowned newspapers and on credible websites. As evidenced above, ignoring the bashing rhetoric against EPAs will not make it go away, nor will it deter others from making similar false and denigrating comments about them in the future.

**CALL TO APTA, CAPTE AND FSBPT**

Therefore, the authors call on the APTA, CAPTE, and FSBPT to address the problem by renewing their respective positions and support of EPAs in physical therapy. To list EPAs in the APTA's Guide to Physical Therapist Practice 4.0,\textsuperscript{2} mandate all physiotherapy schools to include them in academic curricula (CAPTE),\textsuperscript{45} and test students on the topic of EPAs before licensing (FSBPT),\textsuperscript{46} conflicts with the resounding silence coming from these professional organizations regarding the long history of bashing against EPAs.

Are there similar adverse reactions from groups of physical therapists, or physical therapy organizations, against the practice of EPAs in other countries around the world? The answer is a definite "no". Just like Canada, Australia and Great Britain, to name only a few, the U.S. (APTA) is a one of the 127-country members of the World Physiotherapy (WP)\textsuperscript{47} which advocates for the profession by representing national physiotherapy associations on the world scene. Before admission to WP membership, a national physiotherapy association must meet set criteria. For example, physical therapists from each national association must be able to implement a variety of therapeutic physiotherapy interventions, including integumentary repair and protection techniques, electrotherapeutic modalities, physical agents and mechanical modalities safely and effectively.\textsuperscript{48} Moreover, the U.S. (APTA), via its own Academy of Clinical Electrophysiology & Wound Management (ACEWM)\textsuperscript{49} which includes the Biophysical Agents subgroup,\textsuperscript{50} is also a member of the WP’s International Society for Electrophysical Agents in Physiotherapy (ISEAP).\textsuperscript{51} As such, the APTA is rightly aligned with the rest of the world as to the inclusion of EPAs in physical therapy (PT) and physical therapy assistant (PTA) academic programs. The problem is not with the official recognition of EPAs in US physiotherapy curricula. The problem is with those members of the APTA who chose to bash EPAs in U.S. public media without any response from the official governing bodies of physical therapy in this country, namely the APTA, CAPTE and FSBPT organizations.

U.S. physical therapists (PTs) and physical therapist assistants (PTAs), as well as the public - our present and future patients - are confused. Should PTs and PTAs continue to include EPAs in their plan of care? Should the public seek therapeutic services from those PTs and PTAs who include EPAs in their plan of care, or those who do not? Also confused are university and college faculty members and academic administrators. Should the teaching of EPAs in the PT/PTA programs in the U.S. be augmented, maintained, diminished, or simply abandoned?\textsuperscript{52,53} To let this abusive rhetoric continue without an official rebuttal response from the APTA, CAPTE or FSBPT will simply add to the confusion, and further tarnish not only the reputation of all stakeholders in the field of EPAs but, also, that of the physical therapy profession as a whole, in the public arena.

**CALL TO PHYSICAL THERAPISTS**

Fraud, abuse, and waste are, unfortunately, part of the delivery of healthcare services around the world. In the U.S., health insurance fraud cost is estimated today to be approximately $308 billion.\textsuperscript{54} The physical therapy profession, like medicine and any other health profession, is no exception. The sad reality is that there will always be unethical health practitioners. What can be done to counter fraud, abuse, and waste in physical therapy?

The authors call on our physical therapist colleagues to stop using newspapers and social media platforms as communication media through which they can expose their grievances against the practice and stakeholders of EPAs. Instead, we strongly recommend that they turn to professional and relevant published resources on the subject. For example, in its document entitled "Preventing Fraud, Abuse, and Waste: A Primer for Physical Therapists",\textsuperscript{55} the APTA outlines the problems and provides physical therapists with ways to deal with them. The FSBPT, in one of its forum-type articles, entitled "Fraudulent Billing and the Role of the Jurisdiction Licensing Board",\textsuperscript{56} also provides useful information on how to deal with fraudulent practices. Physical therapists who have solid reasons or facts to suspect fraud, abuse, or waste, not only related to the application of EPAs but also of any other therapeutic interventions listed in the APTA’s Guide to Physical Therapist Practice 4.0,\textsuperscript{2} have the obligation, under their Code of Ethics,\textsuperscript{57} to report their concerns to their respective state licensing boards, not to journalists. One other thing physical therapists could do is read the blog article, published on the WebPT platform, entitled "So you wanna blow the whistle: How to report fraud and abuse in health-care".\textsuperscript{58} The bottom line is that only the licensing boards, not physical therapists and journalists, have the statutory authority to address malpractice, fraud, abuse and waste in physical therapy in the U.S.

The authors also call on physical therapists to use common sense and display ethical behavior when dealing with the topic of EPAs or any other topics in the profession, before interacting with public media. Claiming that EPA interventions are voodoo treatments shows ignorance of the
overwhelming body of research evidence behind EPAs. Suggesting that physical therapists who include EPAs in their plan of treatment may be committing fraud is unethical. The authors urge physical therapists to stop making unfounded sensationalistic comments to the public media. They ask them to test their beliefs, prejudices and allegations against the truth before stereotyping the stakeholders in the field of EPAs. There is simply no substitute for using sound judgment and moral principles, regardless of the situation one may wish to comment on.

CONCLUSION

Stakeholders in the field of EPAs have endured enough invective. The goal of this commentary is to put an end to the backlash of EPAs. Calling on the APTA, CAPTE, and FS-BPT to clarify their existing positions on the recognition and practice of EPAs appears to us as one of the best antidotes against further bashing rhetoric. The authors trust that their intervention will calm, and hopefully end, the mocking and denigrating rhetoric behind the usage of EPAs. To call on physical therapists to report their grievances against the inappropriate use of EPAs to their respective state licensing board, as opposed to the public media, is just common sense and the right and ethical thing to do.

Freedom of expression is a fundamental right, and everyone is entitled to express his or her own beliefs, prejudices, allegations, and stereotypes, albeit within certain limitations. However, the authors are convinced that it is unwise, unethical, and self-serving to do so without testing them against the facts and without full, unbiased consideration of what such rhetoric might do to the respected, good reputation of other clinicians, like physical therapists, physical therapist assistants, athletic trainers and sports physicians who make regular and evidence-based use of EPAs in their plans of care for the benefit of all their patients, which also include amateur and professional athletes from around the world.59

Lastly, and perhaps more importantly, the American public needs to know the truth about the usage of EPAs in physical therapy. They need to know that EPAs, when used based on the best evidence and concomitantly with other therapeutic interventions, are efficacious in that they provide proper symptom management and positively affect soft tissue healing, commonly without side effects, in comparison to medications and surgical techniques, which come with their respective load of potential side effects and severe risks to health. The profession of physical therapy in the U.S. has much to gain by rectifying the abusive rhetoric against the EPAs put forward in renowned public media by some of its members. In doing so, the APTA will exert its leadership by reaffirming its compliance with the World Physiotherapy organization as to the curriculum related to and practice of EPAs, in addition to recognizing all its members who belong to its ACEWM - Biophysical Agents subgroup, as well as all those international members who belong to the ISEAP. By putting an end to the bashing of EPAs, the ultimate winners will be the patients and athletes we serve.

CONFLICT OF INTEREST

Dr. Belanger reports potential conflicts of interest regarding textbook royalties, consulting fees and payment for expert reports related to the field of EPA. Dr. Selkowitz reports a potential conflict of interest regarding his former role as an international content expert for ElectroPhysical Forum. Dr. Lawson reports a potential conflict of interest regarding his role as Editor of the Journal of Electrophysiology and Wound Management, and as Vice-Chair of the Biophysical Agents Special Interest Group of the APTA.

Submitted: April 23, 2023 CDT, Accepted: August 16, 2023 CDT
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MSK ULTRASOUND BITES: TIPS AND TRICKS

THE APPLICATION OF MUSCULOSKELETAL ULTRASOUND IN THE DIAGNOSIS OF SUPRASPINATUS INJURIES

Robert C. Manske, PT, DPT, MEa, SCS, ATC, CSCS, FAPTA
Michael Voight, PT, DHSc, SCS, OCS, ATC, CSCS, FAPTA
Phil Page, PT, PhD, ATC, CSCS, FACSM
Chris Wolfe, PT, DPT, OCS, Cert MDT

Abstract
Musculoskeletal (MSK) diagnostic ultrasound has become an invaluable tool in the assessment of musculoskeletal pathologies, including rotator cuff injuries, notably the supraspinatus tendon. MSK ultrasound, characterized by high-resolution and real-time imaging capabilities, presents a cost-effective, safe, and patient-friendly alternative. This modality allows precise visualization of the supraspinatus tendon’s structure and function, aiding in the identification of pathological alterations, such as thickening, thinning, or disruption, critical in diagnosing conditions like tendonitis, partial tears, and ruptures. In this manuscript, we detail the diagnostic utility of MSK ultrasound in assessing supraspinatus injuries, discussing the indications, techniques, and findings relevant to the supraspinatus tendon. Moreover, we examine the advantages and limitations of this imaging modality and provide a step-by-step guide for accurate supraspinatus tendon evaluation. The evidence suggests that MSK ultrasound is a dependable and cost-effective imaging technique for diagnosing supraspinatus injuries when executed by skilled operators.

