Dynamic Postural Stability and Cognitive Loading in individual with and without ACLR: Insights from Comparative Studies

by

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ABSTRACT

Background: Postural stability is the ability to maintain posture against gravity while responding to internal or external perturbations. Evidence suggests that poor postural stability is a significant risk factor for sustaining non-contact anterior cruciate ligament (ACL) injuries. Following ACL reconstruction (ACLR), individuals often exhibit residual postural stability deficits, which can impede their recovery and increase the risk of re-injury. Dynamic postural stability is critical for movement control and injury prevention after ACLR.

Objective: This dissertation aims to comprehensively explore kinetic measurements and postural stability in individuals following ACLR through four original research papers. The primary objectives include (1) describing current approaches and methodological reporting for kinetic measurements post-ACLR, (2) identifying force plate parameters that distinguish post-ACLR individuals from Healthy Controls and are responsive to changes over time in post-ACLR individuals during countermovement jumps (CMJ) and/or drop jumps (DJ), (3) comparing dynamic postural stability between post-ACLR individuals and Healthy Controls, and (4) examining the dual-task effect on postural stability in these groups.

Methods: This dissertation employed a stepwise research approach, beginning with a scoping review of 158 original papers to identify methodological approaches in kinetic measurement systems for ACLR individuals. A systematic review and meta-analysis of 33 studies was conducted to pinpoint discriminative and responsive force-plate parameters during CMJ and drop jumps. An investigation was then conducted into dynamic postural stability differences, including sex-specific differences, between 21 ACLR individuals (10 females) and 20 Healthy Controls (10 females). Finally, the dual-task effect on postural stability was examined using the Stroop task in both ACLR and Healthy Control groups.

Results: The scoping review revealed a significant increase over the last decade in the evaluation of kinetic outcomes in ACLR populations, though with marked heterogeneity in methodologies, hindering comparisons across studies, and suggested methodological reporting considerations. The systematic review and meta-analysis included 1185 individuals with ACLR (50.38%) and 1167 Healthy Controls (49.62%), categorized data into single-leg CMJ, double-leg CMJ, single-leg DJ, and double-leg DJ. The review identified reduced jump height in single-leg (MD = -3.13; $p < 0.01$; 95% CI: [-4.12, -2.15]) and double-leg (MD = -4.24; $p < 0.01$; 95% CI: [-5.14, -3.34]) CMJs among ACLR individuals. Concentric impulse and eccentric/concentric impulse asymmetry could distinguish ACLR (MD = 3.42; $p < 0.01$; 95% CI: [2.19, 4.64]) from non-ACLR individuals (MD = 5.82; $p < 0.01$; 95% CI: [4.80, 6.80]). In double-leg DJs, peak vertical ground reaction forces were lower in the involved side (MD = -0.10; p = 0.03; 95% CI: [-0.18, -0.01]) and higher in the uninvolved side (MD = 0.15; $p < 0.01$; 95% CI: [0.10, 0.20]) compared to controls, showing significant changes between 6 months and 3 years post-ACLR.

Dynamic postural stability assessments showed higher combined resultant vector time to stabilization (RVTTS-C) and higher vertical time to stabilization in the operated leg (VTTS-op) among individuals post-ACLR compared to Healthy Controls (p=0.03, p=0.02 respectively). Males with ACLR exhibited higher combined vertical time to stabilization (VTTS-C) and VTTS-op values than females post-ACLR (p=0.03, $p<0.01$ respectively) and higher VTTS-op compared to healthy males (p=0.03). No differences in postural stability indices (PSI) were found between groups. Under dual-task conditions, both groups showed longer RVTTS-C, with the ACLR group showing a 0.61±0.14 second increase ($p<0.01$) and Healthy Controls showing a 0.98±0.12 second increase ($p<0.01$). Significant increases in PSI variables under dual-task conditions were observed in the ACLR group for MLSI-C (0.05±0.02, p=0.01) and DPSI-C (0.06±0.02, p=0.03), and in Healthy Controls for APSI-C (0.05±0.01, p=0.02), MLSI-C (0.07±0.01, $p<0.01$), DPSI-C (0.08±0.01, $p<0.01$), and matched MLSI-op (0.08±0.03, p=0.02). The Stroop effect on RVTTS-C was higher among Healthy Controls by 0.37±0.76 seconds ($p=0.03$), with no other significant differences between groups.

Conclusion: This dissertation underscores the importance of dynamic postural stability assessment in individuals with ACLR, offering practical recommendations that may improve assessment protocols and inform tailored rehabilitation strategies. The research highlights the need for standardized assessment methods, and considering the integration of cognitive loading in the assessment and treatment of people post-ACLR

PREFACE

This thesis is an original work by Wasim Labban under the supervision of Dr. Lauren Beaupre, Professor in the Department of Physical Therapy at the University of Alberta; Dr. Mark Sommerfeldt, Assistant Clinical Professor in the Division of Orthopaedic Surgery, Department of Surgery, Faculty of Medicine and Dentistry, University of Alberta; and Dr. Lindsey Westover, Associate Professor in Faculty of Engineering at the University of Alberta. The University of Alberta's Health Research Ethics Board approved the research studies in this thesis (No: Pro00111475). The studies in Chapter 3 and Chapter 4 were published in the Journal of Experimental Orthopedics. The studies in Chapter 5 and Chapter 6 are being prepared for submission to peer-reviewed journals.

DEDICATION

I dedicate this work to the precious treasure in my life, my family, and to everyone who believed in me.

You are my source of inspiration. This achievement is as much yours as it is mine.

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CHAPTER 1: INTRODUCTION

BACKGROUND

Anterior cruciate ligament (ACL) rupture is a devastating injury that frequently occurs in sports[10] and accounts for 50% or more of all knee injuries.[10, 38] Most ACL injuries occur without a direct knee contact[47] when the limb decelerates during landing or change of direction activities such as cutting and pivoting.[28] Due to the vital role of the ACL in the knee joint stabilization,[32] ACL injuries can lead to impairments of the knee stability and balance.[34] Therefore, anterior cruciate ligament reconstruction (ACLR) is frequently indicated to restore knee joint stability.[13] ACLR is usually followed by a course of rehabilitation with the ultimate aim of returning patients to their pre-injury level of function.

Rehabilitation following ACLR is crucial for restoring the lower extremities' strength and functional deficits resulting from the injury and the subsequent surgery.[12] However, often rehabilitation is under-utilized after surgeries due to premature patient discharge or inadequate rehabilitation resources.[17] The process of rehabilitation should acknowledge the timeframe for physiological tissue healing. While there is a lack of consistency in the timeframe for graft ligamentization, evidence suggest that maturation takes at least 9 months following ACLR to occur.[18] Therefore, appreciating these timeframes when designing the rehabilitation protocol is important to progress patients to return to their previous level of activity and participation.[11]

The efficacy of any rehabilitation protocol should be measured with rigorous outcome assessments after ACL injuries and ACLR.[46] However, there is a lack of consistency as to the timing of when a particular outcome measure should be used during the process of rehabilitation.[46] During the last few years, functional assessment has become the first criterion to return to sport (RTS) after ACLR; however, more standardization in rehabilitation protocols and functional testing methods is needed.[6] The objective assessment of motor functions has become increasingly important over the last decade.[29]

Several biomechanical assessment devices have been utilized to examine various functional activities in individuals following ACLR. Biomechanical assessment systems include kinetic and kinematic measurement systems. These systems can be synchronized with electromyography to examine muscular activity when required.[44] Kinetic and kinematic measurement systems are used to measure force (e.g., force plates) and joint angles (i.e., motion capture systems), respectively. Moreover, these two systems can be used together to measure important kinetic parameters such as joint moments. With the rapid advancement in the field of biomechanics, recent studies are examining the use of different motion capture systems to estimate kinetic parameters such as ground reaction forces and joint moments.[25, 26, 37] However, the methodologies used to estimate joint moments are debatable[7] and kinetic measurement systems are still considered the gold standard when measuring forces.[35]

Different kinetic measurement systems have emerged as instruments to objectively assess various functions such as jumping,[3, 39] gait[43] and postural control[1, 14] These systems use force sensors to quantify forces exerted during performance of activities or tasks.[8] They are utilized by clinicians and researchers to assess functional progression throughout rehabilitation and may assist in determining the ability to return to sport (RTS) in post-ACLR individuals.[19] Previous studies have examined various kinetic parameters in the ACLR population; however, there is a lack of consistency in the literature regarding which parameters to assess and what assessment protocol(s) to follow. Over the last decade, several studies examined balance and postural control using the force plate technology in the ACLR population.[1, 5, 9, 14, 16, 19–21, 45] This highlights the increasing attention toward postural control after ACLR, and its potential significance in facilitating the decision to return to sport.

Postural control is the ability to control body alignment and position in space through the interactions between the musculoskeletal and nervous systems.[31] Postural control has two components: postural orientation and postural stability. Postural orientation is the ability to manage the relationship between different body parts (e.g., upper and lower limbs) as well as the relationship between body parts and the environment for task performance.[31] Postural stability is the ability to maintain posture against gravity in response to internal and/or external perturbation.[31] Several postural stability tests have been reported to examine several components related to balance and postural control in individuals following ACLR.[4, 15, 23, 27, 30]

In a clinical setting, postural stability is usually tested statically. Patients are asked to stand on a single-leg while maintaining their balance on a stationary platform. Several parameters related to the center of pressure can then be compared between the injured and non-injured legs or between patients and healthy participants.[40] Although static balance testing may be valuable for measuring postural control,[2] static postural stability measures have been described as non-functional, insensitive, and do not correlate with dynamic values.[42] Therefore, measurement of more challenging and dynamic aspects of postural control that mimic athletic activities may provide important insight into athletes' functional abilities with and without ACLR.[2, 22]

Further, as loading is one of the main mechanisms of ACL injuries, the measurement of dynamic postural stability immediately after landing while performing dual tasks may provide critical information on neuromuscular deficits in individuals with ACLR. Athletic activities often require athletes to perform dual tasks or multitask simultaneously when making purposeful movements, evaluating the surrounding environment and making cognitive-motor decisions. Dual-task performance is defined as "the ability to perform two separate tasks simultaneously".[33] The cognitive-motor assessment is based on two assumptions: 1) the human body can process multiple tasks utilizing limited attentional resources, and 2) the task difficulty can influence the utilization of attention resources.[41] For example, introducing a secondary cognitive task to an individual performing a jumping-landing activity may be more challenging as the attentional resources are diverted to maintain dynamic postural stability after landing.

Although several studies examined standing postural stability while performing a cognitive task, very few papers reported on the knee biomechanics under dual-task conditions,[36] namely while performing dynamic activities such as jumping-landing. A recent study examined the effect of dual tasks on landing biomechanics in healthy female athletes and reported kinematic and kinetic changes when cognitive tasks were introduced.[24] However, we are not aware of any study examining the effect of dual tasks on dynamic postural stability variables at landing immediately after countermovement jump (CMJ). This information could be of clinical significance to guide rehabilitation protocols and decisions to return to sport.

OBJECTIVES

The overarching goal of this dissertation is to examine the effect of task complexity on dynamic postural stability after CMJ landing in individuals following ACLR compared to Healthy Controls. We tried to achieve this aim through a comprehensive exploration of kinetic measurement systems and postural stability assessments, with the focus on understanding the complexities, challenges and advancement in this domain. Specific objective of the research were to:

- Investigate the methodological approaches used in kinetic measurement systems for individuals following ACLR, identify potential gaps, and explore the potential association between kinetic measures and patient-reported outcome measures (PROMs).
- Identify which kinetic parameters are most discriminative and responsive in individuals post-ACLR during CMJs and drop jumps (DJs), and provide insights into the most effective measures for monitoring recovery and rehabilitation progress.
- Examine the differences in dynamic postural stability after CMJ landing between individuals with ACLR and Healthy Controls, measured by time to stabilization (TTS) and postural stability indices (PSI) outcomes and explore sex-specific differences in these measures.
- Compare the impact of dual-task conditions on dynamic postural stability between individuals with and without ACLR, using a cognitive tasks and assess their effect on dynamic postural stability.

Addressing these objectives is important to provide recommendations pertaining the integration of postural stability testing under single and dual task conditions in rehabilitation protocols and clinical reasoning when making a return to sport decision.

DISSERTATION STRUCTURE

Chapter 2 is a literature review that provides the theoretical foundation for the dissertation. Chapter 3 is a scoping review (published in the Journal of Experimental Orthopedics) that discusses the methodologies used in kinetic measurement system, the heterogeneity in the assessment protocols and kinetic parameters used, the development of this field, and it also explores the papers on the associations between kinetic measurement systems and PROMs. Chapter 4 is a systematic review and meta-analysis (published in the Journal of Experimental Orthopedics) that looked at the most discriminative kinetic parameters between individuals with and without ACLR while performing CMJs and DJs. It also looked at the parameters that are most responsive to changes over time in the ACLR population while performing CMJs or DJ. Chapter 4 is a cross-sectional study (currently in preparation for submission to the “Physical Therapy in Sport” journal) that looked at differences in dynamic postural stability after CMJ landing between individuals with ACLR and Healthy Controls, measured by time to stabilization (TTS) and postural stability indices (PSI) variables, and explored sex-specific differences in these measures. Chapter 6 is another cross-sectional study (currently in preparation for submission to the “Clinical Biomechanics” journal) comparing the impact of dual-task conditions on dynamic postural stability between individuals with and without ACLR, using a dual task paradigm to simulate real-world conditions and assess their effect on dynamic postural stability. Finally, chapter 7 discusses the main findings of the dissertation, the clinical implications, strengths and limitations and provides directions for future research.

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CHAPTER 2: LITERATURE REVIEW

THE ANTERIOR CRUCIATE LIGAMENT (STRUCTURE, BIOMECHANICS AND SIGNIFICANCE)

The anterior cruciate ligament (ACL) is one of the two cruciate ligaments in the knee. The anterior and posterior cruciate ligaments cross each other to form an "X" joining the distal femur to the tibia.[70] The ACL receives its blood supply from the middle genicular artery and is innervated by the posterior articular branches of the tibial nerve.[20] In addition, it is highly innervated with mechanoreceptors (Ruffini end organs, Pacinian corpuscles, Golgi-like organs, free nerve ends) that constitute 2.5% of the ACL and provide afferent signals to the central nervous system (CNS).[95, 111] Histologically, the ACL is composed of cells (fibroblasts & fibrocytes) and a matrix made of water, collagen, proteoglycans, fibronectin, and elastin that interact together in a network of seams to form an integral part of the ligament's viscous element.[70] The ultrastructural organization of the ACL and elastic system allow it to withstand multidirectional tensile forces.[20]

The ACL is one of the main four ligaments in the tibiofemoral joint contributing to knee joint stability.[20, 70] It resists anterior tibial translation, internal rotation of the tibia and the valgus angulation at the knee.[36] The ACL absorb 75% of the anterior tibial translation load in full extension, and 85% of the load when the knee is between 30 and 90 degrees of flexion.[36]

EPIDEMIOLOGY

ACL injuries occur frequently in sports[19] and accounts for 50% or more of all knee injuries.[19, 86] ACL injuries are associated with short and long-term consequences. In the long term, ACL injuries may cause osteoarthritis and significant progressive disability even after ACL reconstruction (ACLR).[80] ACLR is often recommended to restore joint stability and minimize potential damage to articular cartilage and menisci.[4] It has been reported that the proportion of individuals who return to a competitive level of sport following ACLR is 55%, while 81% return to any level of sport.[7] Further, up to 38% of elite athletes reduce their participation levels or stop their career within 3 years after ACLR.[98]

Reported short-term outcomes estimate a likelihood that a person may incur a secondary ACL injury in the operated and contralateral knee in Alberta are 3.9% and 3.6%, respectively.[79] The percentage is higher among collegiate athletes, estimated around 1 in 14 (7%).[80] This is substantially higher than the risk of the primary injury that is reported to be 1% to 1.6%.[29, 61] The rate of a secondary ACL injury increases over time to 17.2%, 27% and 31% at 5-,[88] 10-[80] and 15-year[45] follow-up, respectively. While the likelihood of sustaining a secondary ACL injury on the contralateral side is slightly higher than having an ipsilateral secondary injury in Alberta,[79] other studies reported the risk of having a secondary ACL injury in the contralateral side to be twice the percentage of having an ipsilateral graft failure.[30, 88]

MANAGEMENT OF ACL INJURIES

The overall goal of managing ACL injuries is to restore knee function, prevent additional injuries to the menisci and cartilage that may progress to osteoarthritis, and optimize quality of life including addressing psychosocial barriers to activity participation.[22] However, the current evidence is inconclusive about the best line of ACL rupture management.[52]

Emerging evidence suggests that the ACL has the capacity to heal itself. A systematic review of 9 studies that included 734 participants with ACL rupture reported consistent findings across the studies indicating spontaneous ACL healing.[81] Building on those findings, another study reported that spontaneous healing of ACL was evident in 16/54 participants (30%).[23] The authors postulated that the potential for spontaneous healing of the ACL to facilitate better outcomes is, perhaps, greater than previously considered.[23]

ACL injuries can be treated conservatively or surgically; however, ACLR is still considered to be the gold standard. According to a systematic review by Krause *et al*., 2018, only two randomized control trials have examined the difference in the effectiveness of conservative vs. surgical treatment.[52] While one of those studies reported better functional outcomes of the ACLR group compared to those with conservative management, the other study found no harm in starting with a conservative management, even though 51% of participants ended up having delayed surgery.[52] The review reported the results of 13 observational studies in which six reported better knee functional outcomes after ACLR, and the remaining seven found no differences between the conservative and surgical lines of management in terms of improving knee function.[52]

While the previous systematic review by Krause et al., considered only ACLR as a surgical method to reconstruct the ACL, other methods such as ACL repair is regaining more attention. A more recent meta-analysis included data of 638 patients and reported no difference between arthroscopic ACL repair and ACLR in the failure rate, complications, Lysholm score, Tegner score and satisfaction.[76] However, patients after ACL repair had significantly higher rate of hardware removal and significantly higher grade of anterior tibial translation, but better International Knee Documentation Committee (IKDC) score when compared to patients post ACLR.[76]

The conflicting findings of the currently available evidence on the effectiveness of different treatment approaches could be related to the heterogeneity of the implemented treatment protocols and the functional outcomes measured.[22] In addition to the physical and functional finding, data on other contextual factors may contribute to the overall success of the treatment method, the return to pre-injury level of physical activity and the prevention of secondary ACL injuries.[5]

RISK FACTORS FOR SECONDARY ACL INJURIES

Despite the high risk of secondary ACL injuries, information regarding risk factors associated with these injuries are yet to be consolidated. Moreover, most studies to date have been limited to investigating non-modifiable risk factors. Younger age was consistently listed as a risk factor for sustaining secondary ACL injuries. The Multicenter Orthopedic Outcomes Network (MOON) group reported that risk of sustaining a secondary ACL reduces by 0.09% for every year increase in age.[48] Other non-modifiable risk factors for an ACL injury include female sex, family history, and anatomical risk factors such as a smaller intercondylar notch, a larger lateral tibial slope and a larger β angle.[93] Conversely, some risk factors are modifiable and can be addressed with different interventions. These include BMI, graft type, neuromuscular, biomechanical, and other factors related to postural control. Evidence suggests that the use of autografts have better outcomes than allografts in reducing post-operative complications and re-operations.[31] Similarly, the risk of secondary ACL injuries reduces as BMI increases.[17] The following sections will address the neuromuscular, biomechanical, and other modifiable factors related to postural control that can influence the risk of secondary ACL injuries.

Neuromuscular risk factors

Reduced trunk motor control after rapid perturbations may predict knee, ligament and ACL injuries.[109] Similarly, a deficit in single-leg postural control post ACLR increases the risk of sustaining a secondary ACL injury.[78] Moreover, different hip and knee muscles activation strategies were linked to sustaining ACL injuries. Females with reduced relative hamstring strength and higher relative quadriceps strength may have higher risk of ACL injuries.[67] Further, females adopt different hip and knee abduction angles and moments that are associated with sustaining ACL injuries.[59, 66]

Biomechanical risk factors

Several biomechanical evaluations have identified hip external rotation, knee abduction, and lower extremity asymmetries as strong predictors for ACL injuries.[39, 78] In a prospective study of 205 female athletes, kinematic outcomes were measured during a landing task in athletes who subsequently sustained ACL injuries compared to their teammate controls. Participants who sustained ACL injuries demonstrated wider knee abduction angles and 2.5 times greater knee abduction moments during landing.[39] More specifically, the knee abduction angle increased with loading during the transition from mid-stance to the end of stance after drop jumps.[51] Hip movements in the coronal plane significantly contribute to increased knee abduction and are likely to increase the risk of sustaining ACL injuries.[39, 46] In addition to the differences found in the coronal plane, evidence suggested differences in the sagittal plane including increased hip flexion, knee flexion, ankle dorsiflexion, anterior pelvic tilt and thoracic to pelvis flexion angles in those who sustained a secondary ACL injury, specifically in the contralateral side.[51] Furthermore, the vertical GRF was consistently higher among athletes who sustained secondary ACL injuries compared to the athletes who did not.[39, 51]

Risk factors related to postural control

Postural control consists of postural orientation and postural stability. Postural orientation is the ability to manage the relationship between different body segments, and the relationship between those segments and the environment. Whereas, postural stability is the ability to maintain posture against the gravity while responding to internal or external perturbation.[89] Postural control is an important concept for the prevention of a secondary ACLR. Poor postural stability had been reported as risk factor for sustaining non-contact ACL injuries.[74] People who demonstrated a single-leg postural stability deficits in the involved knee had 2.3 (95%CI = 1.1-4.7) times the odds of incurring a secondary injury compared to those who did not demonstrate postural stability deficits in the involved knee.[78]

RETURN TO SPORT (RTS)

The decision to RTS following an anterior cruciate ligament reconstruction (ACLR) is a complex process. There is a lack of consistency in the use of the term "return to sport" when discussing criteria related to RTS. Several studies used different terminologies such as "return to sport", "return to play", or "return to participation” interchangeably without adequate operationalization. According to the consensus group of the First World Congress in Sports Physical Therapy (2016), RTS after any sport injury was described as a continuum that emphasizes a progression from “return to participation” to “return to sport” to “return to performance”.[6] The statement defined “return to participation” as returning to training in sport, but not yet ready to return to full sporting activities.[6] “Return to sport” was defined as returning to the previous level of sports, but still not at the preinjury level, while “return to performance” was defined as returning to the pre-injury level of sport.[6] In 2019, the Panther Symposium ACL Injury Return to Sport Consensus Group adapted the proposed definitions proposed by the First World Congress in Sports Physical Therapy statement, and postulated that RTS criteria could represent different things to different patients.[60] Therefore, the statement suggested that RTS is achieving the pre-injury sports type, level, frequency and quality of performance.[60] Appreciating RTS as a continuum mandates that the approach toward RTS should go through stages, and not be a single decision made toward the end of the rehabilitation process.[60]

Commonly used criteria to make this decision include: time from ACLR, functional performance, clinical examination findings, hop tests results, muscular strength, knee range of motion, neuromuscular control, and patient-reported outcome measures (PROMs).[16] Several studies used lower limb symmetry indices (LSI) when reporting on different functional, physical and biomechanical criteria. However, the validity of these criteria, when studied individually or combined, have been increasingly questioned,[18] and the use of LSIs has been debated.[97]

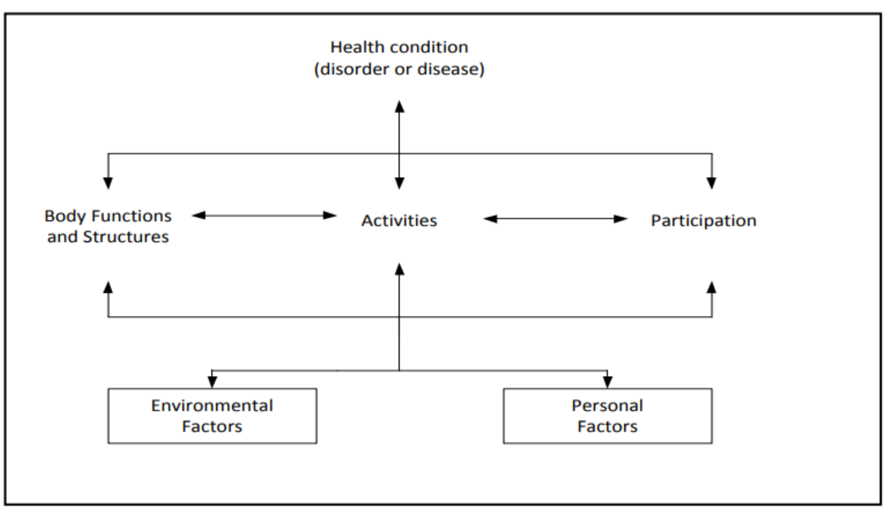
While accelerated rehabilitation programs target earlier RTS following ACLR, studies suggest the rate of a secondary ACL injury can be reduced by 50% for every month the RTS is delayed up to 9 months.[33] Other authors suggest to extend the RTS time to as long as 2 years following ACLR to moderate the risk of re-rupture.[68] The lack of consistency in published evidence on the best time for individuals to RTS following ACLR suggests that the time criteria should be avoided. This agrees with recommendations of the Panther Symposium ACL Injury Return to Sport Consensus Group stating “purely time-based RTS decision-making should be abandoned in clinical practice”.[60]

The use of LSI has been of particular interest in the recent literature when making RTS decisions. It is crucial to appreciate that achieving "above threshold" symmetry between the two limbs does not mean that athletes have achieved the preinjury activity level (like in the case of strength testing), nor does it correlate with quality of the performed task (like in the case of single-leg hop tests). Moreover, there is a lack of consistency on the symmetry threshold between the literatures with most of them reporting an LSI threshold between 85%-90%. Gokeler et al. (2017), reported that individuals who achieved an LSI of above 90%, still demonstrated clinical deficits in performance for both limbs when compared with controls.[28] Accordingly, using the LSI for performance testing may over estimate knee function,[103] and therefore the interpretation of the LSI must be done with substantial caution.[97]

COMMONLY USED CRITERIA TO ASSESS RTS

This section will discuss the commonly used criteria to RTS and will be presented according to the International Classification of Function (ICF) conceptual model (Figure 2.1) as a framework for classifying those criteria into impairment, activity, participation, and contextual factors.[112]

Figure 2.1 The International Classification of Functioning, Disability and Health (ICF) Model. Adapted from: A practical manual for using the ICF [112]



Strength tests (impairment)

In addition to the reduced muscle strength resulting from the lack of sport participation after the ACL injury and right after the ACLR, the graft type can also be a strength deficit factor. Xergia et al, (2011) demonstrated in a meta-analysis that individuals who undergoes ACLR using Bone-Patellar-Tendon-Bone (BTB) graft show a greater deficit in the knee extensors muscle strength, and lower strength deficit in the knee extensor muscles when compared to individuals with hamstring grafts.[108]

Hip abductors weakness also play a major role in the reduced hip abduction and external rotation during knee valgus while landing.[78] In a cohort study of 523 participants, Higbie et al. (2021), reported that isometric hip abduction was reduced in almost 70% of the participants.[40]

Several studies reported testing muscle strength as a RTS criterion following ACLR. With no date limitations, a scoping review on the criteria used to facilitate RTS decision after ACLR included 86/209 (41.1%) studies that reported on muscle strength as a RTS criterion. The study did not comprehensively report on the testing protocols; however, testing was either isometric, isokinetic, or both. The review also reported on the heterogeneity in the cut off points of the Lower Limb Symmetry Index (LSI) that varied among the included studies between 65%-90%. Moreover, there was inconsistency with the selection of knee angular speed when testing knee flexor or extensor strength. The review did not include any studies that tested the hip abductors strength as a criterion for RTS, although the correlation between hip abductor weakness and increased knee valgus was established years ago.[78] The findings of the scoping review align with the work of Higbie et al. (2021) who suggested that more research is needed to address the hip strength as a criterion for RTS following ACLR.[40] Moreover, a muscle strength testing guideline is required to inform clinician with evidence based approaches to measure muscle strength around the knees and hips including important items (e.g., joint starting angle and angular speed) and the best parameters to be measured (i.e., peak torque vs average torque, angle specific torque, total work, power, and rate of force development).

Balance tests (impairment)

During athletic activity, postural stability is processed unconsciously, as the attention is mainly on the field of play and not on maintaining upright posture. Nevertheless, the typical assessments of postural stability often focus on the conscious control of posture, not on the automatic (unconscious) response of the body to maintain its upright posture during performing athletic activities.[69] Dual task paradigms are usually employed to assess the automatic nature of postural stability.[11] This involve the maintenance of upright posture (single task) while employing a second motor, visual or cognitive task. Postural control has been examined in individuals following ACLR using different means including sophisticated balance platforms, force plates, as well as Nintendo Wii Balance Boards. While there has been more studies on balance following ACLR,[87] there is still paucity of literature studying postural stability after ACLR.

Performance-based functional testing

Performance-based functional testing of the knee can be quantified objectively with a battery of tests such as hop tests to examine the quality of movements and/or biomechanical (kinetic and kinematic) testing. The following section will discuss the hop test, and kinetic and kinematic measurements. These types of evaluations frequently compare between results between the injured and contralateral limb using the LSI.

Hop tests (activity)

Hop tests are frequently reported in the literature as a part of the functional criteria in the RTS decision. They are considered practical and easy to administer tests that require minimal equipment and time. The tests are usually performed on both limbs so that the performance on the operated limb can be expressed as a percentage of the performance on the contralateral side to establish an LSI. Hop tests are believed to reflect individual's performance reflecting the integration of strength, neuromuscular control as well as confidence.[2, 18] The reliability of the LSI of the three hop for distance tests (single-leg hop for distance

(SLHD), triple hop for distance (THD), crossover hop for distance (CHD)) was strong (ICC values of 0.92, 0.88, and 0.84, respectively). The 6-meter timed hop test (T6H) demonstrated lower ICC value of 0.82.[84] Similarly, the longitudinal construct validity has also been tested and reported.[84] However, recent literature has shown that meeting the 90% cut-off point for the single-leg hop test was not related to maintaining sports participation over the first year after RTS clearance. Moreover, using more than 2 hop tests does not appear to provide greater sensitivity to detect abnormality.[96]

Biomechanical testing (impairment)

Biomechanical testing can measure the quality of the movement while performing functional tasks, and examine specific deficits that may contribute to a secondary ACL injury or facilitate decision to RTS. Several jumping, landing, squatting, cutting, and walking tasks have been examined to assess biomechanical deficits following ACLR.

While motion capture systems with reflective markers are considered the gold standard for measuring kinematic variables, several studies proposed the use of normal cameras to assess movements in different planes. Similarly, the force plate is the gold standard for measuring kinetic parameters such as ground reaction force. Yet, other tools for measuring GRF are emerging (e.g., pressure sensor insoles).[49] As technology is rapidly developing in this area, it is becoming easier for clinicians to measure kinematic and kinetic parameters at any clinic, or testing center. However, there is a lack of consistency in the literature on what testing protocol to follow, and what parameters to measure. Future research is needed to identify the most discriminative and the most responsive parameters. Likewise, guidelines are required to standardize the testing protocols across future research evaluations.

Patient-reported outcome measures (PROMs)

PROMs can assess patient reported function (activity and participation) or psychological readiness to return to work (contextual factors).

Functional PROMs (activity and participation)

Beside the musculoskeletal impairments following ACLR, patient reported function scores are affected early after ACLR, during and sometimes even after the completion of rehabilitation. Several patient reported measures have been validated to measure functions following musculoskeletal knee problems such as Knee Injury and Osteoarthritis Outcome Score (KOOS) or the International Knee Documentation Committee (IKDC). Roe et al. (2021), demonstrated in a systematic review that 49/63 (77.8%) of the studies reported using PROMs of which 12 were related to function.[87] Among all the identified functional outcome measures, the IKDC was the most frequently reported outcome measure (54.0%), followed by the KOOS (23-28%). The IKDC is an 18-item instrument that measures symptoms, functions and sports activity. Symptoms items include pain, swelling, stiffness, joint locking and joint instability. The sports related items assess the ability to go up and down stairs, kneel, squat, sit with knee bent, rise from chair, run, and jump, while function related items include ability to perform activities of daily living. The IKDC is widely used for its reliability and has been validated in different languages.[41] The patient acceptable symptoms state (PASS) threshold for the IKDC was set at 75.9 with a sensitivity and specificity of 0.83 and 0.96 respectively.[65]

The KOOS has 42 items in six different subscales measuring symptoms, stiffness, pain, daily living functions, sport and recreational functions and quality of life.[21] It is also widely used in the knee literature and has been validated to be used for various knee problems.[21] The patient acceptable symptoms state (PASS) for the KOOS-Pain (sensitivity, specificity) was 57.1 (0.78, 0.67), for the KOOS-symptoms 100.0

(0.70, 0.89), for the KOOS-ADL 75.0 (0.87, 0.88), for the KOOS sport and recreational functions, and 62.5 (0.82, 0.85) for the KOOS-quality of life.[65]

Self-reported measures of knee function should be monitored during and following rehabilitation in individuals with ACLR. Functional outcome measure scores can significantly influence the rate of RTS.[102] Better self-reported functional score at 2 year after RTS was associated with higher quadriceps strength symmetry and higher quadriceps peak torque.[47] However, while several function outcome measures were validated, it is not clear which outcome measure is the best to measure function among different age groups in the ACLR population.

Psychological readiness PROMs (contextual factors)

Fear of movement, kinesiophobia, is a psychological concept that is associated with poor outcomes in individuals with ACLR.[72] Pain and physical impairments during the acute stage following ACL injury as well as ACLR may contribute to fear development against any movement that could cause more loading on the ACLR limb. Consequently, this may increase the risk of delayed return to sport or even previous activities.[56] Nwachukwu et al., (2019) reported in a systematic review that fear of re-injury was the most common reason not returning to pre injury levels of activity. Other reasons included lack of confidence in the treated knee, depression, and lack of motivation.[72] The review identified several psychology related tools for assessing the influence of psychology on RTS. They included the Tampa Scale for Kinesiophobia, the Hospital Anxiety and Depression Scale, the ACL–Return to Sport after Injury scale, and the Knee Self-Efficacy Scale.[72] The validity and reliability of the Tampa Scale of Kinesiophobia when utilized with individuals following ACLR was examined. The scale showed an excellent reliability with a Cronbach's alpha of 0.92.[101] Moreover, the Tampa Scale of Kinesiophobia was shown to be associated with the IKDC score in individuals at 1 year following ACLR.[54]

The presence of several tools to examine psychology related factors that may impact RTS following ACLR, makes it difficult for clinicians to decide on which tool to use when assessing several psychological constructs. Moreover, the studies that reported on the association between psychology related self-reported outcome measures and other biomechanical measures are scarce.

Future research is needed to further understand the extent of this relationship.

POSTURAL CONTROL

Postural control emerges from the interaction between the individuals, the task with its inherited complexities, and the surrounding environment.[94] It involves controlling the body's position in space for the purposes of stability and orientation.[94] All the motor tasks we do require postural control. Therefore, every task has the orientation and stability components that will vary according to the task and the environment, highlighting a trade-off relationship between stability and orientation. We will discuss in the section below the biomechanical, environmental and cognitive contributions to postural control.

Environmental contribution

Motor tasks can be performed in several environments, and can be facilitated or constrained by features within the environment. Shumway-Cook & Woollacott divided the attributes of the environments that can affect motor tasks into regulatory and non-regulatory features.[94] Regulatory features are those features that shape the movement such as the type of terrain or walking surface.[94] In contrast, the non-regulatory features are those that may affect the performance or the movement quality but not the task itself.[94] For example, the noise in the environment or cognitive distraction may affect the quality and change the biomechanics of the movement. Thus, understanding the contribution of the environment to postural control is crucial when assessing patient motor performance or even designing a rehabilitation program that could utilize those environmental features to meet the demands of different environments.[10]

Biomechanical contribution

The biomechanical features of an individual contribute mostly to the stability component of postural control. Therefore, we will refer to postural stability when discussing the biomechanical contribution to postural control.

Joint stability is defined as the ability of the joint to maintain its alignment (static stability) or return to proper alignment (dynamic stability) through the balance between different forces.[107] The static stability is controlled by structural components (i.e., ligaments, joint capsule, cartilages, and the geometry of the articulating joint surfaces). They are assessed through joint stress testing which is defined as clinical joint stability testing.[91] However, during the execution of physical motor tasks, those components are not adequate to maintain joint stability. While static stability components provide the foundation for joint stability during functional activities, the dynamic components, including the neuromuscular control of skeletal muscles around the joint,[3] are essential for the safe and accurate execution of the physical task. Dynamic joint stability is formed by the integration of the static and dynamic components to keep the joint stable when subjected to sudden loads while performing motor tasks.[91] Poor static and dynamic joint stability may result in postural stability deficits.

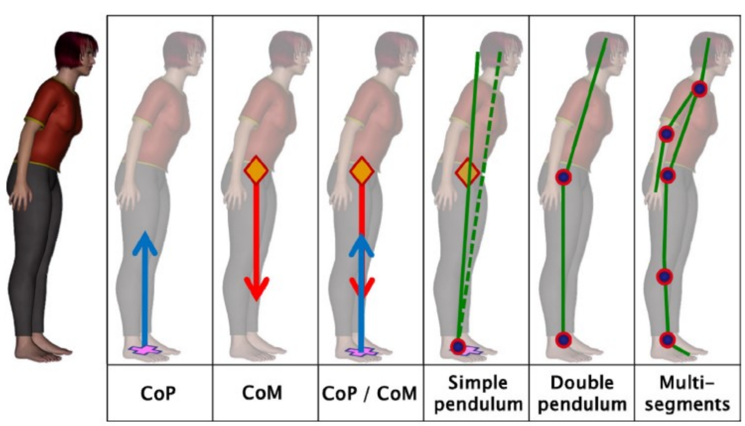
Postural stability can be assessed statically and dynamically. Static postural stability is the ability to maintain balance while the body is stationary (static state) with the feet arranged in various positions (e.g., single-legged, double stance, tandem, etc.).[9] Dynamic postural stability is the ability to maintain center of mass within the base of support while part of the body is in motion or when transitioning from a dynamic to a static state.[106] As the majority of non-contact ACL injuries occur during landing and changing directions, the assessment of dynamic postural stability may be more suitable to assess function in individuals following ACLR. Several methods are used to assess dynamic postural stability. For example, during the star excursion balance test, participants following ACLR are asked to stand on one leg while reaching in different directions with the contralateral leg.[24, 104] As the non-contact ACL injuries occur during the loading phase of a single or double-leg landing or change of direction,[99] assessing the dynamic postural stability immediately following a motor task such as jumping-landing may have better discriminatory capacity.