Keywords: MSK ultrasound, supraspinatus, rotator cuff, diagnostic imaging, tendon injuries

Introduction
MSK ultrasound is increasingly recognized as a primary investigative tool for a wide array of musculoskeletal disorders, especially those affecting tendons, ligaments, muscles, and joints. As a real-time, non-invasive, cost-effective, and dynamic imaging technique, MSK ultrasound provides unprecedented insights into soft tissue structures that may be difficult to examine using conventional imaging modalities. The supraspinatus muscle, a crucial component of the rotator cuff, plays an essential role in shoulder function. Injuries to the supraspinatus tendon are relatively common and can lead to pain, weakness, and restricted range of motion. Therefore, accurate diagnosis is vital for effective management. Traditional methods of diagnosing supraspinatus injuries include physical examination, magnetic resonance imaging (MRI), and arthrography.

Although MRI has historically been the primary imaging modality, MSK ultrasound has emerged as a reliable alternative, offering real-time dynamic evaluation, accessibility, and cost-effectiveness.

The Role of MSK Ultrasound in Diagnosis of Supraspinatus Injuries
Diagnostic precision is paramount, and herein lies the strength of MSK ultrasound for supraspinatus tendon injuries. A recent meta-analysis concluded that MSK ultrasound is highly sensitive and specific in diagnosing supraspinatus tears, equivalent to MRI imaging.1 MSK ultrasound, with its sophisticated imaging, facilitates precise visualization of the supraspinatus tendon’s internal milieu. This advanced imaging technique allows medical professionals to examine the internal structures of the shoulder in real-time, producing detailed and accurate images of the supraspinatus tendon. With its ability to identify pathologic changes over time and to help guide treatment, MSK ultrasound has become an integral part of the management of these types of injuries. By providing a detailed, real-time view of the anatomy and pathology within the tendon, the use of MSK ultrasound can help to ensure that patients receive timely and appropriate treatment in order to achieve the best possible outcomes. As an asset in the clinician’s diagnostic toolkit, it’s invaluable for detecting pathological shifts over time and is pivotal for therapeutic strategy formulation. Key advantages include

1. **Cost-effectiveness:** In stark contrast to other imaging modalities like MRI, MSK ultrasound is relatively inexpensive.

2. **Dynamic assessment:** MSK ultrasound allows for real-time visualization of the rotator cuff during shoulder movement, aiding in the evaluation of tendon function and potential impingements.

3. **Immediate feedback:** Instantaneous imaging results facilitate prompt diagnosis and patient communication.

4. **Radiation-free:** Unlike radiographs and computed tomography (CT) scans, ultrasound does not involve ionizing radiation exposure, making it a safer option, especially for repeat evaluations.

5. **Accessibility:** Ultrasound equipment is portable and can be used in a variety of clinical settings, including the outpatient clinic, emergency department, and sports events.
Yet, MSK ultrasound isn't devoid of challenges. Diagnostic accuracy is intricately tethered to the operator's proficiency, and certain extrinsic factors, such as patient anatomy or equipment settings, can influence image clarity.

**Ultrasound Imaging Techniques**
The European Musculoskeletal Ultrasound Study Group in Physical Medicine Rehabilitation and Ultrasound Group of the International Society of Physical Medicine Rehabilitation (EURO-MUSCULUS/USPRM) have published guidelines on the basic and dynamic protocols for shoulder scans. The technique encompasses:

1. **Patient positioning:** The patient should be seated with the elbow flexed at 90 degrees and the hand resting on the ipsilateral thigh. This position relaxes the deltoid muscle, improving visualization of the supraspinatus tendon.

2. **Transducer selection:** A high-frequency linear transducer (7-12 MHz) is recommended for superficial structures like the supraspinatus tendon.

3. **Image acquisition protocol:** Start by identifying the acromion and the greater tuberosity of the humerus. The supraspinatus tendon can be seen running between these two landmarks. Begin with a longitudinal view of the supraspinatus tendon, scanning from its origin at the supraspinatus fossa to its insertion at the greater tuberosity of the humerus. The transducer is then rotated 90 degrees for transverse views.

4. **Dynamic assessment:** Perform shoulder abduction and internal/external rotation while observing the tendon's movement, looking for dynamic impingements or subacromial-subdeltoid bursal effusion.

5. **Interpretation:** Use a systematic approach to evaluate the tendon for signs of tendinopathy (thickening, loss of fibrillar architecture), partial tears (discontinuity of the tendon fibers), or full-thickness tears (complete disruption of the tendon with fluid filling the defect).

**Diagnostic Findings on MSK Ultrasound**
Ultrasound can discern normal from pathological tendons, showcasing signs of tendinopathy, partial and full-thickness tears, bursal effusions, calcific tendinitis, and hyperemia. Diagnostic findings on MSK ultrasound include:

1. **Normal tendon:** A normal supraspinatus tendon appears as a fibrillar, hyperechoic structure.

2. **Tendinopathy:** Characterized by tendon thickening, heterogeneous echotexture, and reduced echogenicity.

3. **Partial-thickness tears:** Display as hypoechoic or anechoic defects within the substance of the tendon.

4. **Full-thickness tears:** Presented by a discontinuity of the tendon or complete anechoic gap in the tendon with visualization of the humeral head beneath.

5. **Bursal effusion:** An anechoic or hypoechoic region can represent bursitis or fluid from a tear. Elevation of the echogenic bursal line may be noted, suggesting inflammation.

6. **Calcific tendinitis:** Manifests as hyperechoic foci within the tendon with posterior acoustic shadowing.

7. **Doppler imaging:** Hyperemia or increased blood flow can indicate inflammation or tendinopathy.

**Challenges and limitations include**:
- **Operator dependency:** Ultrasound requires skilled professionals for accurate interpretation.
- **Cannot visualize structures deep to bone:** Ultrasound is limited in visualizing structures beneath bony surfaces.
- **Overlying structures:** Fat or scar tissue can occasionally obscure the view.
- **Limited field of view:** Smaller field of view compared to MRI.

**Conclusion**
MRI offers superior contrast resolution and a more extensive field of view. MSK ultrasound provides unmatched benefits in dynamic assessment, cost-effectiveness, and immediate results. However, it is operator-dependent, and image quality may vary depending on certain patient populations. With appropriate training and expertise, MSK ultrasound serves as an invaluable tool in the evaluation of supraspinatus injuries. Both modalities can co-exist harmoniously in a diagnostic algorithm, with the choice depending on clinical needs, patient factors, and resource availability.

MSK ultrasound has firmly established its role in the diagnostic pathway of supraspinatus injuries. Its capacity for dynamic assessment, accessibility, and cost-effectiveness makes it a valuable tool in both initial assessment and follow-up evaluations of these injuries. Using MSK ultrasound, healthcare professionals can accurately diagnose supraspinatus injuries and guide appropriate treatment planning. Moreover, MSK ultrasound can help track healing progress and assess the effectiveness of treatment.
References:


**PATIENT POSITION**

**Figure 1a: Patient position.**
The patient can be in a seated position with their upper extremity placed in a Modified Crass Position. The Modified Crass Position is described with the patient's hand placed near the ipsilateral hip and the elbow directed posteriorly. Have their hand as high up on their hip region as they can tolerate and achieve. This placement allows for the distal supraspinatus tendon to be positioned anterior to the acromion. This position will be maintained for both the short axis and long (oblique) axis transducer placement.

**Figure 1b: Transducer placement.**
Short Axis (SAX) probe placed parallel to the floor and perpendicular over the supraspinatus tendon as it inserts on the humeral head.

**Figure 1c: Transducer placement.**
Long axis (LAX) or oblique axis probe placed parallel with the supraspinatus tendon as it inserts on the humeral head.
Figures 2a and 2b: Proximal Supraspinatus Tendon in Short Axis View.
Look for the bony cortex of the humeral head (the rim) and then the supraspinatus tendon that is described as a “tire on the rim”. The tendon lies on the humeral head like a tire wraps around a car rim and remains uniform in nature. Identify the humeral head, hyaline cartilage (anechoic interface above the cortex), supraspinatus tendon and the potential space for the bursa. One may see a layer of fat superior to the tendon and then identify the deltoid muscle. In a short axis view, the normal supraspinatus tendon over the humeral head is of uniform thickness.

Figures 3a and 3b: Supraspinatus Tendon in Long Axis View.
The long axis view technique is more of an oblique view to remain parallel with the tendon fibers. The supraspinatus tendon tapers sharply onto the humeral head. Identify the bony landmarks initially, the sloping contour of the greater tuberosity where the tendon attaches, the indentation or concavity of the humeral head, and the anatomical neck. Criteria for normal tendon attachment would be the tapering contour of the tendon to a nice sharp point and the linear anechoic margin known as the tendon footprint. Superior to the tendon would be the bursa and deltoid muscle.
TENDINOSIS IN SHORT AXIS (SAX)

Figure 4:
Supraspinatus tendon in short axis view shows a thickness > 6 mm. This thickness greater than 6 mm is known to indicate increased cellularity and is one of the criteria that is used to diagnosis tendinosis.

FULL THICKNESS TEAR IN SHORT AXIS (SAX)

Figure 6:
Supraspinatus full thickness tear in short axis view showing advanced degenerative changes along with a hypoechoic tendon and loss of visualization of the fibrous tendon fibers. Above the tendon tear, is the bursal effusion sagging down into the full thickness tear.