Dynamic postural stability can be assessed objectively through measuring the center of pressure (CoP) movement by force plates while maintaining balance following movements.[92] As several systems are involved [71] to maintain dynamic postural stability (i.e., somatosensory, visual, audio and vestibular),[94] it is postulated that the somatosensory deficits are the largest contributors to dynamic postural stability deficits.[32, 43, 85] Postural deficits are seen in several patients with neurological (e.g., Parkinson’s disease,[75] multiple sclerosis,[82] spinal cord injuries, etc.) and musculoskeletal disorders such as osteoarthritis,[38] low back pain,[77] recurrent ankle sprains[12] and ACL injuries.[63, 78]

Models of postural analysis

Several biomechanical models have been developed to further understand how postural stability is maintained. Cretual (2015) looked at 252 studies published between 2011 and 2015 to understand the most commonly used model for postural analysis. The author identified six models (figure 2.2) and found that the simplest model (the center of pressure) to be the most commonly used in almost 64% of the studies followed by the multi-segments model in 11.1% of the studies.[14]

Figure 2.2 Different models used in postural analysis. From left to right: Center of Pressure alone (CoP), Center of Mass alone (CoM) Center of Pressure and Center of Mass (CoP/CoM), single pendulum, double pendulum and multi-segments. Adapted with persmission from Crétual A. (2015)[15] (see appendix A)



The simple pendulum (the inverted pendulum) has also been considered in several studies as an acceptable model[64]. It assumes that only the ankle joints contribute to the sway movements. However, that assumption was challenged by the findings that movements at the hip joints should not be neglected, suggesting that the simple pendulum model should be replaced by the double pendulum model.[110]

Hsu et al, postulated that the human stance is inherently not stable.[44] They revealed small movements along the longitudinal axes of the body in the ankles, knees, hips, the lumbosacral junction, the cervicothoracic junction and at the atlanto-occipital junction. These movements were destabilizing and re-stabilizing to maintain postural stability. Therefore, more recent studies suggested that the multi-segments model may provide deeper insights into postural stability analysis where the contribution of each joint to postural stability is estimated by the center of pressure movement, joint degree of freedom, the joint's torques and the correlation between the displacement of the center of mass and the joint angular displacement.[50]

The knee role in postural stability

The multi-segments model suggests that several small angular movements at different joints to maintain postural stability.[44] Gage et al, suggested that the angular displacement at the knee was larger than at the ankle during quiet standing, and postulated that the knee movements contributes to allowing the lower extremities to track the center of mass.[25] The multi-segments model demonstrated a strong coupling movement between the knee and ankle and a relatively weaker coupling movement between the knee and hip.[34] Accordingly, it was postulated that the knee joint provides more dynamic control over quiet standing.[34]

Cognitive contribution

Recently, a growing interest has been emerged on cortical activities while performing motor tasks.[26, 27, 83] Maekawa et al, demonstrated that an increase in cortical activities was associated with a reduced postural sway area.[57] Interestingly, increased cortical activities were also noticed before performing the motor task.[83]

In the context of ACL injuries, the rupture of the ACL and the surgical intervention put a major impact on the ACL mechanoreceptors. ACLR does not restore the sensorimotor system that controls the afferent inputs from the ACL to the nervous system.[8, 73] With the absence of somatosensory afferents, the brain is challenged to control movements and maintain stability through the efferent neuromuscular pathways.[73] As a result, persistent changes in cortical activation patterns have been noticed suggesting a neural adaptations that may contribute to the frequently observed impairments in postural control and landing mechanics,[27] and higher secondary injury rate after return to sport following ACLR.[105]

DUAL TASK PARADIGM

Dual task is defined as the ability to perform two tasks simultaneously, while each of those tasks can be measured independently.[37] Dual task assessment is based on the assumptions that attentional resources are limited and that task complexity can influence the utilization of attentional resources.[90] This section will cover the performance of the dual task and its use in sports injuries.

Dual task performance

Typically, dual task performance is evaluated after breaking it into its two components; primary and secondary components. The primary task is usually a functional motor task that is relevant to the population of interest. The secondary task is defined as any task that compete for attentional resources. Therefore, most of the studies use cognitive tasks as secondary tasks; however, other manual tasks can also be employed.[13]

Several cognitive tasks have been applied under the dual task paradigm including visuospatial,[100] auditory[62] and arithmetic[100] tasks. The Stroop test is one of the widely used test as a secondary task with proven high internal consistency (α=0.88) and reliability (r=0.87).

<u>Dual task in the context of sport injuries</u>

Dual task has been applied when testing elderly[1] or populations with neurological disorders.[82] However, several recent studies have evaluated the dual task effect in individuals with sport injuries.[11, 35, 42, 58] Mohammadi-Rad et al. assessed the single-leg postural stability under single and dual task condition and highlighted cognitive performance deficits in individuals following ACLR.[63] Interestingly, dual task rehabilitation programs had a positive effect on improving function in people with neurological disorders[55] and others with sports injuries.[53] This highlights the potential of dual task paradigm to assist assessment and treatment of several disorders.

CONCLUSION

In conclusion, the ACL is vital for knee stability. ACL injuries have a high incidence and significant long-term consequences, with a notable risk of secondary injury after ACLR. Risk factors for secondary ACL injuries include modifiable factors such as BMI, graft type, neuromuscular, and biomechanical elements, alongside non-modifiable factors like age, sex, and anatomical features. The complexity of RTS decisions following ACLR necessitates consideration of muscle strength, balance, functional performance, and patient-reported outcomes. Ensuring robust postural control, influenced by biomechanical, environmental, and cognitive contributions, is crucial for preventing secondary injuries. The dual-task paradigm, integrating cognitive and motor tasks, presents promising avenues for assessment and rehabilitation.

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CHAPTER 3- KINETIC MEASUREMENT SYSTEM USE IN INDIVIDUALS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION: A SCOPING REVIEW OF METHODOLOGICAL APPROACHES

A version of this chapter has been published. Labban W, Stadnyk M, Sommerfeldt M, Nathanail S, Dennett L, Westover L, Manaseer T, Beaupre L (2021) Kinetic measurement system use in individuals following anterior cruciate ligament reconstruction: a scoping review of methodological approaches. J Exp Orthop J Exp Orthop. 10.1186/s40634-021-00397-0

ABSTRACT

Purpose Our primary objectives were to (1) describe current approaches for kinetic measurements in individuals following anterior cruciate ligament reconstruction (ACLR) and (2) suggest considerations for methodological reporting. Secondarily, we explored the relationship between kinetic measurement system findings and patient-reported outcome measures (PROMs).

Methods We followed the PRISMA extension for scoping reviews and Arksey and O'Malley's 6-stage framework. Seven electronic databases were systematically searched from inception to June 2020. Original research papers reporting parameters measured by kinetic measurement systems in individuals at least 6-months post primary ACLR were included.

Results In 158 included studies, 7 kinetic measurement systems (force plates, balance platforms, pressure mats, force-measuring treadmills, Wii balance boards, contact mats connected to jump systems, and single-

sensor insoles) were identified in 4 main movement categories (landing/jumping, standing balance, gait, and other functional tasks). Substantial heterogeneity was noted in the methods used and outcomes assessed; this review highlighted common methodological reporting gaps for essential items related to movement tasks, kinetic system features, justification and operationalization of selected outcome parameters, participant preparation, and testing protocol details. Accordingly, we suggest considerations for methodological reporting in future research. Only 6 studies included PROMs with inconsistency in the reported parameters and/or PROMs.

Conclusion Clear and accurate reporting is vital to facilitate cross-study comparisons and improve the clinical application of kinetic measurement systems after ACLR. Based on the current evidence, we suggest methodological considerations to guide reporting in future research. Future studies are needed to examine potential correlations between kinetic parameters and PROMs.

INTRODUCTION

The decision to return to sport (RTS) following anterior cruciate ligament reconstruction (ACLR) is a complex process [9]. Common criteria used to make this decision include: time from ACLR, functional performance, clinical examination findings, hop tests results, muscular strength, knee range of motion, neuromuscular control, and patient-reported outcome measures (PROMs) [39]. However, the validity of these criteria, when studied individually or combined, has been increasingly questioned [31, 44, 79, 107]. This mandates researchers and clinicians to incorporate objective and accurate biomechanical assessment systems to inform RTS decision-making post-ACLR [50].

Biomechanical assessment systems include kinetic and kinematic measurement systems. These systems can be synchronized with electromyography to examine muscular activity when required [160]. Kinetic and kinematic measurement systems are used to measure force (e.g., force plates) and joint angles (i.e., motion capture systems), respectively. Moreover, these two systems can be used together to measure important kinetic parameters such as joint moments. With the rapid advancement in the field of biomechanics, recent studies are examining the use of different motion capture systems to estimate kinetic parameters such as ground reaction forces and joint moments [1, 2, 184]. However, the methodologies used to estimate joint moments are debatable [170] and kinetic measurement systems are still considered the gold standard when measuring forces [3].

Different kinetic measurement systems have emerged as instruments to objectively assess various functions such as jumping [8, 146], postural control [4, 54], and gait [155]. These systems use force sensors to quantify forces exerted during performance of activities or tasks [34]. They are utilized by clinicians and researchers to assess functional progression throughout rehabilitation and may assist in determining the ability to RTS in post-ACLR individuals [67]. Previous studies have examined various kinetic parameters in the ACLR population; however, there is a lack of consistency in the literature regarding which parameters to assess and what assessment protocol(s) to follow. Thus, the primary objectives of this scoping review were to (1) describe the approaches for kinetic measurements in individuals following primary ACLR and (2) propose methodological reporting considerations for future studies. The secondary objective was to explore how commonly kinetic measurement system findings were related to PROMs. This review will provide clinicians and researchers with further information on the use of kinetic measurement systems in the ACLR population and may also inform future studies which, ultimately, may advance this field of study.

METHODS

The current review followed the six-stage methodological framework by Arksey and O'Malley (Table 3.1) [10] while considering the recommendations by Levac et al. [95], and the Joanna Briggs Institute Manual for Scoping Reviews [187]. It was conducted and reported according to The PRISMA Extension for Scoping Reviews (PRISMA-ScR) [167]. The current refined review's protocol was uploaded on the University of Alberta Education and Research Archive: https://doi.org/10.7939/r3-e9fz-et12.

Table 3.1: Arksey and O'Malley 6-stage methodological framework

Stage 1	Identify the scope and inquiries
Stage 2	Identify data sources and search
Stage 3	Record screening and study selection
Stage 4	Data charting
Stage 5	Collate, summarize, analyze and report the results
Stage 6	Stakeholders' consultation

Stage 1: Identifying the scope and inquiries

The primary research questions that guided this scoping review were:

What are the current approaches for kinetic measurements in individuals following ACLR?

Is there a need to propose methodological reporting considerations for future studies?

Eligibility Criteria

All inclusion and exclusion criteria are reported in Table 3.2. The constructs of "participants", "primary ACLR", and "kinetic measurement systems" are operationalized in Table 3.3.

Table 3.2: Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Human participants	Animal models or cadavers
• Primary study design (quantitative & mixed methods) with original published data	• Qualitative studies and not primary study design or original data (conference proceedings or abstracts, editorials, commentaries, opinion-based papers and systematic, scoping, or narrative reviews) • Theses and Dissertations • Case Studies
• Studies with participants post-ACLR	• Studies with participants post-ACL repair (i.e., surgical reattachment of the ACL, instead of performing a reconstruction) [24]
• Studies with a population of primary ACLR participants	• Studies with only secondary ACLR participants • Studies where participants have other significant comorbidities, including; musculoskeletal, neurologic and/or systemic disorders • Studies where more than 50% of the participants had meniscal procedures at the same time as the ACLR
• Studies with kinetic measurement systems outcomes	• Studies with no kinetic measurement systems outcomes. Studies that included force plates only to confirm foot contact with ground (confirmatory kinetic measurement system)
• Only studies with extractable data of individuals who were at least 6 months following a primary ACLR (i.e., following completion of standard rehabilitation) were considered	• Reported data before 6 months post-ACLR

Table 3.3: Definitions

Participants	Any individual with primary ACLR; no limitation to a specific age group, sex, sport or activity level.
Primary ACLR	A first time ACLR; surgical tissue graft replacement of the anterior cruciate ligament to restore its function after injury [25].
Kinetic measurement systems	This review included all platforms that use similar kinetic measurement systems technologies including force plates, balance platforms, pressure platforms, force measuring treadmills, Wii balance boards, contact mats connected to jump systems (computer software or device), and single-sensor insoles.

Stage 2: Identifying data sources and search

Information sources

Potentially relevant studies were identified through literature searches of the following electronic databases: MEDLINE (Medical Literature Analysis and Retrieval System Online), EMBASE (Excerpta Medica dataBASE), CINAHL (Cumulative Index of Nursing and Allied Health Literature), SPORTDiscus, Scopus, Web of Science, and ProQuest Dissertations and Theses Global for unpublished theses. These databases were searched since inception with no language limitations.

Search strategy

The search strategy was developed by an experienced librarian scientist (LD) with refinement of the search terms through iterative discussions between the study team and research collaborators to ensure identification of relevant records. The search terms included keywords and subject headings (MeSH) that have emerged in this research field, as appropriate. (Appendix 3.1 shows the search strategy.)

Stage 3: Record screening and study selection

Potentially relevant records were exported into a reference management software (EndNote X9.3.3) where duplicates were removed [28]. The titles and corresponding abstracts of remaining records were independently screened by 2 raters (WL, MMS) using Covidence (Veritas Health Innovation, Melbourne, Australia; available at www.covidence.org). Initially, the 2 raters (WL, MMS) independently screened a random sample of 100 titles and abstracts to assess the appropriateness of the selection criteria and determine the inter-rater agreement between reviewers using a Microsoft® Excel workbook explicitly designed for screening [173]. The raters reached substantial agreement (Cohen Kappa 90% = 0.75; 95% CI 0.60 - 0.90). The study team further refined the selection criteria prior to commencing full title and abstract screening. Finally, the 2 raters independently performed full-text review to determine final study selection. Disagreement on study eligibility during the title and abstract screening and full-text review stages were resolved through discussion between the two raters; a third rater (MFS) was approached if necessary, until consensus was reached.

Stage 4: Data charting

Table 3.4 outlines the data items extracted from each study. Prior to data extraction, the form was assessed through comparison of data extracted by the 2 raters independently (WL, MMS), using a purposive sample of 10 studies of various designs. Discrepancies in charted data were resolved through discussions between raters.

Table 3.2: Data Items

Category	Item(s)
Study characteristics	Author(s), year of publication, language, study design and location of investigation
Study objectives	Study objectives and purposes
Participant sample characteristics	Sample size disaggregated by sex, age, reported activity and activity level
Primary ACL surgical details	Graft type, side of surgery (dominant/non-dominant), time from surgery
Testing protocol details	Activity measured or assessed (jumping/landing, balance, gait, or other functional activities) Testing equipment used (force plate, balance platform, etc.), sampling frequency, testing protocol and tasks performed, number of trials per test
Outcomes	Testing equipment parameters, clinical assessment tools Self-reported outcome measures related to function, physical activity, readiness to return to sports, quality of life, and kinesiophobia

Stage 5: Collate, summarize, analyze and report the results

We conducted a descriptive and numerical analysis of the extracted variables. To align our results with our research questions, we collected the reported objectives and methods for each paper and categorized the outcomes (parameters) based on the movements assessed by the kinetic measurement systems (i.e., jumping, landing, step-over, stop-jump, lunges, cutting movement, squatting, gait, and standing balance). We reported the parameters as defined by the authors of the included studies. We recorded testing protocols, including: the testing environment setup, participants' preparation, testing conditions, protocol details, number of repetitions, and duration of tasks, as applicable (see Appendix 3.2). We also identified studies that included PROMs and kinetic measurement system parameters. An iterative process was followed to suggest methodological reporting considerations. Specifically, the primary author (WL) drafted methodological reporting considerations based on study findings and team recommendations. Subsequently, the study team met and provided comments and feedback, resulting in the final version of the suggested methodological reporting considerations.

Stage 6: Consultation

To employ an integrated knowledge translation and dissemination approach, we engaged a knowledge user (a biomechanist) and a research collaborator (an engineer with expertise in force plates and balance platforms) for their input on the study findings.

RESULTS

Identification of Studies

An overview of the study identification process is provided in Figure 3.1. Of 5787 identified records, 2027 unique records underwent title/abstract screening, 705 were reviewed in full, and 158 studies were included. Papers evaluating the same cohort with different (a) aims, (b) tasks evaluated, or (c) outcomes were treated independently.

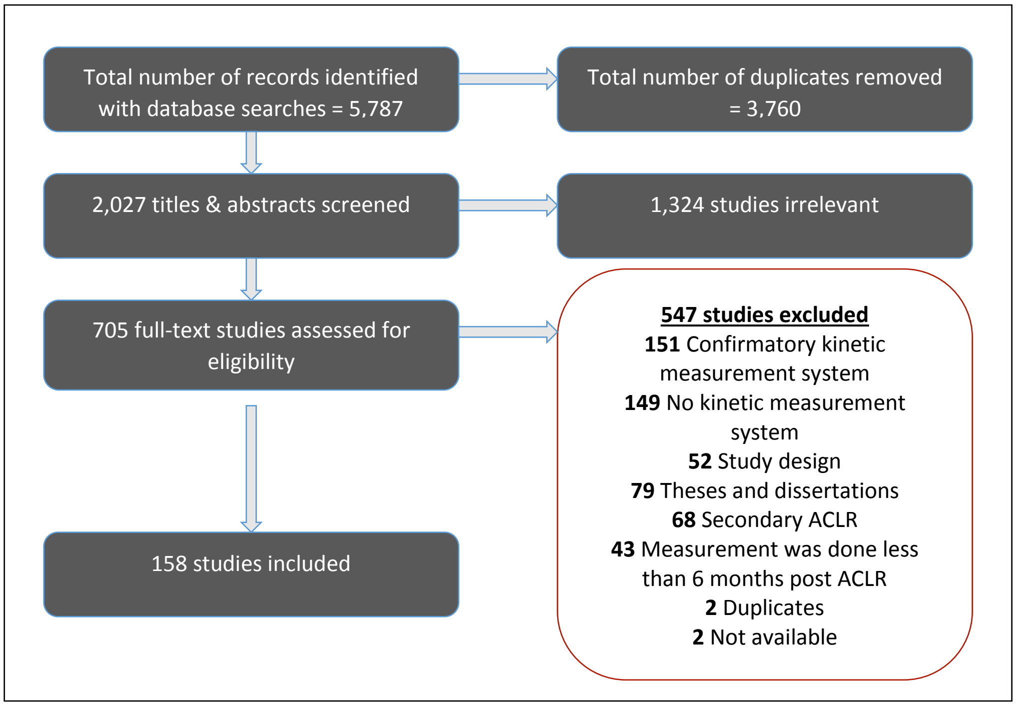

Figure 3.2: Search Results and Study Selection

Characteristics of Studies

The characteristics of the 158 included studies are summarized in Appendix 3.2. All studies were quantitative including 111 (70.25%) cross-sectional studies, 35 (22.15%) longitudinal, 10 (6.33%) interventional, and 2 (1.27%) case-control studies. Studies were published between 1990 and 2020 with 99 (62.66%) studies published since 2015. Studies were conducted in 28 countries with the highest number conducted in the United States (58 [36.7%]). Overall, 7909 participants were included (female = 2787 [35.2%]; male = 5122 [64.8%]). The mean age of participants ranged from 15.6 (±1.7) to 48.2 (±5.5) years. 5570 participants (70.4%) had ACLR, 158 (2.0%) were ACL deficient (ACLD), and 2331 (27.6%) were Healthy Controls. Participants represented a variety of physical activity and sport participation levels. Healthy Control groups existed in 91 (58%) studies.

Movement Tasks

We identified 7 different types of kinetic measurement systems that assessed 9 different movements (tasks) in 4 main categories: landing/jumping, standing balance, gait, and other functional tasks. Table 3.5 contains full descriptions of movements and categories, identified kinetic measurement systems, and frequency of use across the studies. The majority of studies assessed landing, jumping, standing balance, and gait parameters. The force plate was the most commonly used system and the only system with potential to measure all identified movement tasks.

Data was collected and reported, where possible, for the parameters identified, system setup (kinetic measurement system type, sampling frequency), participants' preparation (warm up, barefoot/shoed, hand position), and protocol details (movement platform, movement direction, movement type, single/double-leg jumping, single/double-leg landing, task after landing, eyes open/closed, single/dual task, number of repetitions). Overall, there was substantial heterogeneity among studies in the parameters examined and the protocols used. Below, we summarize the identified parameters and protocols according to the 4 main movement categories.

Table 3.3: Frequency of different kinetic measurement systems used to assess different movements (tasks) across the studies

Kinetic Measurement Systems	Movement Tasks								
	Landing/Jumping		Standing Balance	Gait	Other Functional Tasks				
	Landing	Jumping			Cutting Movement	Squatting	Stop Jump	Step-Over	Lunges
Force Plates	56*	6*	23	26	8	5	2	1	1
Balance Platforms	0	1	28	0	0	0	0	0	0
Pressure Mats	0	1	2	1	0	1	0	0	0
Force Measuring Treadmills	0	0	0	6	0	0	0	0	0
Wii Balance Board	0	0	4	0	0	0	0	0	0
Contact Mats Connected to Jump system	0	3	0	0	0	0	0	0	0
Single-Sensor Insoles	2	0	0	0	0	0	0	0	0

*Three studies assessed both jumping and landing and were included under both "Landing" and "Jumping" columns, bringing the total number of studies assessing landing and jumping using force plate to 59.

Landing/Jumping

Sixty-six studies examined landing and/or jumping tasks, with 43 (65.2%) published during the last 5 years. Studies included data from 3307 participants: 981 (29.7%) females, 2326 (70.3%) males; 2170 (65.6%) ACLR, 64 (1.9%) ACLD, and 1073 (32.4%) Healthy Controls.

Fifty-three unique kinetic variables were identified using 5 different measurement systems (force plates, contact mats connected to jump systems, single-sensor insoles, balance platforms, and pressure mats; Table 3.5). The following sections describe the parameters identified (as defined and reported by the authors of the included studies) and the measurement protocols used for each measurement system.

Force Plate (Measurement System 1): Force plates were used in 59/66 (89.4%) studies. Of the 59 included studies, 53 (89.8%) assessed landing only [15, 16, 59, 63–65, 72, 78, 81, 82, 86, 87, 32, 88–92, 103, 104, 108, 110, 115, 33, 116–118, 120, 127, 129, 140, 144, 147, 148, 43, 151, 154, 156–158, 161, 168, 171, 174, 175, 45, 179, 180, 182, 51, 55, 57, 58], 3 studies assessed jumping only [19, 56, 142], and the remaining 3 studies assessed jumping and landing together [85, 114, 122].

Force Plate Parameters: Forty-six unique parameters were identified. Vertical Ground Reaction Force (vGRF) and peak vGRF were the most frequent parameters, each identified in 16 (27.1%) [32, 45, 151, 156, 158, 161, 171, 51, 58, 72, 81, 82, 115, 127, 144] 15 (25.4%) [32, 33, 157, 158, 171, 174, 179, 180, 43, 86, 103, 110, 116, 117, 122, 147] and 15 (25.4%) [32, 33, 157, 158, 171, 174, 179, 180, 43, 86, 103, 110, 116, 117, 122, 147] studies, respectively, followed by the peak Ground Reaction Force (GRF) in 6 (10.2%) studies [55, 65, 110, 118, 122, 182]. The remaining parameters were each measured between 1 to 5 times with a median of 1. (Appendix 3.2, *Table 1*)

Testing Protocol: This includes system setup, participants' preparation, and jumping/landing protocol details.

Related to *system setup,* force plate sampling frequencies were reported in 48 (81.4%) studies and ranged between 50Hz and 5000Hz. The most frequently used sampling frequencies were 1000Hz and 1200Hz in 17 (28.8%) [19, 55, 142, 144, 148, 156–158, 161, 56, 72, 78, 81, 82, 85, 120, 140] and 12 (20.3%) studies [16, 45, 171, 174, 51, 57, 103, 104, 115, 116, 127, 147], respectively.

Regarding *participants' preparation,* participants were asked to warm up prior to testing in 18 (30.5%) studies [19, 33, 87, 88, 108, 117, 118, 144, 161, 182, 45, 51, 56, 58, 72, 78, 81, 82]. There was substantial heterogeneity in warm up duration and components across the studies. Participants were barefoot in 5 (8.5%) studies [19, 72, 103, 104, 129], and wore shoes in 20 (33.9%) studies [16, 51, 88, 90, 91, 120, 144, 147, 157, 174, 175, 179, 55, 63, 64, 78, 81, 82, 86, 87]. The remaining 34 (57.6%) studies did not specify whether participants wore shoes or not [15, 32, 85, 89, 92, 108, 110, 114–118, 33, 122, 127, 140, 142, 148, 151, 154, 156, 158, 161, 43, 168, 171, 179, 182, 45, 56–59, 65]. Of 22 (37.3%) papers that reported hand placement while testing, 18 studies requested participants to keep hands on hips [19, 43, 91, 120, 129, 140, 142, 171, 179, 180, 51, 56, 59, 72, 78, 81, 85, 90], 2 instructed participants to cross their arms on their chest [45, 63] and 2 studies, by the same author, had participants hold a short rope behind their back [103, 104].

Finally, *jumping/landing protocols* varied substantially in terms of the jumping platforms, jumping directions, type of jump, number of jumping/landing tasks per study, use of single-/double-leg to jump or land, movement after landing, and number of trials.

Different *jumping platforms* were used across the included studies. In 37 (62.7%) studies [15, 16, 63, 65, 72, 78, 81, 82, 89, 92, 108, 115, 32, 116, 127, 129, 144, 147, 148, 151, 154, 156, 157, 33, 158, 168, 171, 174, 179, 180, 43, 45, 51, 57–59], participants jumped off a box that ranged in height from 10 to 60 cm, with a median height of 30 cm, onto force plates. The box was placed just behind the force plate in 27 (45.8%) studies [43, 45, 82, 89, 108, 114–116, 127, 129, 144, 148, 51, 154, 156–158, 168, 179, 180, 57, 59, 63, 65, 72, 78, 81], and at a distance that ranged between 10 cm to 50% of participant's height in 10 (16.9%) studies [15, 16, 32, 33, 58, 92, 147, 151, 171, 174]. Participants in 21 (35.6%) studies jumped from the floor [15, 16, 90–92, 117, 118, 140, 142, 147, 151, 171, 32, 174, 33, 56, 58, 85–88], and from an inclined surface in 1 study [55]. The horizontal distances between the starting line and the force plates was reported in only 4 (18.2%) studies and varied substantially (100 cm [110], 70 cm [175], 75% of the body height [120], and a predetermined maximum distance [64]).

Likewise, different *jumping directions* were reported across the studies. Participants dropped/stepped down off a box onto a force plate in 25 (42.4%) studies [43, 45, 82, 89, 108, 114–116, 127, 129, 144, 148, 51, 154, 156–158, 168, 57, 59, 63, 65, 72, 78, 81], jumped forward off a box onto a force plate in 10 (16.9%) studies [15, 16, 32, 33, 58, 92, 147, 151, 171, 174], jumped forward from the floor in 7 (16.9%) studies [19, 64, 73, 110, 120, 122, 182], jumped to the side in 3 (5.1%) studies [103, 104, 161], and jumped vertically from the floor, from a box, and from an inclined surface in 11 (18.6%) [56, 85, 142, 86–88, 90, 91, 117, 118, 140], 2 (3.4%) [179, 180], and 1 (1.7%) study [55], respectively.

While most studies (n=43 [72.9%]) assessed only 1 jumping/landing task [15, 16, 59, 63–65, 72, 78, 85, 89–91, 19, 92, 103, 104, 108, 110, 115–117, 120, 127, 32, 140, 142, 147, 151, 156–158, 168, 171, 174, 43, 175, 179, 182, 45, 51, 56–58], 12 (20.3%) studies assessed 2 tasks [33, 86, 161, 180, 87, 88, 114, 118, 122, 129, 148, 154], 1 (1.7%) study assessed 3 tasks [144], and 3 (5.1%) studies assessed 4 tasks [55, 81, 82].

Of the studies that reported on jump type, 8 studies requested participants to perform counter movement jumps (CMJ) [27, 85, 90, 91, 117, 118, 140, 142], 3 required participants to perform squat jumps [19, 55, 56], 1 study reported vertical jumps while not allowing for countermovement [88], and 3 studies requested participants to do lateral jumps over hurdles of different heights (15 to 24 cm) and then rebound [103, 104, 161]. Of those studies that performed a drop landing, only 2 studies instructed participants to land on their toes [51, 108].

In studies reporting landing on 2 legs (n=32 [54.2%]), participants took-off from double- and single-leg stances in 27 studies [15, 32, 85–88, 90–92, 108, 110, 114, 33, 116, 127, 142, 144, 147, 148, 174, 45, 51, 55, 57, 58, 65, 72] and 3 studies [156–158], respectively. The remaining 2 studies did not report on the take-off stance position [81, 82]. When landing on a single-leg (n=25 [42.4%]), 18 studies reported jumping from a single-leg stance position [19, 43, 122, 140, 154, 161, 168, 179, 180, 182, 56, 59, 64, 78, 103, 104, 115, 120], 6 studies reported jumping from a double-leg stance position [63, 117, 118, 129, 171, 175], while 1 study did not report the starting position [151]. After landing, activities varied across studies according to the landing strategy (i.e., single- vs. double-leg landing). Maintaining balance was most commonly reported after landing on a single-leg (10/25 studies [40.0%]) [89, 103, 104, 129, 140, 154, 175, 179, 180, 182] while maximum vertical jump was the most reported activity performed after landing on both legs (19/32 [59.4%]) [15, 32, 114, 116, 127, 147, 156–158, 168, 174, 33, 57, 58, 65, 72, 81, 90, 91]. Other activities such as "cut and run" [110] or "pivot and run" [92] were each reported once, following participants' landing on both legs. Repetitions/trials were completed between 1 and 10 times across studies, with a median of 3 trials per study. (Appendix 3.2, *Table 1*)

Balance Platforms (Measurement System 2): One study assessed jumping using a balance platform to identify the number of jumps and the peak and minimum values of GRF [41]. Jumping was performed on a single-leg with no information given on testing conditions. (Appendix 3.2, *Table 1*)

Pressure Mats (Measurement System 3): One study used pressure mats to assess peak load and flight time during jumping. Participants were requested to jump barefoot on single and double-legs [42]. No further information was provided regarding warm up or testing conditions. (Appendix 3.2, *Table 1*)

Contact Mats and Jump Systems (Measurement System 4): Three studies reported on contact mats synchronized with jump systems (i.e., computer software or device) to assess jumping [27, 125, 133]. Jump height [27, 133], total power [27], relative power [27], and limb symmetry index [125] were the 4 unique parameters identified.

Several protocol items were inconsistent across 2 studies [27, 133], while 1 study did not provide protocol information [125]. Two studies did not report whether participants warmed up or not, were shoed or barefoot, nor did they discuss hand placement. One study described the jumping activity as 3 consecutive double-leg CMJs with the aid of the arms with a 10-second break between trials [27]. The other study had participants perform 3 10-second jumping trials (for maximum number and height possible) while keeping hands on hips [133]. The best trials were used for analysis in both studies. (Appendix 3.2, *Table 1*)

Single-Sensor Insoles (Measurement System 5): Two recent studies using the same cohort of individuals with ACLR and Healthy Controls reported on single-sensor insoles to assess landing [130, 131], using the same variables and protocols to address different aims. One evaluation compared knee bracing and no bracing conditions during landing [130], while the other compared hop distance and loading symmetry [131]. Participants were requested to hop as far as possible taking off and landing on 1 leg (single hop), to hop 3 consecutive times (triple hop), and to hop 3 consecutive times while laterally crossing over a 6-inch-wide strip with each hop and progressing forward. Each test was repeated twice [130, 131]. (Appendix 3.2, *Table 1*)

<u>*Standing Balance*</u>

We identified 57 studies examining standing balance published between 1994 and 2020, with 28 (49.1%) papers published since 2015. These studies included 3173 participants; 1206 (38.0%) females, 1967 (62.0%) males; 2148 (67.7%) ACLR, 103 (3.2%) ACLD, and 922 (29.1%) Healthy Controls.

Forty-eight balance parameters were identified using 4 different kinetic systems (force plates, balance platforms, Wii balance boards, and pressure mats). Each protocol described the kinetic measurement systems used, participant preparation (barefoot or shoed), standing position (single-/double-leg stance, hand placement, looking at a target (yes/no)) and testing conditions (eyes open/closed, single/dual tasks, static/dynamic task).

Force Plate (Measurement System 1): Of 57 studies assessing standing balance, 23 (40.3%) used force plates [4, 17, 58, 59, 62, 67–70, 89, 123, 134, 24, 163, 164, 186, 25, 26, 29, 47–49, 54]. Center of pressure (CoP) velocity was the most commonly measured parameter (n=10 [43.4%]) [4, 24, 25, 29, 47, 54, 58, 62, 123, 186]. CoP displacement in anterior-posterior and medio-lateral directions [4, 17, 25, 26, 54, 123], and CoP length of path [17, 70, 89, 134, 163, 164] were the second most frequently used parameters, where each was measured in 6/23 (26.1%) studies. The CoP sway area was measured in 5/23 (21.7%) studies [4, 47, 54, 62, 134]. The remaining parameters were each used in 1 to 2 of the 23 studies. (Appendix 3.2, *Table 2*)

Testing Protocol: This includes system setup, participants' preparation and balance testing protocol details. Protocols for measuring standing balance using force plates demonstrated limited consistency across studies and lack of reporting for important items. The following sections discuss consistency or lack thereof in protocol reporting.

System setup varied among studies assessing balance using force plates. While most studies reported asking participants to stand directly on the force plate, 1 study placed foam [17] and another placed a wobble board on top of the force plate [4]. Force plates were sampled at frequencies ranging from 40Hz to 2000Hz, with a median of 100Hz. Three studies did not report the frequency used [62, 69, 186].

Likewise, *participants' preparation* varied amongst studies and lacked detailed reporting. Warm-up sessions were reported in 6 (26.1%) studies [47, 58, 67, 68, 70, 186]. Participants were requested to be barefoot in 10 (43.5%) studies [26, 48, 49, 54, 58, 123, 134, 163, 164, 186], shoed in 1 (4.3%) study [68], while the remaining 12 (52.2%) studies did not report this detail [4, 17, 71, 89, 24, 25, 29, 47, 59, 62, 67, 69]. Hand placement was also inconsistent; hands were placed on the hips in 7 (30.4%) studies [47, 58, 59, 67–70], crossed on the chest in 6 (26.1%) [25, 26, 29, 62, 163, 164], placed free at the side of the body in 5 (21.7%) [48, 49, 54, 186], and not reported in the remaining 5 (21.7%) studies [4, 17, 24, 89, 123].

Finally, *balance testing protocols* were heterogeneous in terms of testing conditions (single-/double-leg stance, focusing on a target or not, eyes open/closed, single/dual tasks). Standing balance was assessed under both single- and double-leg stance in 5 (21.7%) studies [25, 26, 48, 49, 54] and in double-leg stance in 3 (13.0%) studies [4, 134, 163]. The remaining 15 (65.2%) studies assessed single-leg standing balance only [17, 24, 71, 89, 123, 164, 186, 29, 47, 58, 59, 62, 67–69]. Participants were asked to look at a target in 7 (30.4%) studies [4, 54, 59, 67, 70, 123, 164]. In 6 (26.1%) studies, balance was tested in eyes open and closed conditions [17, 29, 69, 123, 134, 186], while 5 (21.7%) studies assessed balance under eyes closed conditions only [25, 26, 47, 58, 62, 163], and the remaining 11 (47.8%) studies had the participants' eyes open. Most studies (22/23 (95.6%)) assessed balance using a single task [4, 17, 58, 59, 62, 67–70, 89, 123, 134, 24, 163, 164, 186, 25, 26, 29, 47–49, 54]; only 1 study used dual tasks (a concurrent physical and cognitive task) [4]. (Appendix 3.2, *Table 2*)

Balance Platforms (Measurement System 2): Balance platforms were used in 28 studies [5, 6, 94, 97, 106, 111, 112, 119, 121, 124, 126, 128, 7, 138, 139, 145, 159, 169, 172, 183, 185, 13, 14, 46, 60, 66, 77, 83]. Stability index was the most widely used parameter, reported in 12 (42.9%) studies [13, 14, 183, 185, 94, 97, 106, 111, 112, 124, 138, 172], followed by anterio-posterior and medio-lateral stability indices, reported in 9 (32.1%) studies [6, 13, 106, 111, 112, 124, 138, 172, 183]. The remaining parameters were reported only 1 to 4 times across all studies. (Appendix 3.2, *Table 2*)

The *testing protocols* for balance platforms were described in all but one study [185]. In general, most protocols included information on participants' preparation, and the testing protocol used. However, many studies did not report important protocol items.

With regard to *participants' preparation*, participants had warm-up sessions in 3 (10.7%) studies [77, 106, 183]. They were requested to participate barefoot in 11 (39.3%) studies [5, 6, 126, 13, 60, 94, 97, 111, 112, 121, 124] and remain shoed in 1 study [128]. The remaining 16 (69.6%) did not specify whether participants were barefoot or not. Further, of 13 (46.4%) papers reporting hand position, 7 studies requested participants to cross arms on chest [6, 66, 77, 119, 128, 138, 169], 4 placed hands on hips [94, 97, 111, 112] and 2 studies reported participants' hands hanging by their sides [13, 60].

The *testing conditions and protocols details* were heterogeneous and lacked sufficient reporting when assessing standing balance using balance platforms systems. The majority of papers (n=17 [67.9%]) reported assessing single-leg standing balance [5, 6, 121, 124, 126, 128, 138, 159, 183, 66, 77, 83, 94, 97, 111, 112, 119], while 5 (17.9%) assessed balance in double-leg stance [7, 14, 60, 139, 172] and 5 (10.7%) reported investigating balance in both conditions [13, 46, 106, 145, 169]. Only 6 (21.4%) studies compared standing balance under eyes open and closed conditions [5, 66, 83, 111, 112, 126], while 11 (47.8%) papers had participants focusing on targets while attempting to maintain balance [6, 66, 172, 77, 97, 106, 111, 112, 126, 159, 169]. Most studies (n=20 (71.4%)) assessed either static (n=9 (32.1%)) [5, 66, 77, 97, 121, 126, 138, 139, 159], or dynamic balance (n=11 (39.3%)) [6, 7, 172, 13, 94, 106, 111, 112, 119, 124, 128], while 7 (25.0%) studies compared both conditions [14, 46, 60, 83, 145, 169, 183]. Only 1 study added a cognitive task while participants were trying to maintain balance [5]. (Appendix 3.2, *Table 2*)

Wii Balance Boards (Measurement System 3): Wii balance boards were utilized to assess standing balance in 4 (7.0%) studies published between 2013-2017, reporting 8 different parameters [36, 37, 40, 74]. CoP displacement in anterior-posterior and medio-lateral directions [36, 40], CoP length of path [36, 74], CoP velocity [37, 40] and standard deviation [37, 40] were each calculated in 2 (50%) studies. Other parameters such as CoP amplitude [37], CoP fast/slow sway [36], discrete wavelet transform and sample entropy of the CoP trace [37], were each calculated once across studies. (Appendix 3.2, *Table 2*)

There was reasonable consistency among the 4 reported *testing protocols*. Participants were barefoot in all studies. Hands were placed on hips in 2 studies [37, 74], crossed on chest in 1 study [40], and not reported in the remaining study [36]. In 1 (25.0%) study, participants were asked to move their arms to measure balance under a dual task condition [74]. All participants had their eyes open; however, in 2 studies, they were instructed to look forward at a target [37, 74]. Three studies [37, 40, 74] investigated single-leg balance and 1 study assessed double-leg balance [36].