TENDINOUS FAILURE IN LONG AXIS (LAX)

Figure 5:
If the tendon insertion has been compromised, then one will see some “retraction” on the ultrasound image shown here at the distal tendon insertion. Note the anechoic distal attachment indicating a partial tear.
It is clear that for the last fifteen years, the primary care physician has been proclaimed the “gatekeeper” to healthcare in America. There have been billions of dollars invested over the last decade, in particular, in the consolidating of large primary care groups in order to drive margins, particularly in the Medicare Advantage space, and control the healthcare spend by attempting to change healthcare delivery. However, a new reality is increasingly being acknowledged by the employers and payors whose healthcare plan members are those who are still working and on employer, or commercial, insurance plans. This reality is summarized by the following facts:

- 27% of the total cost of care for commercial insurance is spent on MSK services

- Myriad data and publications demonstrating the importance of a "PT-First" strategy in dramatically reducing total MSK spend including
  - 30% reduction in imaging
  - Up to 68% reduction in surgeries
  - 70% reduction in ER visits for non-emergent MSK problems

- 76% of employers rank MSK conditions as top three cost drivers

It is clear that the physical therapist is now poised to be the new ‘gatekeeper’ in the MSK space and the key to developing an effective value-based MSK strategy to reduce the total cost of care. It is my belief, and the belief of Genie Health, that the role of the physical therapist in the MSK space will be one of rapid ascension as the value to the healthcare system that PTs will bring to VBC strategies will be measurable and extremely impactful.

However, I also believe that there are several key challenges in developing a VBC strategy for MSK care that is scalable nationally. These challenges include (1) the ability standardized care pathways so outcomes can be measured and improved; (2) the ability to effectively leverage technology to address the shortage of physical therapists at a time when the capacity is less than the demand for their services; and (3) the ability to reproducibly diagnosis movement problems virtually and customize rehabilitation solutions that focus on real improvements in total physical well-being. This last issue is the challenge I wish to focus on in this Editorial. I believe that a standardized algorithm for evaluating human movement that can be deployed virtually is a strategic must for large-scale and nationwide virtual diagnosis of MSK disorders. I am going to highlight two of the thought leaders in the functional movement screen space, Lee Burton and Gray Cook, from FMS. They have a new App called Symmio (www.symmio.com) that enables therapists to deploy a virtual functional movement evaluation and corrective exercises or rehabilitation to the individuals who are desiring to maximize their physical well-being. At Genie Health, partnering with thought leaders like Gray and Lee are central to our strategy and our position as the leading technology platform in VBC Healthcare Delivery in the MSK Space. Here’s the interview:
Q: Lee, why did you develop Symmio?
A: FMS has known for many years we needed a more scalable and holistic solution to better address movement health. From data and experience, we were guided to look at lifestyle and behavioral factors, that when coupled with movement screening, could give a more complete picture of someone's MSK health. The fusion of this holistic mindset and technological advances has allowed us to create a very simple and user-friendly platform.

Q: What makes it valuable to therapists?
A: Symmio allows patients to self-assess the key contributors to overall MSK health and wellness and then report that data to the provider. Doing this prior to a visit can provide valuable insight into not only movement limitations but other lifestyle factors that may be contributing to their MSK problem. This process will provide awareness to both the clinician and patient of the importance of the lifestyle component.

Q: What problems do you feel Symmio can address in helping PT’s make virtual diagnosis for movement disorders?
A: We are all getting less time with our patients so we must be creative in how we collect patient assessment data. By leveraging technology and empowering the patients we can facilitate and enhance the patient interaction. The clinician will now be armed with not only movement data but with additional valuable lifestyle information which will allow a much more targeted and efficient encounter. Even on discharge the providers can stay engaged through this platform and intervene prior to more significant problems arising.

Q: How about prescribing treatments?
A: Symmio provides automated exercises and tips to specifically target the areas that were found to be most problematic. This programming, along with the clinician’s skill set on improving movement problems will most certainly enhance the patient experience and overall outcomes.

In conclusion, we believe that physical therapy will play an increasingly central role in the VBC Strategy to reduce the total cost of MSK healthcare spend. Genie Health is committed to partnering with technologies like Simio in order to fulfill our mandate to enable physical therapy providers to drive value in the healthcare marketplace and establish PT’s as the epicenter for triaging the vast majority of MSK healthcare delivery.
Deliver a virtual therapy solution to your organization

Genie Health at a glance...

Founded by two prominent orthopedic surgeons and leveraged by two of the top 10 largest orthopedic groups in the country, Genie Health is managed by therapists and industry experts.

Featuring a monitored HEP using computer vision, Genie Health offers both fee-for-service and value-based-care models on the same platform.

PT Genie
Digital physical therapy solution combining remote monitoring and telehealth

Sports Genie
In-clinic and remote sports/functional assessment and management

WoRx Genie
Risk assessment and remote management tools for occupational health

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Drive revenue through remote monitoring
ABSTRACTS FROM THE ORTHOPAEDIC CONGRESS
SEPTEMBER 19-23, 2023. | BOSTON, MASSACHUSETTS

The International Journal of Sports Physical Therapy is pleased to publish abstracts from the thirteenth Orthopaedic Summit (OSET) taking place in Boston, September 19-23, 2023. The IJSPT hosted the third 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 20 research abstracts were accepted and presented at OSET 2023. Awards for outstanding abstracts were presented on September 22.

The 2023 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.

Phil Page PhD, PT, ATC
Chuck Thigpen PhD, PT, ATC
OSET Research Committee Co-Chairs
ABSTRACT 1
Effects of Blood Flow Restriction (BFR) on the Shoulder's Internal and External Rotators Post-Activation Potential (PAP) Performance using Hand Held Dynamometry (HHD).
Hochrein A, Keller K, Stoddard S, Riemann BL, Davies GJ.
Waters College of Health Professions, Department of Rehab Sciences, Department of Health Sciences & Kinesiology, Georgia Southern University, Savannah, GA.

Introduction: Subjects use a variety of techniques to enhance performance prior to activity. Research demonstrates BFR can recruit fast twitch muscle fibers sooner due to the metabolic changes that occur in the muscle. (Lambert et al 2023). This study wanted to determine if using BFR could also be used to enhance muscle performance. Bowman et. al 2020, Lambert et. al 2021 performed upper extremity (UE) training using BFR and found that low-weight resistance BFR training provided a greater increase in strength and hypertrophy in the UE and distal muscle groups when compared to a control group that did not use BFR. Garbisu-Hualde et al found PAP was most beneficial when used with loads that began at 65% of 1 Repetition Maximum (1RM).

Purpose: Perform a prospective RCT using BFR on UE to assess muscle PAP/performance.

Hypothesis: BFR will demonstrate significant increases in PAP/performance on HHD for experimental groups 1 and 2 compared to control group.

Methods: Subjects: 40 (27 females) physically active subjects, ages 18-30, were randomized into the 3 groups. Methods: Resting limb occlusion pressure (LOP) was measured using a Doppler ultrasound (Karanasios et. al 2022). Subjects performed a warm-up using the UE ergometer and stretching of the shoulder. HHD measured isometric internal/external rotation (IR/ER) strength of the shoulders for pre/post-testing. Experimental group 1 performed ER/IR using BFR at 50% LOP in the dominant UE using a resistance Theraband for 4 sets of 30/15/15/15 reps at 6-8 on the Omni-Resistance scale. Group 2 performed a similar protocol performing 15/8/8/8 reps. Control group did not perform BFR exercises.

Statistics: Pre-post within group changes and between group changes for both the control and experimental groups were assessed using repeated measures ANOVA.

Results: There was no statistically significant difference in the change in HHD for shoulder ER on the dominant arm between groups as determined by one-way ANOVA (F(2,37) = 2.505, p = .095). There was no statistically significant difference in the change in HHD for shoulder IR on the dominant arm between groups as determined by one-way ANOVA (F(2,37) = 1.353, p = .271). There was no statistically significant difference in the change in HHD for shoulder ER on the non-dominant arm between groups as determined by one-way ANOVA (F(2,37) = .257, p = .775). There was no statistically significant difference in the change in HHD for shoulder IR on the non-dominant arm between groups as determined by one-way ANOVA (F(2,37) = 1.490, p = .239).

Discussion: Results did not support the hypothesis, therefore, using BFR for PAP/performance enhancement was not effective within the design of this study.

Summary/clinical application: More research is needed to determine the effectiveness of BFR in facilitating various aspects of human performance.

Presenting author: gdavies@georgiasouthern.edu
ABSTRACT 2

Effects of Blood Flow Restriction on Upper Extremity to Assess Neurocognitive Performance using Blaze Pods.

Keller K, Hochrein A, Stoddard S, Riemann BL, Davies GJ.
Waters College of Health Professions, Department of Rehab Sciences, Department of Health Sciences & Kinesiology, Georgia Southern University, Savannah, GA.

Introduction: Subjects use a variety of techniques to enhance performance prior to activity. Some of the methods involve static stretching, dynamic stretching, foam rollers, percussion devices, etc. The research demonstrates Blood Flow Restriction (BFR) can recruit fast twitch muscle fibers sooner due to the metabolic changes that occur in the muscle. Therefore, this study wanted to determine if using BFR could also be used to enhance neurocognitive reactive performance. There is limited research on UE testing using BFR with outcomes measuring neurocognitive testing. The neurocognitive Open Kinetic Chain (OKC) and the Closed Kinetic Chain (CKC) Blaze Pod reactive testing have not been used as outcome measures in any published studies to date.

Purpose: Perform a prospective randomized controlled trial using BFR on the upper extremity (UE) to assess neurocognitive reactive performance using the Blaze Pods.

Hypothesis: BFR will demonstrate significant increases in CKC and OKC neurocognitive reactive performance with Blaze Pods for experimental groups 1 and 2 compared to the control group.

Methods: Subjects: 40 (27 females) physically active subjects as per ACSM guidelines, ages 18-30, were randomized into three groups (control, experimental 1, and experimental 2) using randomizer.org. Resting limb occlusion pressure (LOP) was measured using a Doppler. Order of neurocognitive reactive performance testing was randomized. Subjects performed a warm-up using the UE ergometer and stretching of the shoulder. The Blaze Pods measured neurocognitive reactive performance in Closed and Open Kinetic Chain for pre/post-testing, then rested 5 minutes between testing. Experimental group 1 performed shoulder external rotation (ER)/internal rotation (IR) using BFR at 50% LOP in the dominant UE using a resistance Theraband for 4 sets of 30/15/15/15 repetitions at 6-8 on the Omni-Resistance scale. Experimental group 2 performed a similar protocol with 15/8/8/8 repetitions. Control group did not perform BFR exercises.