Pressure Mats (Measurement System 4): Pressure mats were used by only 2 (3.5%) studies to assess standing balance [35, 84]. Five parameters were identified including ellipse area [35, 84], CoP standard deviation in anterior-posterior and medio-lateral directions, CoP path length, CoP velocity, and sway area [84].

While participants in 1 study were barefoot [84], the other study did not report whether they were shoed or not [35]. Likewise, 1 study reported the arms being free at participants' sides [35], while the other didn't specify [84]. Participants in both studies were asked to look forward during testing; however, 1 study also assessed balance under an eyes-closed condition [35]. Both studies investigated balance in both single- and double-leg stances. (Appendix 3.2, *Table 2*)

<u>Gait</u>

Thirty-three studies examining gait were published between 1997-2020 with 27 (81.1%) published since 2015. They represented data from 1261 participants: 708 (56.1%) males, 553 (43.9%) females, 1059 (84.0%) ACLR, 10 (0.8%) ACLD, and 192 (15.2%) Healthy Controls.

Forty-four unique variables were identified to assess gait using 3 different systems (force plates, force-measuring treadmills, and pressure mats; Table 3.5). The following section discusses the parameters identified, and the measurement protocols used for each of those systems including, where applicable; system setup (sampling frequency), participants' preparation (barefoot/shoed) and protocol details (self-selected/predetermined speed, single/dual task, testing condition, distance and duration). (Appendix 3.2, *Table 3*).

Force Plates (Measurement System 1): Force plates were used in 26 (78.8%) studies. Overall, there was a lack of consistency in the measured parameters across studies using force plates to assess gait. Important protocol items such as gait speed and shoe wear conditions were reported in 20/26 (70%) [20, 22, 135–137, 152, 153, 157, 166, 177, 178, 181, 23, 30, 76, 101, 102, 109, 114, 132], and 14/26 (53.8%) [20, 21, 157, 162, 177, 178, 76, 101, 109, 132, 135–137, 148], respectively.

Force Plates Parameters in Gait Assessments: Thirty-six parameters were identified in the 26 studies that assessed gait using force plates. Peak vGRF was the most frequently measured variable in 8 (30.8%) studies [21–23, 76, 136, 137, 157, 166], followed by vGRF, which was measured in 6 (23.1%) studies [109, 152, 162, 177, 178, 181]. (Appendix 3.2, *Table 3*)

Gait Testing Protocol: This includes force plate system setup, participants' preparation, as well as the gait testing protocols using force plates. Regarding *system setup*, the sampling frequency was reported in 22 (84.6%) of 26 studies [12, 20, 102, 132, 136, 137, 147, 148, 152, 153, 157, 162, 21, 166, 181, 22, 23, 30, 38, 76, 96, 101]. Sampling frequency ranged between 400Hz and 1200Hz with a median of 1080Hz. The most commonly reported frequencies were 1200Hz and 1000Hz in 9 [20–23, 76, 96, 101, 136, 147] and 5 studies [12, 137, 148, 157, 166], respectively.

Related to *participants' preparation,* only 2 studies reported asking participants to warm-up prior to testing [96, 102], and only half of the studies reported whether their participants were shoed (n=3) [132, 157, 162] or not (n=10) [20, 76, 101, 109, 136, 137, 147, 148, 177, 178].

Different *testing conditions and protocols* were followed across the studies. Most studies assessed only walking gait (n=21 (80.8%)) [12, 20, 137, 147, 148, 152, 153, 157, 166, 177, 178, 181, 21–23, 38, 76, 101, 102, 136], while 2 (7.7%) studies assessed only running gait [132, 162], and 3 (11.5%) studies assessed both walking and running gaits [96, 109, 114]. Of 21 (80.8%) studies that reported speed, 16 (76.2%) reported that participants walked at a self-selected speed [20, 22, 137, 147, 152, 177, 178, 181, 23, 30, 38, 76, 102, 109, 132, 136], while 4 (19.0%) studies used a pre-determined speed [101, 153, 157, 166], and 1 (4.8%) study indicated testing participants in both conditions [114]. No study tested gait in a dual task condition. Participants in 5 (19.2%) studies were asked to look forward at a target [38, 101, 132, 136, 137]. Walking distance greatly varied in the 6 (23.1%) studies, with reported distances ranging from 3 to 20 m (median=6.5 m) [20, 21, 30, 102, 136, 137]. (Appendix 3.2, *Table 3*)

Force-Measuring Treadmills (Measurement System 2): Six studies used force-measuring treadmills in gait assessment and reported 8 *parameters* including vGRF [52, 61, 100], vGRF limb symmetry index [100], peak vGRF [98, 99], peak vGRF normalized to body weight [113], instantaneous vGRF loading rate [98, 100], instantaneous vGRF loading rate normalized to body weight [99] instantaneous vGRF loading rate limb symmetry index [99], and root mean square error between actual vGRF and biofeedback target vGRF [98].

Testing protocols and reporting standards varied among the studies measuring gait using force-measuring treadmills. Only 1 study reported a warm-up session prior to testing [61]. Two studies reported that participants had their shoes on during testing [61, 113] while the remaining studies did not specify [52, 98–100]. While 4 studies examined walking at a predetermined speed [52, 98–100], 1 study assessed walking and running at a predetermined speed [113], and 1 study assessed running at a self-selected running speed

[61]. Only 1 study assessed gait with and without real time biofeedback about participants' GRF (as a dual task and a single task) [98]. (Appendix 3.2, *Table 3*)

Pressure Mats (Measurement System 3): One study used a pressure mat with a sampling frequency of 150 Hz to identify spatiotemporal parameters including velocity, cadence, step length and width. Participants walked at both self-selected normal and fast speeds for 8.5 m. It was not specified whether participants were shoed or barefoot [11]. (Appendix 3.2, *Table 3*)

<u>*Other Functional Movements*</u>

In addition to the aforementioned movement tasks, our review identified papers assessing other functional movements including; *cutting movements, squatting, stop-jumps, step-overs, and lunges.*

First, *cutting movements:* Eight studies used *force plates* to assess *cutting movements* (change in direction) kinetics. They were published between 2011 and 2020, with 6 (75%) papers published in the last 5 years. The studies represented data from 536 participants: 404 (75.4%) male, 132 (24.6%) female; 386 (72.0%) ACLR, 10 (1.9%) ACLD, and 140 (26.1%) Healthy Controls.

Nine different *parameters* were identified, mostly related to GRF. Identified parameters included GRF [80, 96], time to peak GRF [18, 110], peak vGRF [32, 33, 110], peak vGRF normalized to body weight [110], vGRF loading rate [32], vGRF normalized to body weight (in vertical, medial and posterior directions) [82], and Lyapunov exponent [93]. (Appendix 3.2, *Table 4*)

Testing protocol items: Sampling frequencies used were heterogeneous, ranging between 1000Hz to 5000Hz with a median of 1200Hz. Protocols were also heterogeneous with several studies not reporting on important protocol items. For example, of 8 studies, only 5 (62.5%) reported having participants warm-up prior to testing [32, 33, 80, 82, 96], and only 3 (37.5%) reported that participants wore shoes [18, 80, 82]. The movements or conditions preceding the cutting movement (jumping over a hurdle [32, 33], standing [80], and landing after jumping [110]) were only reported in 4 studies, 2 of which were by the same author and included the same cohort [32, 33]. The cutting movement direction was planned in 3 (37.5%) studies [32, 33, 96], not planned in 1 (12.5%) study [110], while 2 (25%) studies (by the same author) tested cutting movements in both planned and unplanned conditions [80, 82]. One study investigated the effect of vision on participants' performance by testing them under both full and disturbed vision conditions [18]. (Appendix 3.2, *Table 4*)

Second, *squatting:* Eight variables were identified in 6 studies that assessed squatting, utilizing 2 kinetic measurement systems; force plates were used in 5 (83.3%) studies [148–151, 176], and a pressure mat was used in the remaining study [42]. These papers were published between 2003-2020, with 4 [66.7%] published since 2015. The studies represented data from 207 participants (63 [30.4%] female, 144 [69.6%] male; 142 [68.6%] ACLR, 65 [31.4%] Healthy Controls).

Force plates (Measurement System 1) were used in 5 (83.3%) studies [148–151, 176]. Six different *parameters* were identified across studies including: first vertical maximum [148], peak vGRF [149], anterior-posterior GRF [150], medio-lateral GRF [150], vGRF [150, 151, 176], and weight bearing symmetry [176].

Squatting testing protocol: Overall, protocols of measuring squatting kinetics using force plates were heterogeneous and lacked sufficient reporting. Among the 5 studies using force plates, 2 reported the sampling frequency as 1000Hz [148, 150], 2 did not report [151, 176], and 1 reported a sampling frequency of 600Hz [149]. Only 1 study reported asking participants to warm up for 5 minutes on a stationary bike [149], and only 1 study reported that participants were barefoot [150]. Squatting speed was predetermined in 2 studies [148, 176], self-selected in 2 studies [149, 150], and not reported in the remaining study [151]. Participants squatted with both legs in 4 (80.0%) studies [148–150, 176], and with a single-leg in 1 (20%) study [151]. The terminal squatting position was consistent across 3 studies, where participants were asked to descend until the posterior thigh was parallel to the floor [148, 149, 176]. In the remaining 2 studies, participants were asked to squat to a comfortable position while keeping the torso upright [150], or to squat as deep as possible [151]. (Appendix 3.2, *Table 4*)

Pressure Mats (Measurement System 2): One study used pressure mats to assess double- and single-leg squatting in barefoot participants [42]. The study did not report on the squat speed or the terminal squatting position. The pressure mat measured peak load while squatting. (Appendix 3.2, *Table 5*)

Third, *stop-jump:* Of the 158 studies, only 2 assessed a stop-jump task [141, 143]. The 2 papers represented data from 67 participants; 32 (47.8%) females, 35 (52.2%) males; 45 (67.2%) ACLR, and 22 (32.8%) Healthy Controls. The 2 papers reported using force plates to assess stop-jumps. Nine different *parameters* were identified including peak vGRF ratio index, peak vGRF gait asymmetry index, peak vGRF symmetry index, peak vGRF symmetry angle, peak vGRF normalized symmetry index [141], peak vGRF, peak posterior vGRF, loading rate, and impulse [143].

For the stop-jump task, there were several similarities in the study *testing protocol details*. In addition to using the same sampling frequency of 2400Hz, participants in both studies were asked to approach the force plate as quickly as possible, stop, then jump as high as possible. No information was given about landing. Neither studies reported whether participants had a warm-up, or whether they had their shoes on or were barefoot [141, 143]. One study reported having participants jump off one foot, land on two, and perform a subsequent 2-footed jump [143]. (Appendix 3.2, *Table 6*)

Finally, *step-over and lunges* were both reported in only 1 paper which included 36 participants; 13 (36.1%) female, 23 (63.9%) male; 18 (50%) ACLR, and 18 (50%) Healthy Controls [105]. The study used a force plate for kinetic measurements. Three unique *parameters* were identified while performing the step-over task, including the lift up index, movement time, and impact index. In addition, the study reported 4 other parameters while performing lunge tasks including lunge distance, contact time, impact index, and force impulse [105].

For the *step-over* task, with shoes on, individuals were asked to perform a 5-minute treadmill warm-up and then to step up onto a 30 cm box while the lagging leg was carried up and over to land on the opposite side of the starting position. For the *lunge* task, participants were requested to lunge forward with one leg on a long force plate and then return to the original standing position [105]. (Appendix 3.2, *Table 6*)

<u>Kinetic Measurement Systems and PROMs</u>

Of 158 studies, only 6 studies reported on both kinetic measurement system findings and PROMs [12, 94, 100, 117, 156, 159]. The earliest study was published in 1996 and evaluated the association between standing balance and PROMs (Cincinnati Scale and satisfaction score) [159]. The remaining 5 studies were published in 2018 [12, 100], 2019 [94, 156] and 2020 [117]. There was inconsistency in the reported parameters and/or PROMs across these 6 studies (Table 3.6).

Table 3.4 Studies examined the association between kinetic measurement systems variables and PROMs

Reference	Studied Variables	
	Kinetic measurement systems variables	Patient Reported Outcome Measures
Shiraishi et al. 1996 [129]	CoP length of path	Cincinnati Scale & Satisfaction
Azus et al. 2018 [167]	GRF	Knee Injury and Osteoarthritis Outcome Score (KOOS)
Luc-Harkey et al. 2018 [172]	Peak vGRF normalized to body weight Instantaneous vGRF loading rate Linear vGRF loading rate vGRF LSI	Tampa Scale of Kinesiophobia
Lee et al. 2019 [115]	Overall Stability Index	Tegner Activity Scale
Shimizu et al. 2019 [65]	vGRF	KOOS & Marx Activity Scale Score
Niederer et al. 2020 [53]	LSI	Return to sport after injury-ACL (ACL-RSI) Fear of re-injury Visual Analog Scale (VAS)

<u>Methodological Reporting Considerations</u>

Based on the substantial heterogeneity seen across studies in the methodological details and outcomes reported, we created a table of methodological reporting considerations for researchers designing studies using kinetic measurement systems (Table 3.7). The goal of this information is to improve standardized reporting of methodological approaches and kinetic measurements, which should facilitate cross-study comparisons to advance this burgeoning field of research and improve the clinical application of findings. We developed these methodological reporting considerations as they relate to the movement tasks, kinetic system features and selected outcome parameters, participant preparation, and protocol details.

Table 3.7 Methodological Reporting Considerations

Methodological Reporting Considerations				
Movement Tasks	Parameters	Testing Protocol Items		
Jumping/Landing	Definition Justifications of use	System Setup		System type Sampling frequency
		Participant preparation		Warm-up details Shoes/no shoes Hand placement
		Protocol details		Jumping platform – Box (height and distance) – Floor (distance from system) – Inclined surface Jumping direction – Drop jump/step down – Forward jump – Vertical jump – Lateral jump Jump type (CMJ, squat, etc.) Number of jumping tasks Single/double-leg Task after landing Number of trials
Standing Balance	Definition Justifications of use	System Setup		System type Platform surface Sampling frequency
		Participant preparation		Warm-up details Shoes/no shoes Hand placement
		Protocol details		Single/double-leg stance Eyes open/closed Single/dual task Static/dynamic Task duration Number of trials
Gait	Definition Justifications of use	System Setup		System type Platform (floor, treadmill, etc.) Sampling frequency
		Participant preparation		Warm-up details Shoes/no shoes
		Protocol details		Speed Single/dual task Focus on a target Distance and duration
Other Functional Movements	Definition Justifications of use	System Setup		System type Platform surface Sampling frequency
		Participant preparation		Warm-up details Shoes/no shoes Hand placement
		Protocol details	Cutting	Movement preceding cutting Planned/unplanned movement Visual condition
			Squatting	Squatting speed Single/double-leg Terminal squat position
			Stop-Jump	Landing condition after jumping Single/double-leg Stop-jump procedure

			Step over and lunges	Step/hurdle height Step-over and lunges procedure

DISCUSSION

The primary purpose of this scoping review was to describe the approaches for kinetic measurements in individuals following ACLR. While force platforms can be used in conjunction with motion capture systems to measure kinetic variables such as joint moments, the intent of the study was to describe approaches and parameters using kinetic measurement systems only. Results of our evaluation demonstrate a substantial increase in the evaluation of kinetic measures in this patient group in recent years. Further, we noted marked heterogeneity in parameters evaluated and protocols followed, in addition to inconsistencies in reporting. In this review, we highlighted the current gaps in reporting and have generated a table of suggested methodological considerations to facilitate improved reporting when using kinetic measurement systems in the post-ACLR population.

In 1976, the first commercially available force plate was constructed to be used for gait analysis [75]. Technology advancements in recent years have facilitated kinetic assessments allowing more extensive measurement of movements/tasks. While the earliest included paper in this review was published in 1990, more than 66% of the included studies were published since 2015. This is likely related to the tremendous improvement in both hardware and software of kinetic technology. For example, advancement from uniaxial to triaxial force plates has allowed researchers and clinicians to evaluate variables such as multidimensional CoP displacement that cannot be measured with uniaxial force plate technology. Similarly, variables that integrate force and time, such as impulse and loading rate, would have been difficult to assess before recent technology developments that permit efficient calculations of large datasets.

However, with these advances have come a plethora of approaches and parameters to measure. This review identified important heterogeneity and methodological gaps in the current published literature that may limit the clinical application of this research. The first methodological gap is the inconsistency in the selection of parameters as well as their operationalization. For instance, some studies assessed jumping and landing using vGRF only, while others measured both vGRF and posterior GRF, without justifying their selection. All selected parameters may have relevance, but researchers should justify their selection to readers in light of their objectives. The lack of operationalization of commonly reported parameters also creates confusion. For example, using “vGRF” and “peak vGRF” made it challenging to discern if these parameters were the same or different measures across studies (i.e., did “vGRF” consider multiple points in time across the force-time curve, or only the time at which maximal vGRF was achieved?). Together, the heterogeneity and the lack of operationalization for evaluating specific parameters makes it challenging to determine the most clinically relevant parameters in the ACLR population.

The second methodological gap was the heterogeneity in the kinetic measurement systems setup, as the type of selected system and sampling frequency varied across studies assessing the same task(s). Other important methodological gaps include the inconsistency in reporting important protocol items such as participant preparation (e.g., warm-up details, hand position, shoed vs. barefoot) and protocol details (e.g., starting/ending positons, eyes open vs. closed, and single vs. double-leg landing). These methodological considerations can influence the reported outcomes. For instance, a gluteal warm up program may enhance force production while performing squat jumps after 8 minutes of recovery [165]. Similarly, arm swings while performing vertical counter movement jumps can increase jump height by 38% [53]. Therefore, when assessing a task such as CMJs using a force plate, our methodological reporting consideration may guide future papers to define the parameters of interest, justify parameter selections, report on the force plate details, and report the sampling frequency used. Authors should also report warm-up program details, whether participants were shoed or not, and participants’ hand placement while performing the CMJs. When reporting on the CMJ activity, we recommend authors report on the direction of jump, single-/double-leg jumping or landing, and the immediate tasks performed after landing. Researchers need to consider and justify their approaches a priori and ensure that they report them as such. Our findings underscore the need to develop standardized reporting guidelines to enhance the quality of future studies and advance this field of research.

Though we aimed to describe the use of kinetic measurement systems in post-ACLR individuals, it was not our intent to make recommendations regarding which kinetic parameters to examine to inform RTS decisions following ACLR. We did not examine reported outcomes in our included studies, but rather conducted a detailed review of the reported approaches. The findings from the current review may have implications for future research and, consequently, clinical application. The suggested methodological considerations (Table 3.7) will assist in standardizing the reporting of important protocol details in future studies, to allow future meta-analyses which may better inform clinical practice.

The secondary purpose of the current review was to explore papers studying potential associations between kinetic measures and PROMs. Our findings highlighted an evidence gap as we identified only 6 studies that investigated this potential relationship [12, 94, 100, 117, 156, 159]. The identified studies demonstrated inconsistencies in the parameters measured and the types of PROMs utilized. Of the 6 studies, 5 were published since 2018 [12, 94, 100, 117, 156]. This may indicate an emerging research area acknowledging psychosocial factors that may interact with kinetic measurement outcomes; future studies are needed to further understand the extent of this relationship. Due to the heterogeneity in kinetic parameters and PROMs used, and the limited number of papers identified, a systematic review to examine the association between specific kinetic parameters and specific PROMs may not produce clinically useful findings at the current time, but this appears to be a developing field of investigation.

Strengths and Limitations

To our knowledge, this is the first review detailing different parameters and methodological protocols applied to assess various tasks utilizing kinetic measurement systems in the ACLR patient population. In this scoping review, we followed a systematic approach, suggested by the framework of Arksey and O'Malley [10]. We searched for peer-reviewed published literature and did not restrict by publication date or language; this allowed us to identify the widest base of relevant studies on the use of kinetic measurement systems in individuals following ACLR and additionally identify the methodological gaps in the reported literature. The study team was a multidisciplinary group, including individuals with diverse expertise in research methodology, evidence synthesis, orthopaedic surgery, sport and exercise therapy, knee injury rehabilitation, kinesiology, and engineering. This reduced ambiguity and uncertainties related to study selection and reporting.[95]

This review, however, has limitations. We reported only methodological considerations, and therefore cannot state what impact those methodologies had on study outcomes. Prior to comparing outcomes, we must first understand the various methodological approaches. Our intent was not to settle on a single agreement for methodological approach or outcomes post-ACLR, but rather to emphasize the need for clear and detailed methodology reporting to allow comparisons across studies to advance our understanding of the current evidence.

Future Direction

The suggested methodological considerations (Table 3.7) in this review provide important information to support further research aimed at developing and validating a methodological reporting standard checklist for kinetic measurement systems to assess individuals following ACLR. Standardizing reporting of methodology will improve our understanding as to which kinetic measurement systems and protocols may be most clinically relevant in the ACLR population. These reporting considerations can subsequently be applied in future work to objectively inform patients and clinicians when discussing RTS decisions following ACLR. This review highlights areas for potential future systematic reviews to identify the most useful parameters, tasks, and approaches to use in individuals following ACLR.

CONCLUSION

There has been substantial advancement in utilizing kinetic measurement systems in individuals post-ACLR. However, this advancement has been challenged by heterogeneity in approaches and methodological gaps in reporting. Clear and accurate reporting in clinical outcome research is important to demonstrate valid outcomes and to compare outcomes across studies. Therefore, our study suggests methodological considerations as a mechanism to assist authors in the reporting of essential items needed to improve reproducibility and subsequent quality of research in this area. Moreover, our review recommends future systematic reviews to examine the most useful kinetic parameters and approaches to follow when assessing specific functional tasks performed by individuals following ACLR. However, a systematic review to examine the association between specific kinetic parameters and specific PROMs may not produce clinically useful findings at the current time due to the scarcity and heterogeneity in the available evidence.

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CHAPTER 4: JUMPING INTO RECOVERY: A SYSTEMATIC REVIEW AND META-ANALYSIS OF DISCRIMINATORY AND RESPONSIVE FORCE PLATE PARAMETERS IN INDIVIDUALS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION DURING COUNTERMOVEMENT AND DROP JUMPS.

A version of this chapter has been published. Labban W, Manaseer T, Golberg E, Sommerfeldt M, Nathanail S, Dennett L, Westover L, Beaupre L (2024) Jumping into Recovery: a Systematic Review and Meta-Analysis of Discriminatory and Responsive Force Plate Parameters in Individuals following Anterior Cruciate Ligament Reconstruction during Countermovement and Drop Jumps. J Exp Orthop J Exp Orthop. 10.1002/jeo2.12018

ABSTRACT

Purpose

Comprehensive understanding of force plate parameters distinguishing individuals post-primary anterior cruciate ligament reconstruction (ACLR) from Healthy Controls during countermovement jumps (CMJ) and/or drop jumps (DJ) is lacking. This review addresses this gap by identifying discriminative force plate parameters and examining changes over time in individuals post-ACLR during CMJ and/or DJ.

Methods

We conducted a systematic review and meta analyses following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines. Nine databases were searched from inception to March 2022. We included cross-sectional papers comparing post ACLR with Healthy Controls, or longitudinal studies of individuals at least 6-months post primary ACLR while performing

CMJ and/or DJ on force plates. The methodological quality was appraised using the Modified Downs and Black Checklist.

Results

Thirty-three studies including 1185(50.38%) participants post-ACLR, and 1167(49.62%) Healthy Controls, were included. Data was categorized into: single-leg CMJ, double-leg CMJ, single-leg DJ, and double-leg DJ. Jump height was reduced in both single (MD=-3.13;p<0.01;95%CI[-4.12,-2.15]) and double-leg (MD=-4.24;p<0.01;95%CI[-5.14,-3.34]) CMJs among individuals with ACLR. Similarly, concentric impulse and eccentric/concentric impulse asymmetry could distinguish between ACLR (MD=3.42;p<0.01;95%CI[2.19,4.64]) and non-ACLR (MD=5.82;p<0.01;95%CI[4.80,6.80]) individuals. In double-leg DJs, peak vertical ground reaction forces (vGRF) was lower in the involved side (MD=-0.10;p=0.03;95%CI[-0.18,-0.01]) but higher in the uninvolved side (MD=0.15;p<0.01;95%CI[0.10,0.20]) when compared to controls and demonstrated significant changes between 6 months and 3 years post ACLR.

Conclusion

This study identified discriminative kinetic parameters when comparing individuals with and without ACLR, and that monitored neuromuscular function post-ACLR. Due to heterogeneity, a combination of parameters may be required to better identify functional deficits post-ACLR.

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a devastating injury that frequently occurs in sports [14] and accounts for at least 50% of all knee injuries [14, 58]. Anterior cruciate ligament reconstruction (ACLR) is often recommended to restore joint stability and minimize potential damage to articular cartilage and menisci [2]. The reported proportion of individuals who return to a competitive level of sport following ACLR is 55%, while 81% return to any level of sport [3]. Up to 38% of elite athletes reduce their participation levels or stop their career within 3 years after ACLR [67]. Moreover, 20-25% of post-ACLR individuals experience a re-rupture or a contralateral ACL injury early during the return to sport period [68]. This may be related in part to the lack of standardized, validated return to sport (RTS) criteria to adequately assess RTS capacity.

Kinetic measurement systems, such as force plates, have emerged as popular tools to measure various parameters objectively while performing different movement tasks. These systems use force sensors to quantify forces exerted during activities or tasks [10]. Clinicians and researchers utilize these systems to assess functional progression throughout rehabilitation and to assist in determining the ability to RTS in post-ACLR individuals [24]. Previous studies have examined various kinetic parameters in the ACLR population. Our previous work identified several parameters assessing different movement tasks such as jumping and landing [4], standing balance [1, 16], gait [62], and other functional tasks [60]. Notably, jumping and landing were the most frequently studied activities in individuals following primary ACLRs [44, 54].

Countermovement jumps (CMJ) and drop jumps (DJ) have been widely used in the literature to assess performance in individuals with ACLR [44]. The CMJ involves a downward movement to a semi-squat depth position before extending the back, hips and knees to jump vertically as high as possible. The DJ involves dropping down from a box, followed immediately by jumping vertically as high as possible. Several studies utilized those jumps to identify risk factors associated with sports injuries [54], assess association with other measures of performance [5], detect neuromuscular fatigue [5], and to quantify the functional consequences during sports rehabilitation [5], particularly, following ACLR.

Assuming that ACLR causes neuromuscular impairments that can be detected with a force plate while performing CMJ and/or DJ [45], it is essential to understand which force plate parameters can best detect any functional impairments or deficits. Therefore, the primary objective of the current systematic review was to identify force plate parameters that are discriminative between individuals following primary ACLR and Healthy Controls while performing CMJ and DJs. The secondary objective was to identify force plate parameters that are responsive to changes in neuromuscular function over time in individuals following primary ACLR while performing CMJs and DJs. Based on existing literature, it is hypothesized that kinetic force plate parameters are significantly different between individuals following ACLR and Healthy Controls during CMJ and DJ. Additionally, it is hypothesized that these force plate parameters could demonstrate responsiveness to changes in neuromuscular function over time in individuals following primary ACLR. Findings from the current systematic review may provide clinicians and researchers with objective outcomes to inform RTS decisions in individuals following ACLR.

METHODS

<u>Registration</u>

This systematic review was registered on the Open Science Framework https://doi.org/10.17605/OSF.IO/7FTQP

Framework

The authors conducted and reported the current systematic review according to the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines [52] and PRISMA-Search extension [57].

Eligibility criteria

All inclusion and exclusion criteria are reported in Table 4.1. The constructs of "participants", "primary ACLR", and "kinetic measurement systems" are operationalized in Table 4.2.

Table 4.5: Systemic review - Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
• Human Participants	• Animal Model, cadaver, simulated or computer models
• Original or primary quantitative data (cross-sectional with a Healthy Control group, longitudinal with at least one kinetic force-plate measurement at a minimum of two different time points)	• Not primary data (e.g., systematic review, literature review, meta-analysis, editorial, commentary, opinion papers, or conference proceedings)
• Primary ACLR - With the measurement taken at least, six months post ACLR.	• Case report
• At least one kinetic parameter measured solely by a force plate	• Cross-sectional study with no control group. Exclude if the control is the contralateral limb.
• Performed Drop jump or Countermovement jump	• Secondary ACLR (in ipsilateral or contralateral knee).
	• Concomitant significant injuries or surgical interventions to the medial or lateral collateral ligament
	• Skeletally immature participants
	• Congenital deformities
	• Other musculoskeletal problems that could influence the force plate parameters including; foot disorders, hip disorders, and lower back and pelvic problems
	• Neurological problems that could affect balance or neuromuscular co-ordinations
	• ACL repair (not reconstruction) where the ACL was reattached.
	• Parameters measured with tools that do not employ force plates technology (motion capture system, isokinetic systems, infrared contact mats)
	• Kinetic parameters that cannot be measured with force plates solely (joint moments)
	• Other types of jumps or other functional activities such as walking, running, squatting, cutting, pivoting, etc.

Table 4.6: Definitions

Participants	• ACLR group: Any individual who reached skeletal maturity with at least six months history of primary ACLR; no limitation to age, sex, sport played or activity level. • Healthy Control group: healthy uninjured individuals who reached skeletal maturity with no ACLR history; no limitation to age, sex, sport played or activity level.
Primary ACLR	• A first time ACLR; surgical tissue graft replacement of the anterior cruciate ligament to restore its function after injury [44].
Drop Jump	• Jumping/descending of a box placed behind a force plate, land on the force plate, and jump vertically for a maximum height [32].
Countermovement Jump	• From standing position, participant performs a downward motion to specific/self-selected depth before reversing the motion by triple extending the hip, knee and ankle, jumping up for a maximum height. [58]

Information sources and search strategy

A research team member (WL) and health sciences librarian (LD) developed an extensive list of search terms for each construct. The health sciences librarian (LD) conducted searches in Medline (Ovid MEDLINE(R) ALL), Embase (Ovid interface), CINAHL Plus with Full Text (EBSCOhost interface), Web of Science Core Collection (Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI), SCOPUS, Proquest Dissertations and Theses Full text, Pubmed Central, Science Direct and Google Scholar from database inception until March 13, 2022. The search combined subject headings (where available) and keywords for the concepts of (1) ACL-R, (2) vertical jumps and (3) movement properties. The movement properties construct was searched in the full text if databases allowed for it. The search strategy was optimized for each database. No language or date limits were applied but conference abstracts were removed. Reference lists of included articles and other relevant reviews were reviewed for additional studies. The full search strategy is available in Appendix 4.1.

Selection process

Records were imported into EndNote V.XI. After duplicate removal, records were imported into Covidence platform (Covidence, Veritas Health Innovation). The authors WL and TM independently screened title and abstracts to determine potential relevant records, followed by full text review to determine final record selection. Any disagreement between the two authors were resolved through consensus. Consultation with a third author was not needed. All decision and exclusion reasons were recorded on Covidence.

Data extraction

The authors WL and TM performed data extraction independently in duplicate, using a structured data extraction form on (Google Sheets). Discrepancies were resolved through consensus. Data items included study characteristics, sample characteristics, testing protocols and outcomes. See Table 4.3

Table 4.7: Systemic review - Data Items

Category	Item(s)
Study characteristics	Author(s), year of publication, study design, country and language
Participant sample characteristics	Sample size disaggregated by sex, age, reported activity and activity level
Primary ACL surgical details	Graft type, side of surgery (dominant/non-dominant), time from surgery
Testing protocol details for each type of jump	sampling frequency, testing protocol (hand placement, shoes on/off, warm up protocol)and number of trials per test
Outcomes with estimates and variances	Parameters that were measured solely by force plates with means and standard deviations (SD)

Quality appraisal

The authors critically appraised the methodological quality of included records using the Modified Downs and Black (DB) Checklist [15]. The DB checklist is a quality assessment tool that rates studies based on study design, quality of reporting, internal validity (including potential confounding), and external validity. It employs a 32-point scoring system (11 points for reporting, 3 points for external validity, 7 points for bias, 6 points for confounding and 5 for power [1 point for power in the modified version]) [15, 38]. For observational studies, items number 4, 8, 13, 14, 19, 23 and 24 on the checklist (adding up to 7 points) are not applicable. The tool was selected for its reported intra-rater and inter-rater reliability [15].

The authors used the Oxford Centre of Evidence Based Medicine (OCEBM) 2011 model [22] to identify the level of evidence that the included records represented. The OCEBM 2011 model is simple and its structure reflect clinical decision making [29]. Discrepancies in DB scoring or OCEBM categorization were resolved by consensus between the two reviewers (WL and TM).

Data Synthesis

The extracted data were divided according to the study designs into two main categories; cross sectional and longitudinal. Data from longitudinal studies that included control groups were pooled to form cross sectional data to reduce the chance of data reporting bias. Similarly, data from cross sectional studies comparing between individuals with ACLR and controls at different time points (later than six months following ACLR), or male and female individuals with control groups were pooled to form one ACLR group for comparison [59]. The Research team estimated the pooled mean and the sum of squares of standard deviation (SDs) using the "dplyr package" in R (R v4.1.0, The R Foundation for Statistical Computing).

Then, the authors further subdivided the resulting two study categories into four main groups according to the jump task used including the single-leg CMJ, double-leg CMJ, single-leg DJ, and double-leg DJ with studies assigned accordingly. Data were imported as means and SDs into Review Manager for Meta-Analysis (RevMan v5.4.1; The Nordic Cochrane Centre, Copenhagen, Denmark). The authors estimated SDs for studies that reported means and 95% confidence intervals (CI) following the Cochrane Handbook for Systematic Reviews of Interventions [25]. The authors used a random effects model with standardized mean differences and 95% confidence intervals. Pooled effect size, 95% confidence interval, P-value and heterogeneity were calculated per outcome by means of the I^2 test [26]. I^2 values below 30% indicate mild heterogeneity, values between 30% and 50% suggest moderate heterogeneity, and values over 50%, coupled with significant Q statistics, imply notable heterogeneity among the included studies [26, 27]. We considered sensitivity analysis for meta-analysis when I^2 values are greater than 50%. Meta-analyses were performed for each individual force plate parameter when it was reported with means and SDs in at least two studies.

RESULTS

Identification of Studies

An overview of the study identification process is provided in Figure 4.1. Of 1188 identified records, 375 unique records underwent title/abstract screening. Of these, 104 were reviewed in full and 33 studies were included. Papers evaluating the same cohort with different (a) aims, (b) tasks evaluated, or (c) outcomes were treated independently.

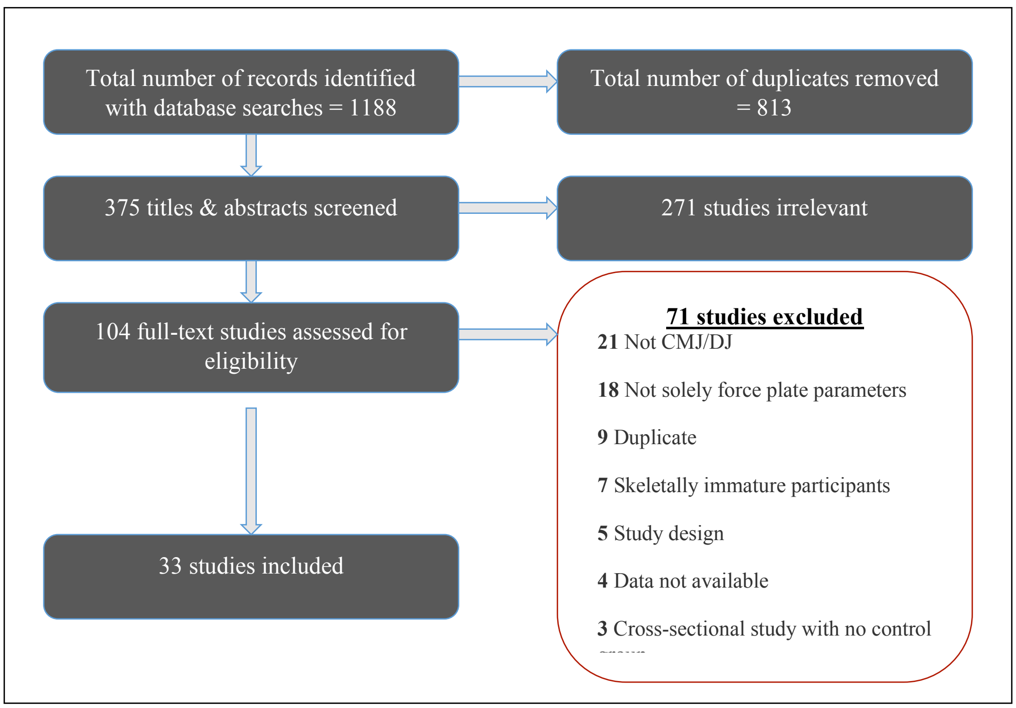

Figure 4.3: Systematic Review - Search Results and Study Selection

Studies Characteristics

The characteristics of the 33 included studies are summarized in Appendix II. These included 27 cross-sectional (81.82%) and 6 longitudinal (18.18%) studies. Studies were published between 2007 and 2022 with 22 (63.64%) studies published since 2018. Studies were conducted in 13 countries with the highest number conducted in the United States (12 [36.64%]). Overall, 2352 participants were included (female =

839 [37.81%]; male = 1380 [62.19%]). The mean age of participants ranged from 16.7 (±3.0) to 31.5 (±7.6) years. Of those, 1185 participants (50.38%) had ACLR, and 1167 (49.62%) were Healthy Controls, representing a variety of physical activity and sport participation levels. Healthy Control groups existed in 29 (87.88%) studies.

Following the methodological considerations recommended in a previous scoping review [44], a lack of reporting and wide degree of heterogeneity were observed across the included studies in terms of force plate sampling frequency, warming up protocol, shoe wearing requirements, hand placement requirements, and jumping protocol across the included studies. For instance, the force plate sampling frequencies were reported in 29 (87.9%) studies, and ranged between 500Hz and 2400Hz. The most frequently used sampling frequencies were 1000Hz (n=16 [48.5%]) [12, 13, 28, 37, 39–41, 46, 47, 50, 51, 55, 56, 63–65] and 1200Hz (n=4 [12.1%]) [17, 33, 48, 61]. While varying warm-up protocols were reported in 17 (51.5%) studies [8, 9, 12, 13, 19, 28, 33, 35–37, 39, 46, 47, 50, 51, 55, 56], 16 (48.5%) studies did not provide information about a warm-up protocol. Similarly, participants were instructed to perform the jumping tasks barefoot in 2 (6.1%) studies [28, 42], and with shoes on in 11 (33.3%) studies [7–9, 31–33, 37, 39, 41, 46, 51], while the remaining 20 (60.6%) studies did not specify whether participants wore shoes or not. Related to hand placement during jumping, participants were instructed to keep their hands on hips in 14 (42%) studies [12, 13, 20, 28, 35–37, 39, 40, 46, 47, 50, 55, 56], or to cross their arms on their chest in 1 (3%) study [7]. Apart from the variation in the number of trials, single and double-leg CMJ protocols remained consistent across the studies. However, while performing DJ, 4 studies reported having their participants jump off a box that was placed at certain distances behind the force plate [19, 31, 32, 41], while the remaining studies instructed their participants to drop off a box onto force plates.