Statistics: Pre-post within group changes and between group changes for both the control and experimental groups were assessed using repeated measures ANOVA.

Results: There was no statistically significant difference in the change in average CKC tests between groups as determined by one-way ANOVA ($F(2,37)=1.693$, $p=.198$). There was no statistically significant difference in the change in average OKC tests between groups as determined by one-way ANOVA ($F(2,37)=1.052$, $p=.359$).

Discussion: Results did not support the hypothesis; therefore, using BFR for neurocognitive performance enhancement was not effective within the limitations of the design of this study.

Summary and Clinical Application: More research is needed to determine the effectiveness of BFR in facilitating neurocognitive reactive performance.

Presenting author: gdavies@georgiasouthern.edu
ABSTRACT 3

The Reverse Lunge: A Descriptive Electromyographic Study.

Ferguson M, Krauss Z, Tran S, Hoogenboom B.
Grand Valley State University, Grand Rapids, Michigan.

Introduction: Activation of key lower extremity musculature throughout the reverse lunge movement via surface electromyography (EMG) was studied. Limited studies have examined the reverse lunge compared to other forms of the lunge. The purpose of this study was to describe EMG activation of key lower extremity muscles of bilateral limbs during the reverse lunge movement. A secondary purpose was to describe the phases of both limbs (stationary [stance] and lead [moving]) during the reverse lunge movement.

Methods: Surface electrodes were placed on target muscles (rectus femoris [RF], biceps femoris [BF], gluteus medius [Gmed], and gluteus maximus [Gmax]) of both lower extremities using standard Seniam placements. Maximum voluntary isometric contractions of each muscle were performed for use in normalizing the EMG data. Verbal cues, a mirror, tape marks on the floor, and a metronome were utilized to normalize the movement across all subjects. Each participant was allowed two practice repetitions of the reverse lunge, on each limb, prior to data collection. EMG data were collected bilaterally during four reverse lunges trials (4 left lead limb, 4 right lead limb), and phases of the lunge were marked during EMG to aid in analysis of phases. Left lead leg lunges were analyzed using Root Mean Squared EMG values and mean maximum and mean average muscle activation throughout the movement were calculated. Descriptive terminology was created to describe the phases of the lunge for the stationary and lead limbs.

Results: Twenty-one healthy, active subjects participated in this study and data from nineteen subjects (10 females, 9 males, mean age 24.05 +/- 1.32 yrs) were analyzed. All values are reported as a percentage of the MVIC (%MVIC). Mean maximum muscle activations in the lead limb during the reverse lunge movement were BF 36.6%, RF 105.67%, GMed 34.29% and GMax 34.88%. The stationary limb mean maximum muscle activations were BF 17.11%, RF 36.16%, GMed 49.2% and GMax 36.61%. Throughout the movement, average muscle activity values in the lead limb were RF 32.41%, BF 10.72%, GMed 11.73%, GMax 12.68% and RF 13.55%, biceps femoris 7.04%, GMed 15.35%, and GMax 14.51% in the stationary limb. All four muscles of the stationary limb and the lead limb RF displayed greatest maximum muscle activations during the rising half of the lunge.

Discussion: Across subjects, only two muscles achieved a strengthening stimulus in their maximum muscular contractions: the lead limb RF (105.67% MVIC) and the stationary limb GMed (49.2% MVIC) all other musculature performed at lower % MVIC’s suggesting stabilization or neuromuscular control functions. The rising phase provided greatest maximum activations during concentric contractions. As expected, average muscle activation throughout the movement was less than maximum activation for all muscles of both limbs showing low to moderate activation throughout. There was difficulty making direct comparisons to the literature due to the limited EMG research related to the reverse lunge.

Conclusions: Operational definitions of the reverse lunge movement were created to describe the phases of the reverse lunge. Only the lead limb RF and stationary limb GMed reached a strengthening stimulus during maximum muscle contractions. These definitions and results may be used both in clinical prescription of the reverse lunge as well as in future research. Future research should compare EMG activation between types of lunges and with the addition of weight.

Presenting author: hoogenbb@gvsu.edu
ABSTRACT 4
The Unilateral Hip Bridge Endurance Test A Reliability and Descriptive Study Involving Female Collegiate Athletes.
Greene C,1 Butowicz CM,2,3,4 Brody LT,1,5 Schuck DE6 Brown K,7 Brumitt J,1,8

Background: Functional performance tests (FPT) can be used to assess core stability and identify female collegiate athletes at risk for lower extremity injuries. Yet, a lack of consensus exists regarding which FPT best assesses core stability. The unilateral hip bridge endurance test (UHBET) is an FPT, which uses a digital inclinometer to assess transverse pelvis displacement and may be well suited to assess core stability in athletic populations. However, the test reliability and descriptive data for collegiate female athletes are unknown.

Purpose: To establish the intra and interrater reliability for left and right sides and the average score for the UHBET using a digital inclinometer for homogenous (Phase I) and heterogenous (Phase II) cohorts of female collegiate athletes. A secondary purpose was to report UHBET descriptive scores for a cohort of female collegiate athletes and if differences exist between levels of competition and sports (Phase III).

Study Design: Descriptive Study.

Methods: Phase I established UHBET intra and interrater reliability using a sample of female collegiate athletes (13 lacrosse athletes). A digital inclinometer was strapped across the athlete’s pelvis to monitor pelvic neutrality in the transverse plane while the sagittal plane was assessed visually. The test terminated when the pelvis tilted greater than 10 degrees in the transverse plane or failure to maintain neutrality in the sagittal plane. The testing protocol from Phase I was repeated in a heterogenous sample (n=16, volleyball, soccer, cross-country/track & field, basketball, softball, and lacrosse) of female collegiate athletes. Three raters participated in Phases I and II. The raters were the primary investigator ([PI] 37 years of experience as a physical therapist and a certified athletic trainer), the second rater was a certified athletic trainer (nine years of experience), and the third rater was a physical therapist assistant (10 years of experience). The PI was the rater for establishing the intrarater reliability for both samples. In Phase III, the PI, using the same protocol, collected test scores of 192 female collegiate athletes representing nine sports (volleyball, soccer, cross-country, basketball, tennis, lacrosse, track & field, softball, and dance) from five universities (three National Association of Intercollegiate Athletics [NAIA] and two National Collegiate Athletic Association [NCAA] Division III Universities). ANOVA was conducted to determine differences between sports and the level of competition.

Results: Excellent intrarater reliability was observed for the left and right sides, and the average score (ICC (3,2) = 0.90 or higher) for both the homogenous and heterogeneous cohorts. Excellent interrater reliability was observed for the left and right sides, and the average score (ICC (3,2) = 0.99 or higher) for both cohorts. Mean UHBET scores for female collegiate athletes were: left side = 48.57 sec, right side = 51.80 sec, and average score = 50.74 sec. Cross-country and track and field athletes demonstrated higher mean scores for the left and right sides and average scores (p < 0.05) than basketball and soccer athletes.

Conclusions: The UHBET using a digital inclinometer to assess core stability has excellent intra and interrater reliability in a homogeneous and heterogeneous group of female collegiate athletes. This study established descriptive data for UHBET in a heterogenous sample of collegiate female athletes and reported that cross-country and track and field athletes have higher UHBET mean scores for the left and right sides and average scores compared to basketball and soccer athletes. One explanation for this difference is that cross-country and track and field athletes may do more core training than the other athletes, but this is speculative. To determine if that is the case, future research would be needed.

1 Rocky Mountain University of Health Professions
2 Research & Surveillance Division, Extremity Trauma and Amputation Center of Excellence, Defense Health Agency
3 Department of Rehabilitation, Walter Reed National Military Center
4 Department of Physical Medicine & Rehabilitation, Uniformed University of Health Sciences
5 University of Wisconsin Clinics Research Park
6 Atrium Health Musculoskeletal Institute Orthopedics & Sports Medicine
7 Hutchinson Regional Medical Center
8 School of Physical Therapy, George Fox University

Presenting Author: charlesgreene86@gmail.com
ABSTRACT 5

A Novel Tool for Assessing Prone Plank Endurance A Descriptive Study of NAIA & NCAA Division III Female Collegiate Athletes.

Greene C,1 Butowicz CM,2,3,4 Brody LT,1,5 Schuck DE,6 Brumitt J1

Background: The prone plank endurance test (PPET) is reported to assess core stability with good to excellent intra-class correlation coefficient (ICC) reliability of 0.78-0.97. The range of reliability may be due to how pelvic neutrality during the test is determined and/or the number of attempts one is allowed to reestablish neutrality. To address this limitation, a prone plank measuring device (PPMD, patent pending) was created to provide objective information about the subject's pelvic neutral starting position. The reliability of this test using the PPMD is unknown.

Purpose: Establish the minimum detectable change (MDC95%) and the intra and interrater reliability of the PPET using the PPMD (Phase I). Report PPET descriptive scores using the PPMD in a group of female collegiate athletes and determine if differences in PPET hold times exist among various sports and levels of competition (Phase II).