<u>Quality appraisal and level of evidence</u>

The studies included in the current review showed a maximum evidence level of 4, as per the OCEBM model. This corresponds to cross-sectional, case control, or lower quality prognostic cohort studies.

In terms of methodological quality, gauged using the DB criteria, the median score was 10/21, with scores ranging from 7/21 to 12/21.

Common methodological limitations among the studies included a partial description of primary confounders, potential selection bias (i.e., no clear differentiation between those who chose to participate versus those who didn't), small sample sizes, and lack of detailed explanation of the validity of the methodological approaches used to evaluate CMJs and DJs.

<u>Jumping tasks</u>

A total of 38 comparisons were identified, of which 31 compared between individuals with ACLR and Healthy Controls, and 7 comparisons studied individuals at different time points at least 6 months post-ACLR. Means and SDs were used for meta-analysis (Table 4.4). One study used the mean differences and degree of freedom, and therefore was excluded from meta-analyses, yet its findings were reported narratively. All the parameters utilized to evaluate CMJs and DJs in individuals with and without ACLR are reported in Appendix 4.2. The operational definitions of those parameters are detailed in Appendix 4.3.

Table 4.8 Details of Comparisons

Comparisons		**Single-leg**	**Double-leg**	**Total**
Cross Sectional	CMJ	4	7	11
	DJ	5	15	20[$]
Total cross-sectional comparisons		**9[†]**	**22**	**31**
Longitudinal	CMJ	0	1	1
	DJ	1	5	6[*]
Total longitudinal comparisons		**1**	**6**	**7[‡]**
Total		**10**	**28[•]**	**38[Δ]**

[$]Twenty comparisons in 19 studies, [†]nine comparisons in eight studies, [*]six comparisons in five studies, ‡seven comparisons in six studies, 28 comparisons in 26 studies looking at double-leg DJ, and [Δ]38 comparisons in 33 studies.

Single-leg CMJ

The authors identified four cross-sectional studies comparing between individuals following ACLR (n=177) with Healthy Controls (n=108) [20, 28, 39, 50]. All four studies included male participants only. Six parameters were identified (peak vertical ground reaction force (vGRF) [20], center of pressure (CoP) length of path [20], time to stabilization (TTS) [20], flight time [20], jump height [28, 39, 50], and peak power [50]). Our meta-analysis, incorporating data from three different studies [28, 39, 50], revealed that jump height was significantly lower in the ACLR compared to the Healthy Control group with a mean difference (MD) of -3.13 cm ($p<0.01$; 95% CI [-4.12, -2.15]) and no observed heterogeneity (I^2=0%) (Figure 4.2). Peak power was reported in only one comparison demonstrating a lower single-leg CMJ peak power in the ACLR group compared to the control group [50]. No other parameters demonstrated significant differences between the two groups. There were no longitudinal comparisons of single-leg CMJ.

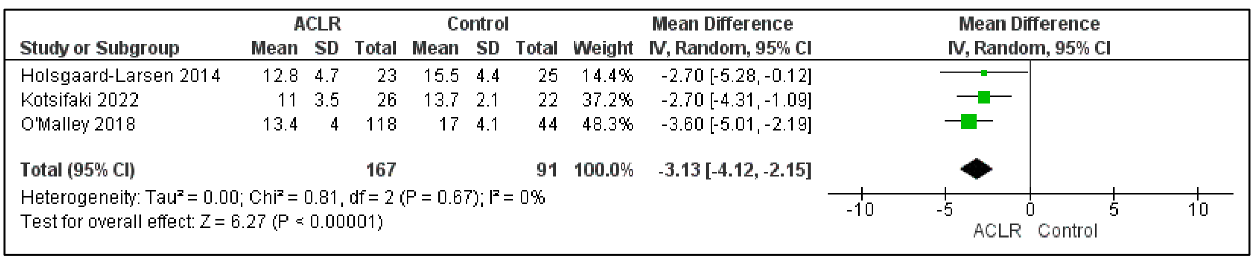

Figure 4.4: Forest plot comparing jump height while performing single-leg countermovement jump in individuals with and without ACLR

Double-leg CMJ

Seven cross-sectional studies compared between participants post-ACLR (n=245 [f=35, m=190) and Healthy Controls (n=494 [f=214, m=260) [7, 12, 35, 36, 40, 47, 56], with one study not reporting participants' sex [40]. We identified 32 unique parameters across the studies. Jump height was the most commonly reported parameter in 4 (57.1%) studies [35, 40, 47, 56], followed by impulse concentric [36, 56], impulse concentric asymmetry [40, 56], impulse eccentric [36, 56], and impulse eccentric asymmetry

[40, 56] each reported in 2 (28.6%) studies. One study reported the mean differences instead of means and SDs for jump height, and was excluded from the meta-analysis [40]. The meta-analysis on the remaining three studies demonstrated lower jump height in the ACLR compared to the Healthy Control group (MD= -4.24 cm; p<0.01 95%CI [-5.14, -3.34]) with no reported heterogeneity ($I^2 = 0\%$). In two separate studies [36, 56], the involved limb exhibited significantly lower concentric impulse, whereas the uninvolved limb displayed significantly higher concentric impulse compared to the control group, (MD= -14.15 N.s; p<0.01 95%CI [-22.84, -5.46]) and (MD= 17.44 N.s; p<0.01 95%CI [7.05, 27.83]), respectively. (Figure 4.3)

Eccentric impulse and concentric impulse demonstrated significantly higher asymmetries in the ACLR group compared to the Healthy Control group, (MD= 3.42; p<0.01 95%CI [2.19, 4.64]) and (MD= 5.82; p<0.01 95%CI [4.80, 6.80]), respectively (Figure 4.4). However, when evaluating eccentric impulse in the involved and uninvolved limbs of the ACLR group compared to the control groups, no significant differences were found.

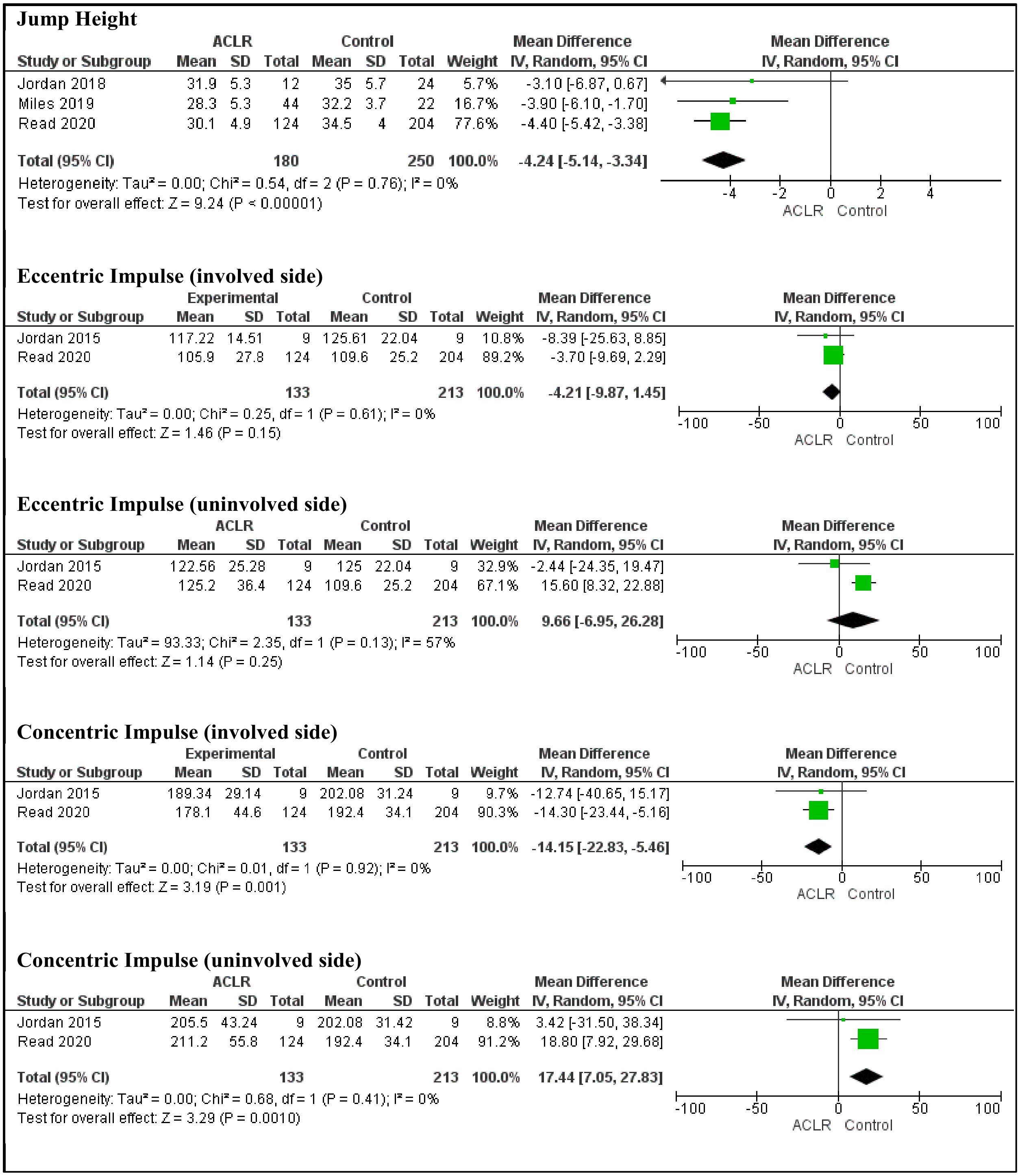

Figure 4.5: Forest plots comparing jump height, eccentric and concentric impulses while performing double-leg countermovement jump in individuals with and without ACLR

Several parameters were only reported in 1 study: Concentric impulse (normalized) [47], eccentric impulse (normalized) [47], landing impulse (normalized) [47], concentric peak vGRF [56], eccentric mean GRF [56], eccentric RFD [56], peak power [56], peak vGRF during landing [56], relative peak power [35], velocity at peak power [35], velocity max [35], concentric peak vGRF asymmetry [56], eccentric mean GRF asymmetry [56], eccentric RFD asymmetry [56], and peak vGRF asymmetry during landing [56]. All of these comparisons between ACLR participants and Healthy Control participants were significantly different favoring the Healthy Control groups (Appendix 4.2).

One longitudinal study evaluated 44 male participants in a repeated measure design at six and 9 months following ACLR. Out of four parameters identified (eccentric deceleration impulse, concentric impulse, landing impulse and jump height) only the eccentric deceleration impulse significantly decreased between six and nine months post-ACLR [13].

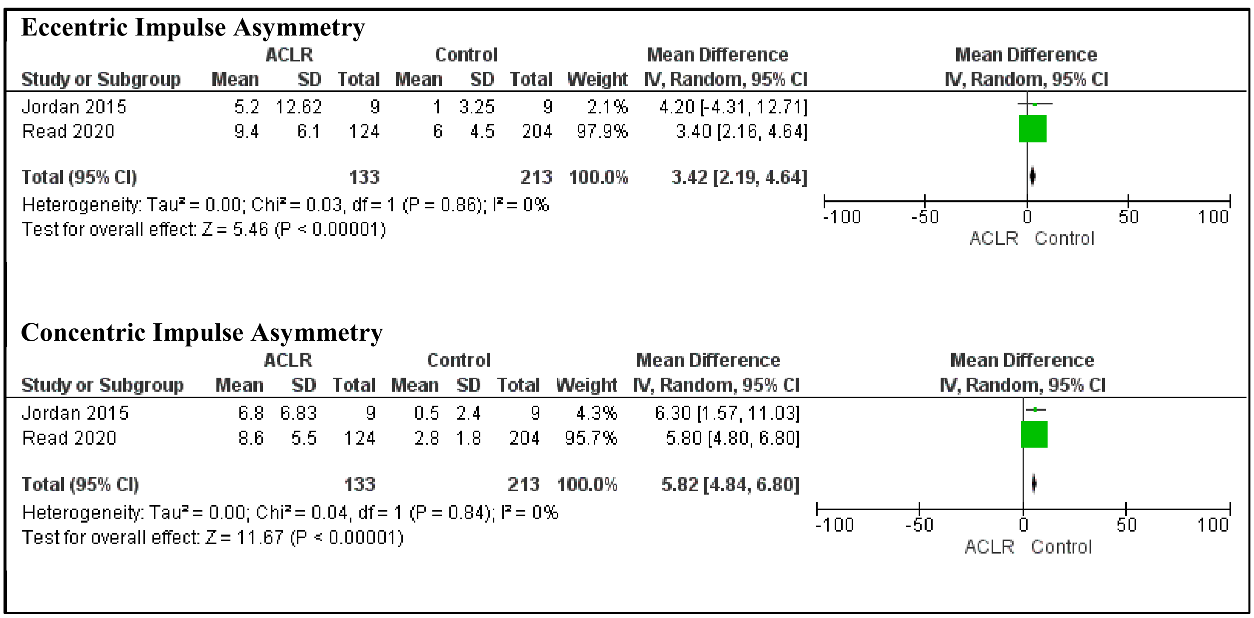

Figure 4.6: Forest plots comparing eccentric and concentric impulses asymmetry while performing double-leg countermovement jump in individuals with and without ACLR

Single-leg DJ

Five cross-sectional studies compared between individuals following ACLR (n=142 [f=33, m=98]) and Healthy Controls (n=260 [f=34, m=217]) [32, 39, 51, 55], with one study not reporting participants' sex [37]. Among the five studies, eleven unique parameters were identified. Each parameter was reported once, except for peak vGRF, which appeared in two different studies [37, 51]. The parameters that exhibited significant differences between the two groups were jump height [39], vertical ground reaction force (vGRF) at initial contact [37], reactive strength index (RSI) [39], and reactive strength ratio (RSR) [39], all favouring the Healthy Control group. Conversely, the ACLR group demonstrated significantly higher jump height asymmetry [55] and RSI asymmetry [55] values in compared to the control group.

However, there were no significant differences observed in peak vGRF symmetry, loading rate symmetry, vGRF at last contact [37], and contact time between the two groups. Notably, peak vGRF showed a significant difference in one study [37] but not in the other [51]. After pooling mean differences, our meta-analysis revealed no significant difference in peak vGRF between individuals with ACLR and Healthy Controls during single-leg drop-jumps (Figure 4.5). However, it's important to note the varied assessment timings between the two studies (at 6-15 months [37] vs. 86.4 ± 50.4 months [51]) post ACLR.

We identified only one longitudinal study assessing single-leg DJ of 64 athletes at different time points post ACLR (8 months and 2 years later). Peak vGRF in involved and uninvolved limbs were not different at 2-year after return to sport compared to it at 8 months post-surgery (p=0.08, p=0.18, respectively). No other kinetic parameters were reported [33].

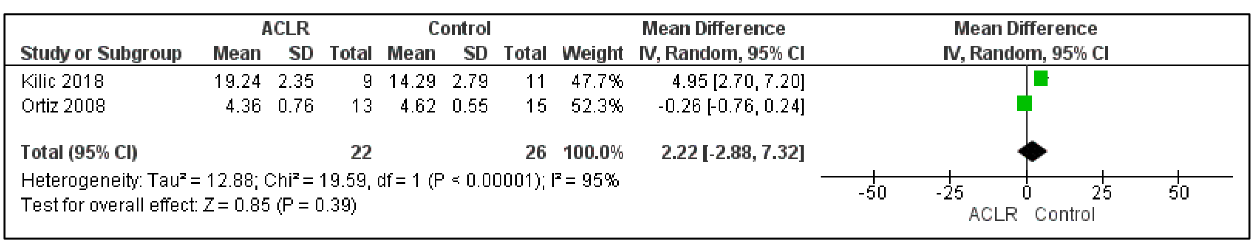

Figure 4.7: Forest plot comparing peak vGRF while performing single-leg drop- jump in individuals with and without ACLR

Double-leg DJ

Fifteen cross sectional studies compared between people following ACLR (n=453 [f=281, m=153]) and Healthy Controls (n=346 [f=222, m=110]) [8, 9, 17, 19, 22, 31, 32, 41, 42, 46, 48, 53, 61, 63, 64]. Two studies did not report the participants' sex [19, 41]. We identified 21 unique parameters across the 15 studies. Peak $vGRF_{(normalized)}$ was the most frequently used parameter being reported in 11 (73.3%) studies. Peak $vGRF_{(normalized)}$ during the eccentric and concentric phases of jumping were reported in 10 (66.7%) [9, 22, 31, 42, 46, 48, 53, 61, 64, 65] and 3 (20.0%) [42, 48, 53] studies respectively. One study reported peak $vGRF_{(normalized)}$ without specifying the phase of the jump [41].

In our meta-analysis of the ten studies [9, 22, 31, 42, 46, 48, 53, 61, 64, 65], the involved limb demonstrated significantly lower peak $vGRF_{(normalized)}$ during the eccentric phase of the jump compared to Healthy Control participants (MD= -0.10 $N\cdot kg^{-1}$; p=0.03 95%CI [-0.18, -0.01]) with a moderate but insignificant heterogeneity (I^2=35%, p=0.13)

Furthermore, out of the ten studies reporting the eccentric peak $vGRF_{(normalized)}$, seven studies provided values both for the involved and non-involved sides [22, 46, 48, 53, 61, 64, 65]. Interestingly, the uninvolved side of individuals who have undergone ACLR demonstrated greater eccentric peak $vGRF_{(normalized)}$ compared to Healthy Controls (MD= 0.15 $N\cdot kg^{-1}$; p<0.01 95%CI [0.10, 0.20]). Importantly, the outcomes of these studies were consistent, with no heterogeneity observed (I^2=0%, p=0.65). (Figure 4.6).