Study Design: Descriptive Study

Methods: In Phase I, three raters consisting of the primary investigator (PI) with 37 years of experience as a physical therapist and a certified athletic trainer and two first-year physical therapy students tested 13 healthy active physical therapy students (8 males; mean (SD) age: 24.92 ± 2.32 years and mean (SD) exercise/wk 3.92 ± 0.86 hours) who were recruited from a midwestern university to perform the PPET using the PPMD on two separate occasions with 24-48 hours between testing sessions. The intrarater reliability and MDC95% were calculated from the data collected from the PI. The PPMD is a device made of PVC pipes with a crossbar that moves up and down along uprights. Once the subject assumed the PPET position, the rater visually determined pelvic neutrality, and the PPDM crossbar was applied to the posterior pelvis. The subject held this starting position as long as possible. The test terminated when the subject disengaged from the PPMD’s crossbar. In Phase II of the study, the PI collected PPET scores from 191 female collegiate athletes (mean (SD) age 19.48 ± 1.43 years, mean (SD) height 166.92 ± 7.60 cm, and mean (SD) weight 67.30 ± 12.77 kg) representing nine sports (volleyball, soccer, cross-country, basketball, tennis, lacrosse, track & field, softball, and dance) from five universities (three National Association of Intercollegiate Athletics [NAIA]) and two National Collegiate Athletic Association ([NCAA] Division III universities) using the PPMD protocol. An analysis of variance was conducted to determine if differences existed among sports, and an independent t-test was conducted to determine if differences existed among levels of competition.

Results: The MDC95% was 5.33 sec for the PPET using the PPMD. An excellent intra and interrater reliability was found for the PPET using the PPMD (ICC (3,1) = 0.99 and ICC (3,2) = 0.99, respectively). The mean PPET time for collegiate female athletes was 72.19 ± 28.45 sec. The mean PPET hold time was longer for track and field athletes than basketball athletes (mean difference 25.40 sec, p = 0.013) and softball athletes (mean difference = 26.66 sec, p = 0.028).

Conclusions: The PPET using the PPMD to assess core stability has excellent intra and interrater reliability. This study established descriptive data for the PPET using the PPMD for female collegiate athletes and determined if differences existed between female athletes in different sports. Also, this study reported longer PPET hold times in track and field athletes compared with their basketball and softball counterparts. It is possible that track and field athletes perform training exercises designed to increase the muscular endurance of the core; however, this is speculative. Future research is warranted to evaluate training habits for different sports.

1 Rocky Mountain University of Health Professions
2 Research & Surveillance Division, Extremity Trauma and Amputation Center of Excellence, Defense Health Agency
3 Department of Rehabilitation, Walter Reed National Military Center
4 Department of Physical Medicine & Rehabilitation, Uniformed University of Health Sciences
5 University of Wisconsin Clinics Research Park
6 Atrium Health Musculoskeletal Institute Orthopedics & Sports Medicine
7 Hutchinson Regional Medical Center
8 School of Physical Therapy, George Fox University

Presenting Author: charlesgreene86@gmail.com
Ultrasound-Guided Dry Needling: An Effective Treatment for Chronic Regional Pain Syndrome – A Scoping Review.
Foret W,^1^ Page P.

Background: Chronic Regional Pain Syndrome (CRPS) is a complex condition characterized by persistent pain, abnormal pain signaling, altered blood flow, temperature changes, muscle dysfunction, skin abnormalities, inflammation and autonomic dysfunction.1-8 Ultrasound imaging is used for diagnosing and treating soft tissue injuries, providing real-time visualization of musculoskeletal structures. By combining ultrasound guidance with dry needling, clinicians can precisely visualize target muscles, trigger points, and surrounding tissues, minimizing the risk and enhancing precision and effectiveness of treatments.

Purpose: Ultrasound imaging can be used to reveal abnormalities such as muscle edema, tenosynovial inflammation, and fibrosis often present in CRPS affected limbs.1-8 By identifying these structural changes, healthcare professionals can make more accurate diagnoses and safely develop personalized treatment plans tailored to each patient's specific needs. This review explored studies that utilized ultrasound guided dry needling to identify pathological myofascial patterns in tissue and effectively treat the dysfunction in patients with CRPS.

Study Design: Scoping review.

Methods: This scoping review was performed in May of 2023 using the following databases: CINAHL, Medline, SPORTDiscus, Academic Search, E-Journals, and Google Scholar. Boolean search terms included: "CRPS" OR "chronic regional pain syndrome" AND "ultrasound guided dry needling." Inclusion criteria were studies that utilized USGDN on patients with CRPS. Exclusion criteria were (1) abstracts without full text (2) literature reviews or Level 5 studies (3) studies that did not include patients with CRPS.

Results/Discussion: Thirteen- Level 4 case studies were selected. Several case studies1,3-9 utilized ultrasound guided dry needling to achieve uniform reversal and complete resolution of disability in 150 patients presenting in various phases of CRPS over the last 12 years. In a multi modality case study,7 stellate ganglion block (SGB) and continuous brachial plexus block (CBPB) were useful in pain management, however neither procedure had an effect on motor impairment; dry needling was found to effectively manage motor and sensorimotor impairment. Various outcome measures were utilized1-8: Numeric Pain Rating Scale; range of motion; edema; grip strength; Disability of Arm, Shoulder and Hand; painDETECT; Patient Health Questionnaire.

Conclusion: Ultrasound guided dry needling may be an effective treatment in managing pain and sensorimotor impairment in patients with CRPS, however due to the low level of evidence this topic warrants further study.

1 Moreau Physical Therapy, Baton Rouge, LA
2 FranU DPT Program, Baton Rouge, LA

Presenting author: wforet@moreaupt.com
Total Knee Arthroplasty and the Screw Home Mechanism of the Knee: A Scoping Review.

Rankin D, Page P.

Background: Total Knee Arthroplasty (TKA) is a common surgical procedure used to treat knee osteoarthritis (OA). Different surgical approaches are used, such as posterior cruciate retaining, posterior stabilized, and medial pivot implants. While these methods have successful outcomes and survivorship, these procedures will affect the kinematics and kinetics of the tibiofemoral joint. In particular, the 'screw-home' mechanism may be affected by different approaches.

Purpose: The purpose was to conduct a scoping review on the influence of TKA on the screw-home mechanism of the tibiofemoral joint.

Study Design: Scoping Review.

Methods: A systematic search was conducted in CINAHL, MEDLINE, and SPORTDiscus databases in June 2023 to identify studies that investigated the screw-home mechanism after TKA. Articles that were not in English, conducted in vitro, or did not include biomechanical analysis of the knee during gait or ADLs were excluded. After performing the database search, duplicates were removed and articles were filtered for inclusion criteria, then screened by their titles and abstracts. Two reviewers evaluated each article for inclusion/exclusion criteria. Inclusion and exclusion were tracked using the PRISMA-2020 process. Potential articles were retrieved and imported into Zotero for reference management.

Results: The initial search resulted in 20 studies of which 5 met inclusion/exclusion criteria and were used for the final analysis. Based on the studies analyzed, external rotation of the tibia was limited no matter the design of the TKA prosthesis.

Discussion/Conclusion: Key findings include that a TKA prosthesis interferes with the natural screw home mechanism of the knee and normal knee kinematics. The findings of this review showed that patients who undergo a TKA demonstrate deficits in reproducing the natural screw home mechanism of the knee.

1 Ochsner Therapy and Wellness, New Orleans, LA

2 DPT Program, Franciscan Missionaries of Our Lady University, Baton Rouge LA

Presenting author: danielle.rankin@ochsner.org

Martin RL,1,2 Takla A,3,4,5,6 Campbell A,7,8 Disantis A,1,9 Kohlriese D,10 Enseki K,11 Lifshitz L,12 Grant L,13 Bizzini M,14 Mike Voight,7,8 Ryan M,15 McGovern R,16 Timothy Tyler,17 Yael Steinfeld,18 Zhang Y.19

Background: Non-arthritic intra-articular hip pain can be caused by a variety of pathologies and lead to impairments in range of motion, strength, balance, and neuromuscular control. Although functional performance tests may offer valuable information, no clear consensus exists regarding the optimal tests for this patient population.


Study Design: Qualitative study.

Methods: 14 expert physical therapists from the International Society for Hip Arthroscopy participated in a modified Delphi technique. These panelists participated in three rounds of questions and related discussions to reach full consensus on the application and selection of functional performance tests.

Results: The panel agreed that functional performance tests should be utilized at initial evaluation, re-evaluations, and discharge, as well as a criterion for returning to sports. Tests should be used as multimodal measures of neuromuscular control, strength, range of motion, and balance. Tests should be applied in a graded fashion, depending on the patient's characteristics. Clinicians should select functional performance tests with objective scoring criteria and prioritize using tests with supporting psychometric evidence. A list of recommended functional performance tests with varying intensity levels was generated. Low-intensity functional performance tests encompass controlled speed in a single plane with no impact. Medium-intensity functional performance tests involve controlled speed in multiple planes with low impact. High-intensity functional performance tests include higher speeds in multiple planes with higher impact and agility requirements. Sport-specific movement tests should mimic the patient's particular activity or sport.

Conclusion: This international consensus statement provides recommendations for clinicians regarding selection and utilization of functional performance tests for those with non-arthritic intra-articular hip pain. These recommendations hope to encourage greater consistency and standardization among clinicians during a physical therapy assessment.

1 Department of Physical Therapy, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA
2 UPMC Center for Sports Medicine, PA, USA
3 Swinburne University of Technology – Hawthorn Campus, Health Science, Hawthorn, VIC, Australia
4 Australian Sports Physiotherapy – Ivanhoe, 3079, Australia
5 Hip Arthroscopy Australia, Melbourne, Richmond, VIC 3121, Australia
6 The university of Melbourne-Parkville, Melbourne AUS
7 Physical Therapy, Nashville Hip Institute at TOA, Nashville, TN 37203, USA
8 Physical Therapy, Belmont University, Nashville, TN 37212-3757, USA
9 UPMC Children's Hospital of Pittsburgh, Pittsburgh, PA USA
10 Orthopedic One, Physical Therapy, Upper Arlington, OH, USA.
11 University of Pittsburgh Medical Center, Rehabilitation Institute, Freddie Fu Center for Sports Medicine, Pittsburgh, PA, USA
12 Medical Director, The Israel Football Association, Ramat Gan, Israel
13 Physiotherapy, PhysioCure, Leeds, UK
14 Human Performance Lab, Schulthess Klinik, Zurich, Switzerland
15 The Steadman Clinic, Steadman Philippon Research Institute, Vail, Colorado
16 Texas Health Sports Medicine, Sports Medicine Research, Allen, TX 15013, USA
17 Physiotherapy, Pro Sports Physical Therapy, New York, USA
18 Faculty of Medicine, Tel Aviv Sourasky Medical Center, Tel Aviv, Israel.
19 Duquesne- China Health Institute, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA

Presenting author: ensekr@upmc.edu

Disantis A,1,2 Zhang Y,3 Martin RL,1,4

Background: The gluteus medius (GMed) is the largest hip abductor and therefore a critical muscle for normal stability of the hip and pelvis during weightbearing functional activity. While Kendall describes manual muscle testing (MMT) in a partially shortened position, the best position to elicit GMed muscle activity and force production has not been studied.

Purpose: To determine if varying the position of the hip (flexion/extension and rotation) or knee (flexion/extension) affects muscle recruitment measured with electromyographic (EMG) or strength measured with a hand-held dynamometer (HHD). It was hypothesized that EMG and strength/force production would be greatest in hip extension with hip external rotation and knee flexion.

Study Design: Cross-sectional study.

Methods: EMG electrodes were placed on the GMed. EMG and HHD data was collected in six positions: 1) hip flexion-hip internal rotation-knee extension; 2) hip flexion-hip internal rotation-knee flexion; 3) hip extension-hip external rotation-knee extension; 4) hip extension-hip external rotation-knee flexion; 5) hip neutral-knee extension; 6) hip natural-knee flexion. All test positions were performed in mid-range hip abduction. Three maximal voluntary isometric contractions were performed in each position with average EMG and HHD output used for analysis.

Results: Fifteen subjects with a lower extremity pathology participated. Subjects had an average age of 23.6 (2.4) years with 66% female. A one-way ANOVA did not find a significant difference between the six test positions in regards to GMed muscle recruitment utilizing EMG (p = 0.39) or GMed strength with HHD (p = 0.76).

Conclusion: The hypothesis of this study was not supported. Varying the position of the knee and hip to alter the muscle length of the GMed during MMT did not significantly effect muscle recruitment or muscle strength.

1 Department of Physical Therapy, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA
2 UPMC Children’s Hospital of Pittsburgh, Pittsburgh, PA USA
3 Duquesne-China Health Institute, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA
4 UPMC Center for Sports Medicine, PA, USA

Presenting author: martinnr280@duq.edu

Zhang Y, Martin RL.

Background: Evidence is needed to define the reliability and responsiveness of the Simplified Chinese Lower Extremity Functional Scale (SC-LEFS) with information that allows the interpretation of score changes over time in younger patients with a variety of lower extremity injuries.

Purpose: To define minimal detectable change (MDC) and substantial clinical benefit (SCB) values for the SC-LEFS in patients with a variety of lower extremity musculoskeletal injuries.

Study Design: Longitudinal prospective study

Methods: Patients 18-50 years of age referred to physical therapy with a lower extremity musculoskeletal injury completed the SC-LEFS at initial assessment and after 4 weeks of physical therapy. Subjects also completed a categorical rating of functional change (ranging from greatly worse to much improved) at 4-week follow-up. Based on self-report after 4 weeks of physical therapy, subjects were classified into “stable/no change”, “improved” and “not improved” groups.

Results: 763 subjects participated, with 342 (44.8%) female, 421 (54.2%) male and a mean age of 32.9 (SD 9.4) years. Using the “stable” group (N = 40), the ICC was determined to be 0.98 (95% CI, 0.97; 0.99), with a MDC95 of 5.1 points. The “improved” and “not improve” groups consisted of 497 and 266 subjects, respectively. ROC analysis found a SCB change score of 9.5 points could differentiate those “improved” from those “not improved” with a sensitivity of 0.68 (95% CI, 0.64; 0.71), specificity of 0.71 (95% CI, 0.67; 0.74), and area under the curve (AUC) of 0.81 (95% CI, 0.73; 0.89; p<0.01).

Conclusion: This study offers evidence of test-retest reliability and responsiveness with MDC and SCB values for the SC-LEFS in Chinese-speaking patients 18-50 years of age with a variety of lower extremity injuries. Values for MDC and SCB will allow clinicians to interpret changes in score on the SC-LEFS after 4-weeks of physical therapy.

Presenting author: martinr280@duq.edu
ABSTRACT

Assessing the Reliability and Validity of a Visual Analog Scale for Rating the Single Leg Squat Test in Individuals with Lower Extremity Injuries.

Zhang Y, Liu Y, Huang X, Pan Z, Garcia CR, Martin RL

Background: The single leg squat test (SLST) is commonly used for visual movement assessment in those with lower extremity injuries. While current methods utilize ordinal rating scoring, adopting a visual analog scale (VAS) may offer potential advantages associated with the continuous data collected.

Purpose: To determine the interrater reliability and validity of a VAS for rating the SLST in individuals with lower extremity injuries.

Study Design: Cross-sectional study.

Methods: 29 subjects with lower extremity injuries participated in this study. Reliability was evaluated by two physical therapists (32 years and 8 years of experience) using a VAS to assess the SLST in three segments: trunk deviation, hip adduction, and lower extremity internal rotation. Intra-class correlation coefficients (ICC 2,1) assessed interrater reliability between the two raters. Validity was assessed by comparing VAS scores obtained from visual assessment to 3-D motion analysis for each subject.

Results: 18 (62%) females and 11 (38%) males with a mean age of 23.1 years (SD = 3.2) were included. Interrater reliability was good for trunk deviation (ICC2,1 = 0.84) and hip adduction (ICC2,1 = 0.78), and excellent for lower extremity internal rotation (ICC2,1 = 0.93). The minimal detectable difference (MDD95) values were 3.6 cm, 2.4 cm, and 2.8 cm, respectively. Agreement between visual assessment and 3-D motion analysis was substantial to moderate (weighted kappa = 0.51-0.65) in the three segments.

Conclusion: This study offered evidence of reliability and validity for using a VAS to rate the SLST. Established MDD values allow for score interpretation between raters. These findings potentially provide a more sensitive, precise, and detailed approach for evaluating individuals with lower extremity injuries on the SLST compared to the previously used ordinal rating scoring. The continuous data collected may allow for defining minimal clinically important difference (MCID) and substantial clinical benefit (SCB) values in future research.

1 Duquesne-China, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA
2 Department of Kinesiology, Colorado Mesa University
3 Department of Physical Therapy, Duquesne University, PA, USA
4 UPMC Center for Sports Medicine, PA, USA

Presenting author: zhangy4@duq.edu
ABSTRACT 12

The Test-retest Reliability and Validity of the Star Performer.®

Zhang Y,1 Liu Y,1 Shangtao PT,1 Wang J,1 Jian L,1 Mehls KD,2 Abbott S,3 Martin RL.,3,4

Background: The Star excursion balance test (SEBT) is well recognized as a reliable, valid, and responsive assessment tool. However, the SEBT is time consuming and inconvenient to perform. The Star Performer® is a new device developed to improve the efficiency in collecting information with the SEBT.

Purpose: To investigate the test-retest reliability of Star Performer® and compare its validity to traditional SEBT methods.

Study Design: Cross-sectional study.

Methods: 25 subjects with lower extremity injuries performed the SEBT twice, with approximately 7 days between tests. The Star Performer® device and a tape measure were used to record three test trials in each of the eight-test directions with the average reach distance being used for analysis. Test-retest reliability was evaluated by calculating the intra-class correlation coefficients (ICC 2,1) between the average reaching distance for each SEBT direction across the two testing sessions. To assess the validity of the Star Performer® device, the averaged reaching distance obtained by the device was compared to measurements obtained from the standard methods.

Results: 17 females (68%) and 8 males (32%) with a mean age of 23.6 years (SD = 3.9) participated. The Star Performer® demonstrated high test-retest reliability, with ICC2,1 value ranging from 0.84 to 0.93 for the eight SEBT directions. The minimal detectable change at the 95% confidence level (MDC95) ranged from 6.43 cm to 14.02 cm for the eight directions. The Pearson correlation coefficients between the Star Performer® and tape measure recordings ranged from 0.90 to 0.94 for the eight directions.

Conclusion: This study provides evidence supporting the validity and test-retest reliability of Star Performer® in SEBT assessments. Obtained MDC values allow clinicians to interpret scores changes over time. These findings suggested that the Star Performer® offers a precise and efficient approach to evaluate SEBT performance in individuals with lower extremity injuries.

1 Duquesne-China, Rangos School of Health Sciences, Duquesne University, Pittsburgh, PA, USA
2 Athletic Training, Duquesne University, PA, USA
3 Director of R&D, GDE Technologies, LLC, PA, USA
4 Department of Physical Therapy, Duquesne University, PA, USA
5 UPMC Center for Sports Medicine, PA, USA

Presenting author: zhangy4@duq.edu
ABSTRACT 13

**A Comparison of Patient Experience, Outcomes, and Utilization Between Telehealth, Clinic, and Hybrid Physical Therapy Patients.**

Denninger T,1,2 Lutz AD1,3 Shanley E1,3 Thigpen CA1,3

**Background:** The COVID-19 pandemic necessitated reduced barriers for policy and reimbursement enabling widespread adoption of telehealth physical therapy (PT) services. To date, there has been minimal reporting of the care parameters, outcomes, and patient experience associated with telehealth PT relative to clinic-delivered PT services. Purpose: The purpose of this study was to compare patient experience and outcome measures and course of care metrics between care delivery cohorts.

**Study Design:** Retrospective cohort.

**Methods:** A convenience sample of non-surgical patient episodes from a national outpatient PT provider between January 2020 and June 2021 (clinic=219,057, telehealth=603, hybrid=2,292; age 51±19, 59% female, BMI 29±7). Patient data, including pre- and post-body region-specific patient reported outcomes (PROs), visit metrics with treatment delivery, patient satisfaction, net promoter score (NPS), and demographic information, were obtained for patients that completed a PT episode between January 2020 and June 2021. NPS is a commonly-used, single item survey that gauges the likelihood a patient will recommend a product or service. Physical therapy episodes were classified as clinic-only, telehealth-only, or hybrid (including both clinic and telehealth treatments). Patients self-selected to treatment group based upon need and personal choice. Telehealth visits were typically 45-60 minutes and similar in makeup to clinic visits aside from proximity and manual interventions. Initial disability was stratified by PRO and divided into quartiles in a standardized direction (1 = high, 4 = low disability). The RA residual was calculated as actual PRO change - RA predicted PRO change. Two-way (treatment delivery x disability quartile) analyses of variance (ANOVAs) were used to compare visits and RA residual. Patient satisfaction and NPS were measured and analyzed by each care delivery method. Tukey’s post hoc testing was performed when significant interaction effects were observed ($\alpha = 0.05$).

**Results:** Significant main and interaction effects for treatment delivery and disability quartile were observed for visits; while only significant main effects for disability quartile was observed for RA residual. Initial PROs were 57.8±20.6 (clinic), 55.6±20.9 (telehealth), and 54.5±20.7 (hybrid); PRO change was 13.7±17.2 (clinic), 14.3±16.3 (telehealth), and 15.3±18.5 (hybrid); and visits were 12.7±7.6 (clinic), 10.9±7.8 (telehealth), and 17.0±11.1 (hybrid). Mean differences (95%CI) in visits relative to clinic were +1.6(1.1,2.7; telehealth) and +4.0(3.9,4.3; hybrid). No clinically important differences were observed in RA residual. Patient experience was nearly equal between groups with NPS (clinic 80% [n=14684], telehealth 79% [n=87], hybrid 80% [n=282]) and patient satisfaction (all 91%).

**Discussion/Conclusion:** Patients who experienced physical therapy through various means of delivery demonstrated compared outcomes and satisfaction with different numbers of treatment sessions. These findings are pragmatic and reflect the impact of patient choice to access and consume care in a real clinical environment. There may be important personal preference and expectation factors that influence patient’s choice that should be examined in future studies.

1 ATI Physical Therapy
2 South College
3 SC SmartState Center for Effectiveness Research in Orthopaedics (CEROtho)

**Presenting author:** Thomas.Denninger@ATIPT.com
ABSTRACT 14

Patient Experience Associated with Outcome Improvement and Course of Care Metrics.

Lutz AD,¹,² Denninger TR,¹,³ Shanley E,¹,² Thipgen CA,¹,²

Background: The Net Promoter Score (NPS), a well-researched measure of consumer loyalty and experience, has not been thoroughly evaluated in the healthcare literature. Research suggests the NPS may best be utilized in healthcare settings where patients have a choice of providers (e.g., physical therapy (PT)). Accordingly, PT organizations have increasingly deployed the NPS following care as a complementary measure of patient experience to other outcomes more routinely collected (e.g., patient reported outcomes [PROs]).

Purpose: The purpose of this study was to assess the relationship between the post-care NPS and care episode metrics including attended visits and change in Penn Shoulder Score (PSS; unadjusted [UA] and risk-adjusted [RA] residual) in patients that received post-operatively PT following rotator cuff repair (RCR).

Study Design: Retrospective Cohort.

Materials and Methods: A sample of convenience (776 PT patient episodes) related to post operative RCR with available post care NPS, initial and final PSS, and requisite risk-adjustment variables (i.e., age, sex, BMI, payer, health history, clinic state, chronicity, initial PSS, initial VR12 Mental & Physical Component Scores) were available. Analyses of Covariance (ANCOVAs) compared UA PSS change, RA residual PSS, and attended visits by response classification (i.e., Promoter [9-10], Passive [7-8], Detractor [0-6]), controlling for chronicity, sex, age, and initial PSS quartile. Estimated marginal means (EMM) described outcome and visit metrics between levels of NPS classification, averaged over remaining control variables.

Results: Post-care NPS demonstrated significant differences (P<0.001) between Detractors and Promoters for each dependent variable. Detractors averaged significantly lower RA residual (-4.1; CI -10.4,2.1 vs 8.2; 6.6,9.8), UA change (37.2; 30.5,43.9 vs 49.8; 48.0,51.5), and visits (20.0; 15.2,24.9; 30.3; 28.9,31.7) than Promoters. Passives were not statistically different from Detractors and Promoters for the PSS measures but were consistent with Promoters for attended visits.

Discussion/Conclusion: Patients classified as ‘Promoters' demonstrated significantly better PROs and attended significantly more visits than patients classified as ‘Detractors'. While we are unable to establish a causal link, the clear differences in visits and PROs between the rating cohorts indicate that better experience is associated with a longer, comprehensive plan of care that yields better outcomes.

¹ ATI Physical Therapy
² SC SmartState Center for Effectiveness Research in Orthopaedics (CEROrtho)
³ South College

Presenting author: Adam.Lutz@ATIPT.com
ABSTRACT 15

Comparing Kinematic Sequencing in Pitcher & Quarterbacks.

Phil Page,¹ Andre Labbe.²

Background: Overhead throwing involves a kinematic sequence of events from the contralateral foot to the hand. After foot contact, the pelvis and torso contribute to throwing velocity through rotation. Hip-Shoulder separation has been suggested as an important component of throwing velocity. While many researchers have evaluated biomechanics in baseball pitchers, few have evaluated football quarterbacks or compared both.

Purpose: The purpose of this study was to evaluate the kinematic sequencing in pitchers and quarterbacks during throwing, including hip-shoulder separation.

Methods: Eleven right-handed male quarterbacks (n=6) and pitchers (n=5) between high school and college level participated in a biomechanical throwing analysis before their respective season. The Noraxon Ultium IMU system (Noraxon USA, Scottsdale AZ) was used to assess kinematic variables during the throwing motion. Athletes performed 9 targeted throws each; pitchers threw fastballs at 90 feet, while quarterbacks threw 20-yard passes. Noraxon MyoResearch 3.18 software was used to identify key events during the throwing motion: left foot contact, maximal shoulder external rotation, ball release, and maximal shoulder internal rotation. Kinematic data was extracted for shoulder external rotation ROM and internal rotation velocity, torso and pelvis ROM and velocity, and torso-pelvic axial angle (hip-shoulder separation). Spatial and temporal values were averaged for key events.

Results: Pitchers demonstrated earlier ball release (30% vs 40% of throwing motion) and longer deceleration compared to quarterbacks. Pitchers also had greater peak external rotation (152º vs. 110º) and greater external rotation at ball release (71º vs. 30º). Hip-Shoulder separation was greater in pitchers (45.4º vs. 23.9º). Peak velocity was greater in pitchers and occurred earlier in the throwing motion (5112+808º/s at 40% vs. 2847.6+345º/s at 68%).

Conclusion: Understanding the different biomechanics of throwing athletes may assist in rehabilitation and performance. Pitchers demonstrated higher ROM, velocity, and hip-shoulder separation. Future research should include larger sample sizes, kinetic analysis, and different throws.

¹ Franciscan University DPT Program, Baton Rouge LA
² Tulane University Medical School Dept of Orthopedics

Presenting author: alabbe@tulane.edu
Instrumented Analysis of Scapular Kinematics: A Scoping Review.
Phil Page,¹ Logan Seal.²

Background: Although controversial, scapular dyskinesis is typically assessed clinically through observational methods. Instrumented measurement of scapular kinematics can provide objective quantification of angular movements simultaneously in three planes of movement. While the most representative measure of scapular kinematics would involve invasive placement of bone pins into the scapula, the “gold standard” for assessing kinematics relies on reflective markers and high-speed cameras in a lab setting. Electromagnetic sensors have been validated as another method of quantifying scapular kinematics; more recently, inertial motion units (IMUs) have been used in biomechanical studies for movement analysis. In addition to angular data, IMUs can provide velocity and acceleration data, often wirelessly. IMUs may provide clinicians more practical and accessible methods of objective measurement of human movement.

Purpose: The purpose of this scoping review was to identify and describe studies assessing scapular kinematics with IMUs that reported data on range of motion (ROM), validity, or reliability.

Methods: Four electronic databases (CINAHL, EMBASE, MEDLINE, and SPORTDiscus) were systematically searched in July 2023 for search terms (scapul* AND (kinematic* OR biomechanic*) AND (marker OR sensor OR inertia* OR IMU). Included studies evaluated scapular kinematics using IMUs on ROM, validity, or reliability. Cadaveric and biomechanical modeling studies were excluded, as well as conference proceedings, dissertations and case reports. PRISMA-2020 guidelines were followed.

Results: 15 studies were included; 8 evaluated reliability while 4 evaluated validity against the “gold standard” camera and reflectors placed on the acromion. The median number of subjects in each study was 23. Four different IMU systems were used: MTS XSens (6); InertiaCube3 (6); MoLab (2); and Showmotion (1). All but one study used 3 or 4 sensors; typically using the “ISEO” protocol placement including the sternum, scapular spine, lateral humerus and forearm. Most studies evaluated elevation in the sagittal plane (flexion) and frontal plane (abduction), while 4 studies evaluated functional tasks. The average scapular ROM (internal/external rotation, upward/downward rotation, and anterior/posterior tilt) was typically non-linear and varied widely across studies, as well as between flexion and abduction movements. Similarly, the intraclass correlation coefficients (ICCs) ranged from –0.2 to 0.9 while the standard error of the measure (SEM) ranged from 1.8º to 3.9º.

Discussion: Most authors used biomechanical terminology; however, they were not always clear in defining movement, often using terms different than clinicians (“protraction” is clinically defined as scapular internal rotation). Average scapular motion during elevation was previously quantified with bone pin placement by Ludewig et al. as 2º of external rotation, 21º of posterior tilt and 37º of upward rotation. Values obtained through IMUs were sometimes reported in excess (44º of transverse rotation; 65º of frontal rotation; 15º of sagittal tilt). These differences may be due to skin artifacts, different sensing systems and placement, or incorrect reporting.

Conclusion: The literature is not consistent in reporting scapular kinematics using IMUs, thus limiting the clinical utility of their use in assessing scapular motion. More research is needed to assess the validity and reliability of IMU use in quantifying scapular kinematics in healthy and patient populations.

¹ Franciscan University DPT Program, Baton Rouge LA
² Baton Rouge Orthopedic Clinic, Baton Rouge LA

Presenting author: lseal@brortho.com
ABSTRACT 17
Phil Page, PT, PhD, ATC, CSCS, FACSM.
Franciscan Missionaries of Our Lady University DPT Program, Baton Rouge LA

As experts in mobility and locomotion, physical therapists (PTs) examine and evaluate the “human movement system.” The movement system functions through the interaction of the musculoskeletal, cardiopulmonary, nervous, and integumentary systems. Biomechanical analysis can provide PTs with quantitative and detailed insights into the interactions of the human movement system in various muscles and joints, across multiple planes and phases of movement. Deviations from ‘normal’ movement can help identify potential impairments or compensations leading to dysfunction.

The component systems of human movement are usually evaluated “statically” for impairments (range of motion, strength, flexibility, etc); however, common activities such as squatting, throwing, or walking should be analyzed “dynamically” through observational or instrumented methods during movement. While instrumented analysis is not commonly available to PTs, technology is rapidly evolving to bring objective data to clinicians through inexpensive and convenient measurement devices. For example, wireless inertial motion units (IMUs) and marker-less motion capture devices can provide kinematic data in real-time through readily available mobile devices.

Dysfunctional movement can be quantified by comparing a patient’s movement pattern with “normal” kinematic and kinetic variables. Clinicians may benefit from a systematic approach of analyzing objective movement data using an algorithm to identify dysfunction and potential impairments. PTs can then combine their clinical examination and patient history with pathomechanical measures, thereby facilitating clinical decision-making to determine appropriate and timely interventions. This presentation describes the development and use of a clinical decision-making algorithm using kinematic parameters of gait analysis to differentiate possible impairments and inform potential interventions.

Presenting author: Phillip.Page@franu.edu
Humeral Torsion Assessment using Musculoskeletal Ultrasound: A Scoping Review.

Trahan A, Vicknair H, Page P.
Franciscan Missionaries of Our Lady University, Baton Rouge LA.

Background: Humeral torsion is defined as the angle formed between the proximal and distal articular axis of the humerus. Torsion is typically quantified through MRI or CT, but musculoskeletal ultrasound (MSKUS) has been used in several studies to quantify humeral torsion in overhead athletes. The purpose of this study was to systematically synthesize the literature describing the use of MSKUS to quantify humeral torsion in overhead athletes in order to evaluate the validity and reliability of the techniques used.

Methods: A systematic scoping review was performed in February 2023 following PRISMA guidelines for scoping reviews. Studies included the use of MSKUS to image and quantify humeral torsion in overhead athletes, and English, full-text articles that were published in peer-reviewed journals.

Results: 46 articles were screened for inclusion and 10 were chosen. All studies used MSKUS to align proximal humeral tuberosities while using a goniometer or digital inclinometer to measure external rotation at 90° abduction. The average humeral retro-torsion on the throwing arm was approximately 12.44° compared to “normal” 7°. The intraclass correlation coefficients (ICC) for intra- and inter-observer reliability were good (0.83-0.1.0). Using 2 examiners resulted in higher reliability.

Conclusion: MSKUS was used to align proximal humeral tuberosities while using a goniometer or digital inclinometer to measure external rotation at 90° abduction with either 1 or 2 observers. The patient position was consistent throughout all studies and all techniques utilized. This review found that quantifying humeral torsion with MSKUS is reliable and valid for clinical practice. The two examiner method provided slightly higher reliability.

Presenting author: aabbytrahan@franu.edu
Does Localized Intermittent Pneumatic Compression Change Soft Tissue Pain and Stiffness?

Authors: Page P, Vicknair H, Doskey L.
Franciscan University DPT Program, Baton Rouge LA.

Background: Intermittent pneumatic compression (IPC) is a popular modality for recovery after physical activity or during injury rehabilitation. Previous research supports its use in reducing pain and swelling. Graded circumferential pressure is applied to the entire limb with an inflatable bladder or cuff using an external compression device. A new IPC device, the Normatec Go (Hyperice, Burlington MA) was designed to provide localized compression to the calf muscles without a tethered external compression device. While researchers have validated the use of traditional Normatec compression boots, no studies have evaluated the Normatec Go device.

Purpose: The purpose of this study was to pilot test an experimental protocol on healthy subjects to evaluate the effects of the Normatec Go on pain, swelling, and muscle stiffness and damping.

Methods: A convenience sample of 22 young healthy subjects received 30 minutes of compression simultaneously to both lower legs with the Normatec Go (setting 4) for 30 minutes. Subjects were tested before and after the intervention for pain pressure threshold (PPT) using a digital pain algometer (Wagner FPX, Greenwich CT), girth at 15cm inferior to the knee crease, and muscle stiffness and damping using the PACT sense (Impact Biosystems, Boston MA) muscle scanner. Reliability of the PACT was examined using 3 consecutive pre-treatment measures to determine the intraclass correlation (ICC). Dependent t-tests were used to analyze pre- and post-test differences (significance set at p < 0.05) and Cohen's d effect sizes were calculated. An a priori power analysis (G Power; \( \alpha = 0.05 \), power = 0.8, effect size = 0.5) indicated 34 subjects were needed to avoid a Type 2 error. Each subject was tested on both calves, resulting in a sample of 44.

Results: Test-retest reliability of the PACT sense device was excellent to good (0.91 for stiffness and 0.86 for damping). Stiffness (\( p = 0.04 \)), damping (\( p = 0.001 \)), and girth (\( p = 0.01 \)) were significantly different after the intervention; there was no difference in PPT. Cohen's d effect sizes for the intervention were trivial to small, except for muscle damping, which was moderate at d = 0.4. There were no adverse effects.

Discussion: The protocol was feasible and safe. The Normatec Go IPC reduced muscle stiffness, damping, and girth immediately after use in healthy subjects. While statistically different, the differences were likely not clinically meaningful.

Conclusion: Normatec Go IPC temporarily enhanced the viscoelastic properties of the calf muscle in healthy subjects. Further testing in muscle recovery is warranted in subjects after physical exertion or injury.

Presenting author: hannahvicknair@franu.edu
ABSTRACT 20

Pre- and Post- Total Hip Arthroplasty Gait Analysis in a Patient with a Four-level ACDF and T1-Sacrum Spinal Fusion.

Peaslee K, Page P.
Doctor of Physical Therapy Program, Franciscan Missionaries of Our Lady University, Baton Rouge, Louisiana, USA

Background: Several research studies have performed gait analyses on patients pre- and post- total hip arthroplasty (THA), but historically patients with concomitant neurologic and orthopedic comorbidities are excluded from these research trials. By presenting this case study, we aim to illustrate the kinetic and kinematic variables in a patient pre- and post-THA with increased medical complexity.

Clinical Case: An 85-year-old man underwent a right anterior approach total hip arthroplasty in September 2022. The patient's recent past medical history includes a CVA with residual R quadriceps, gluteus medius, and anterior tibialis weakness in December 2020, a 4-level anterior cervical discectomy and fusion (ACDF) in September of 2020, and a T1-sacrum fusion in December of 2020. The patient performed two gait analyses using the Noraxon IMU-based body model and Digitsole insoles for analysis of temporal, spatial, and joint angle data: the first was 5 months pre-THA and the second was 3 months post-THA. The patient demonstrated improvements in limb-to-limb symmetry in percentage of time in stance phase, percentage of time in loading response, percentage of time in single leg support, percentage of time in pre-swing, stride time, step time, cadence, length of gait line, center of pressure parameters, dynamic hip ROM (in stance and swing phase), knee flexion ROM, contralateral hip abduction during stance phase, bilateral knee abduction ROM (in stance and swing phase), and bilateral ankle dorsiflexion ROM during stance phase of gait.

Conclusion: This is one of the first cases demonstrating the changes in kinetic and kinematic variables after total hip replacement in a patient with orthopedic and neurologic comorbidities. The clinical significance in this case is that our medically complex patient post-THA demonstrated similar improvements in gait as otherwise healthy patients post-THA.

Presenting author: Katherine.Peaslee@franu.edu