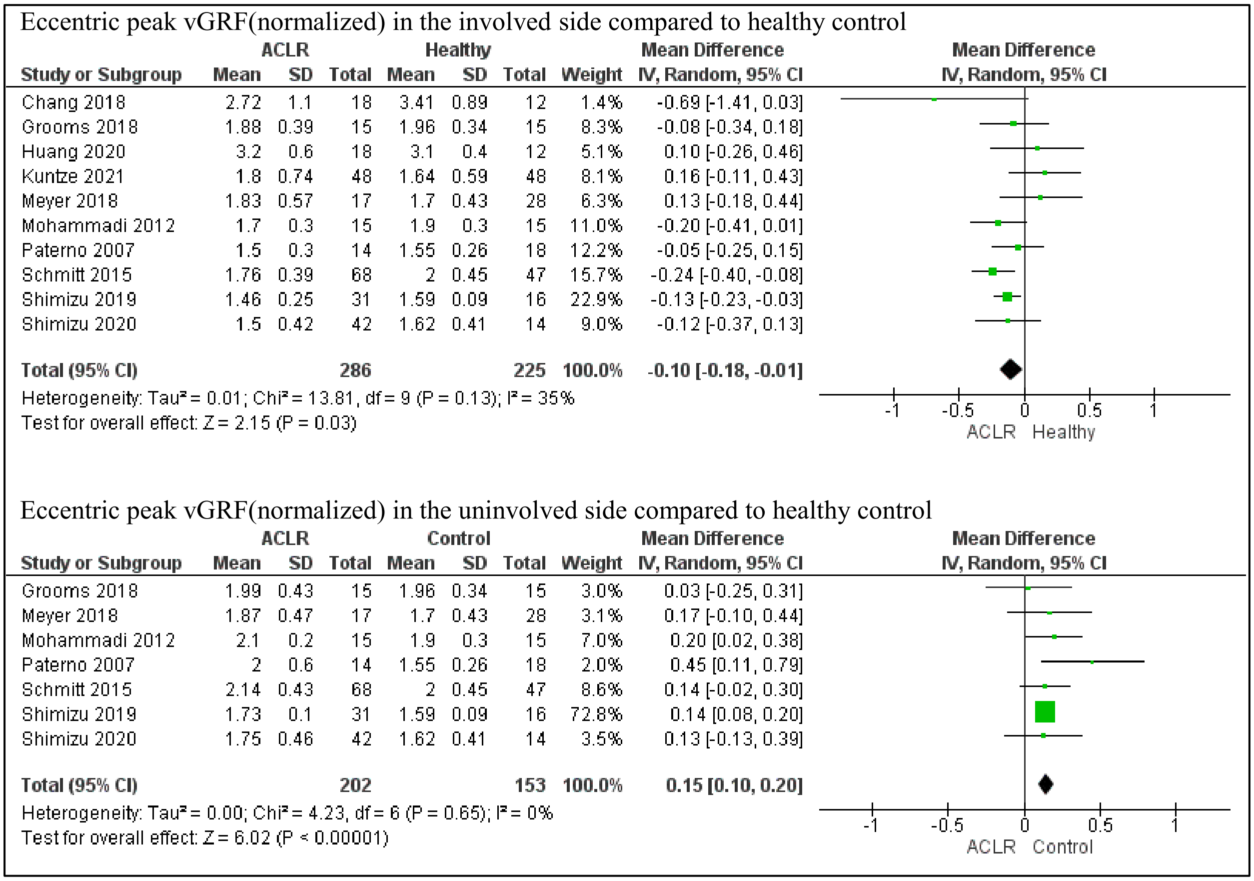

Figure 4.8: Forest plots comparing eccentric peak vGRF in the involved and uninvolved sides while performing double-leg drop jump in individuals with and without ACLR

Concentric peak vGRF$_{(normalized)}$ in the involved and uninvolved sides, eccentric loading rate $_{(normalized)}$ in the involved and uninvolved sides, and eccentric loading rate asymmetry, eccentric peak vGRF asymmetry were all not different in the ACLR group compared to the control group (Appendix 4.4).

Five longitudinal studies assessed DJ in participants with ACLR (n=196 [f=88, m=108]) at different time points [33, 49, 63–65]. We identified six unique parameters across the studies; (peak vGRF$_{(normalized)}$, peak vGRF$_{(normalized)}$ symmetry index, eccentric peak vGRF$_{(normalized)}$, concentric peak vGRF$_{(normalized)}$, contact time, and vGRF impulse). Peak vGRF$_{(normalized)}$ was the most commonly evaluated parameter been reported in all the five studies.

One study analyzed the performance of double-leg DJ at 8 months post ACLR (time to return to sport) and 2-years later [33]. For peak $vGRF_{(normalized)}$, involved limb values increased ($p<0.01$) and uninvolved limb values decreased ($p<0.01$) from the time of return to sport to 2 years later. Accordingly, the peak $vGRF_{(normalized)}$ symmetry index improved at 2 years after return to sport ($p=0.03$) [33]. Another study compared double-leg DJ performances at 6 and 12 months post-ACLR and reported extremely high eccentric and concentric peak $vGRF_{(normalized)}$ values [49]. Given these unusually high values, we excluded this study from the meta-analysis. The final three studies, by the same authors, presented measurements at 6 months and 3 years post-ACLR in two studies [63, 65], and measurements at 6 months, 12 months, 2 years, and 3 years in the third [64]. Interestingly, despite different sample sizes, the mean and standard deviations (SDs) at 6 months and 3 years were identical in two out of the three studies. Given the sample size differences between the studies, we couldn't justify excluding any of the studies, and proceeded to cautiously include all three in a meta-analyses which demonstrated a significantly lower peak $vGRF_{(normalized)}$ during the stance phase of the jump at 6 months compared to 3-year post-ACLR (MD= -0.47 $N\cdot kg^{-1}$; $p<0.01$ 95%CI [-0.52, -0.45]) (Figure 4.7).

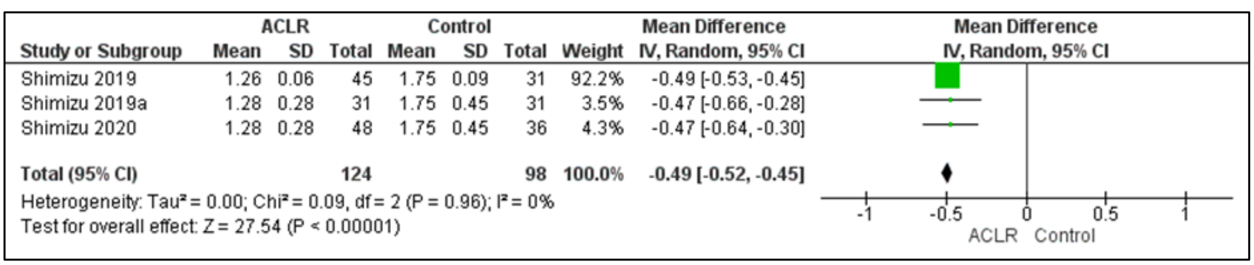

Figure 4.9: Peak vGRF during the stance phase of double-leg drop jump at 6-months and 3-years post ACLR

DISCUSSION

This systematic review provides a rigorous synthesis of evidence and expands on the existing literature, contributing to the ongoing development of this field. The meta-analyses have yielded valuable insights into the use of force plate parameters to differentiate neuromuscular function between individuals following anterior cruciate ligament reconstruction (ACLR) and Healthy Controls during countermovement jumps (CMJs) and drop jumps (DJs). Our findings indicate that specific force plate parameters, such as jump height during single and double-leg CMJs and peak vertical ground reaction force (vGRF) normalized during DJs, exhibit significant differences between individuals with and without a history of primary ACLR. Notably, the discriminative ability of these parameters is influenced by factors such as the type of jump (single vs. double-leg) and the limb side involved. Specifically, jump height was notably lower in individuals post-ACLR compared to Healthy Controls. Additionally, eccentric peak vGRF was significantly higher in the uninvolved side and significantly lower in the involved side in individuals post-ACLR compared to Healthy Controls. However, our sensitivity analysis revealed heterogeneity in the discriminative ability of other parameters, suggesting the potential need for a combination of parameters to more accurately identify functional deficits post-ACLR. These findings have important implications for clinical practice and rehabilitation strategies following ACLR.

When interpreting the results of force plate parameters in individuals following ACLR, it is crucial to consider the time of assessment after ACLR. The recovery process following ACLR is dynamic and can vary over time [23]. Therefore, the functional deficits and neuromuscular function observed at 6 months post-surgery may differ from those observed several months later.

While performing single-leg CMJs, even when assessed at different time points (26.5±6.6 [28] vs. 9.5±2.7 [39] vs. 6.6±1.0 [50] months) post-ACLR, jump height was the most discriminative parameter. It is a simple and easily interpreted measure that might reflect the capacity to generate power through the kinetic chain [30]. The fact that jump height was consistently different between individuals with and without a history of ACLR highlights the relevance of addressing explosive power deficits in rehabilitation programs [6]. However, the findings of our meta-analysis should be taken with caution as only male participants were included in these studies. This may limit the generalizability of findings to female individuals who have a higher risk of ACL injuries [11].

In double-leg CMJs, multiple parameters, including jump height, concentric and eccentric impulse, and several other force measures, demonstrated significant differences. Jump height was notably lower in individuals post-ACLR compared to Healthy Controls. Additionally, the concentric impulse was significantly lower in the involved leg, but higher in the uninvolved leg post-ACLR compared to Healthy Controls. Both eccentric impulse and concentric impulse demonstrated significantly higher asymmetries in the ACLR group compared to the Healthy Controls. This provides a more detailed understanding of potential deficits and functional asymmetries in individuals post-ACLR. These parameters, especially impulse measures, could inform clinicians and researchers about the efficiency of strength generation during jump tasks, which is crucial for safe and effective sports participation and a safe return to sport [56, 66].

In the context of DJs, it was found that vertical ground reaction force (vGRF) during the eccentric phase was discriminative in double-leg DJs, more so when examining the uninvolved side. Our sensitivity analysis revealed less heterogeneity when studying the uninvolved side compared to the involved side. While it is the same sample of individuals performing exactly the same jump, the increased heterogeneity in the involved side could be related to the type of grafts used and the different rehabilitation protocols that were followed mainly in the involved limb. Vertical GRF is a fundamental parameter in understanding the load absorption capacity of the lower limbs, which is of critical importance in preventing re-injury. However, there was inconsistency regarding the phase of the jump during which the peak $vGRF_{(normalized)}$ values were calculated across studies, and the definitions of those phases, limiting our ability to compare these values accurately. Our longitudinal analysis also revealed significant changes over time post-ACLR in certain parameters, notably in peak $vGRF_{(normalized)}$ during the stance phase of DJs. This suggests that some aspects of dynamic function improve during the first few years after ACLR, emphasizing the potential value of extended rehabilitation and monitoring [21, 34].

The included studies generally had low to moderate methodological quality, as assessed by the Modified DB criteria. Common methodological limitations included partial descriptions of primary confounders, small sample sizes, and lack of clarity in the differentiation between participants who chose to participate versus those who didn't. These limitations should be addressed in future studies to improve the robustness of findings.

The findings from this systematic review and meta-analyses bear significant clinical implications for the management of patients following ACLR. The identified force plate parameters, including jump height, concentric and eccentric impulse, and vertical ground reaction force, serve as crucial tools when evaluating neuromuscular function and recovery progress. Their utilization can guide clinicians in designing more individualized, effective rehabilitation programs targeting specific functional deficits post-ACLR. For instance, consistent differences in jump height between ACLR patients and Healthy Controls underscore the need to incorporate training strategies that enhance explosive power in rehabilitation programs. Moreover, the fact that some of the identified parameters are responsive to changes over time following ACLR highlights the importance of extended rehabilitation and long-term monitoring to ensure a safe return to sports. Finally, the observed methodological shortcomings in the reviewed studies signal the need for more rigorous research methodologies in the future. We would like to stress the criticality of reporting data sufficiently and precisely to ensure methodological robustness that can be translated into effective practices and policies [18, 44].

This review, however, has some limitations. The lack of standardized methodological protocols across studies while evaluating kinetic parameters during CMJ and DJ may have impacted the results. Additionally, we reported several heterogeneities among the studies particularly within the individuals following ACLR. While we included studies of participants who are at least 6-months post ACLR, we did not account in our analysis for other factors that could have contributed to the heterogeneity such as the graft type, the time since surgery as well as the rehabilitation protocols followed. However, this systematic review and meta-analysis has several strengths. The comprehensive search strategy and predefined inclusion and exclusion criteria were implemented to mitigate the risk of overlooking relevant studies ensuring the robustness and thoroughness of the study selection process. The study team consisted of a multidisciplinary group, including individuals with diverse expertise in research methodology, evidence synthesis, orthopedic surgery, sports and exercise therapy, knee injury rehabilitation, kinesiology, and engineering. This diverse range of skills and knowledge minimized ambiguity and uncertainties related to study selection, ensuring a comprehensive approach to the research process.

CONCLUSION

In conclusion, this review provides a comprehensive overview of the discriminative ability of force plate parameters in individuals post-ACLR during CMJs and DJs. Future research should strive for improved methodological quality and consider both cross-sectional and longitudinal designs to monitor changes over time. Moreover, standardizing the specific phases of jumps when measurements are taken is necessary to enhance the robustness and the validation of the findings.

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CHAPTER 5: BEYOND STATIC MEASURES: DYNAMIC POSTURAL STABILITY IN INDIVIDUALS WITH ACL-RECONSTRUCTION VERSUS HEALTHY CONTROLS WITH INSIGHTS INTO SEX DIFFERENCES

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Labban W, Sommerfeldt M, Westover L, Forero JM, Nathanail S, Beaupre LA: Beyond Static Measures: Dynamic Postural Stability in Individuals with ACL-Reconstruction Versus Healthy Controls with Insights into Sex Differences

ABSTRACT

Objective: To compare dynamic postural stability, measured by time to stabilization (TTS) and postural stability indices (PSI), after double-leg countermovement jump (CMJ) landing in individuals 9-24 months following anterior cruciate ligament reconstruction (ACLR) and Healthy Controls. Additionally, to explore the effect of sex and ACLR status on postural stability.

Design: Cross-sectional

Setting: Laboratory

Participants: Twenty-one participants (10 females) 9-24 months post-ACLR, and 20 (10 females) Healthy Controls were instructed to perform double-leg CMJs on force plates, land and maintain the landing position for 10 seconds.

Main outcome measures: TTS and PSI variables were calculated after landing and compared between groups and sex.

Results: The resultant vector TTS when combined from both force plates (RVTTS-C), and the vertical TTS in the operated leg (VTTS-op) was higher in the ACLR than the Healthy Controls, (p=0.03, p=0.02

respectively). Males with ACLR demonstrated higher VTTS, combined (VTTS-C) and VTTS-op than females post-ACLR (p=0.03, p<0.01 respectively), and higher VTTS-op compared to healthy males (p=0.03). There were no differences in PSIs between groups.

Conclusion: Our study revealed significant differences in TTS outcomes between individuals with ACLR and Healthy Controls, with notable sex and ACLR differences. Further research is needed to understand sex-specific postural stability mechanisms to customize rehabilitation programs.

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a devastating injury that frequently occurs in sports[9] and accounts for 50% or more of all knee injuries.[9, 28] Most ACL injuries occur without a direct knee contact[37] when the limb decelerates during landing or change of direction activities such as cutting and pivoting.[14] Due to the vital role of the ACL in the knee joint stabilization,[17] ACL injuries can lead to impairments of the knee stability and balance.[19] Therefore, anterior cruciate ligament reconstruction (ACLR) is frequently indicated to restore knee joint stability. ACLR is usually followed by a course of rehabilitation with the ultimate aim of returning patients to their pre-injury level of function and performance.

Dynamic postural stability is a critical aspect of movement control and injury prevention, particularly after ACLR.[33] Individuals often face challenges in regaining optimal postural stability, which can significantly impact their functional performance and risk of re-injury.[24] Understanding the nuances of postural stability in individuals post-ACLR compared to Healthy Controls is essential for tailoring rehabilitation programs and enhancing long-term outcomes.[30]

In a clinical setting, postural stability is usually tested statically. Patients are asked to stand on a single-leg while maintaining their balance on a stationary platform. Several parameters related to the center of pressure can then be compared between the injured and non-injured legs or between patients and Healthy Controls.[31] Although static balance testing may be valuable for measuring postural control,[2] static postural stability measures have been described as non-functional, insensitive, and do not correlate with dynamic values.[32] Therefore, measurement of more challenging and dynamic aspects of postural control that mimic athletic activities may provide important insights into athletes' functional abilities with and without ACLR.[2, 13]

Assessing postural stability after performing a jump task, such as the countermovement jump (CMJ), provides valuable insights into lower limb function and dynamic stability. While previous studies have predominantly focused on single-leg CMJ tasks, examining postural stability immediately after double-leg CMJ landing offers a comprehensive evaluation of bilateral weight-bearing capabilities and control mechanisms of both lower limbs.[4] Various methods exist to calculate and report parameters to estimate postural stability, each with its own advantages and limitations.[40]

Time to stabilization (TTS) and the dynamic postural stability index (DPSI) have been suggested as metrics for evaluating postural stability.[5, 40] They both reflect an individual's capacity to maintain stability during the shift from a dynamic to a static state.[18, 39] TTS is the duration required for the ground reaction force (GRF) signal to stabilize following a landing on a force plate,[5] while DPSI quantifies deviations around a central point to assess fluctuations in stability.[40]

Several studies have also observed sex differences after ACLR in various measures of physical function, for example, hop performance,[6] patient reported outcome measures (PROMs)[1, 34] and 3D knee kinematics.[6, 7] While the impact of sex on postural stability showed mixed findings with different populations according to a systematic review,[8] there is an inconclusive evidence regarding the influence of sex on measures of postural stability in individuals following ACLR.

Our recent systematic review provided a comprehensive overview of several force plate parameters and their discriminative abilities in individuals post-ACLR during CMJs and drop jumps.[15] However, none of the identified outcomes addressed postural stability during double-leg CMJ landing in individuals with and without ACLR.[15] Therefore, the current study aims to fill this gap by delving deeper into the comparison of dynamic postural stability immediately after double-leg CMJ landing in individuals between 9- and 24-months following ACLR and Healthy Controls. Additionally, exploring the effect of the association between sex and the ACLR status on postural stability, as measured by TTS and PSI, will shed light on the sex-specific differences in movement patterns and neuromuscular control strategies during dynamic tasks post-ACLR.

METHODS

Study design

This cross-sectional study was conducted and reported using the Strengthening the Reporting of Observational studies in Epidemiology (STROBE) guidelines[10] and the considerations for methodological reporting suggested in our previous work.[16] The study protocol was approved by the Research Ethics Board at the University of Alberta (Pro00111475). (see Appendix B)

Setting

Testing procedures were performed at the Human Movement Laboratory located at the University of Alberta, Edmonton, AB, Canada. We recruited a convenience sample of participants with and without ACLR. Participants were recruited through study posters at the University of Alberta and community sport centres. A digital copy of the study poster was also circulated to all students in the Faculty of Rehabilitation Medicine, and the Department of Mechanical Engineering at the University of Alberta. Most participants with ACLR were recruited from the Glen Sather Sport Medicine Clinic, University of Alberta. In addition, we included data of 10 participants who were 9-12 months post ACLR participating in an ongoing cohort study that used the same testing protocol, equipment and lab setting.

Inclusion and Exclusion Criteria

Participants in the ACLR group were recruited if they had undergone primary unilateral ACLR within the past 9-24 months, reported no significant concomitant ligamentous injuries, had no bilateral lower limb pathologies or recent orthopedic surgeries, reported regular participation in sports/activities involving jumping, cutting, pivoting, and lateral movements prior to the ACL injury and were planning to return to their sports/activities or had already done so, and had initiated dynamic activities during their ACL rehabilitation. Participants in the Healthy Control group were recruited if they were participating in sports/activities involving jumping, cutting, pivoting, and lateral movements and no history of knee injuries requiring medical intervention. Participants in both groups were between 18 and 35 years old and had no health conditions affecting participation.

Participants were excluded if they had back pain, recent concussion, a balance disorder, scored less than 80% on the knee extensors isokinetic strength symmetry index, or if they were found not fit for jumping/landing activities according to knee clinical examinations performed by a qualified research staff. All participants signed an informed consent form approved by the Research Ethics Board. (Appendix C)

Instrumentation

Ground reaction force (GRF) data were collected separately for each leg by means of two 46.5 centimeter (cm) wide × 51 cm long force plates (model AMTI OR6-7-1, AMTI, Watertown, MA, USA) located side-by-side mounted in the center of a custom-built 122 cm wide x 173 cm long platform. Data for the GRF (sampled at 1000 Hz) were recorded and processed using the Motion Monitor xGen v3.80.3.0 system (Innovative Sports Training, Inc, Chicago, IL, USA) to output the vertical (GRFv), medial-lateral (GRFml) and anterior-posterior (GRFap) force component traces from 3 seconds before the jump and 15 seconds after the landing.

The bioelectrical impedance analysis (BIA) device (Tanita MC-780U) was used to estimate overall body composition. The knee isokinetic dynamometry testing was done using the PrimusRS system (BTE PrimusRS (PR30); BTE Technologies, Hanover, MD, USA).

Procedure

Participants underwent a standardized laboratory procedure to assess various aspects of knee function and postural stability. Anthropometric measurements, including height, weight, and bilateral thigh circumference, were taken. Participants also stood on a BIA to estimate overall body composition. A standardized warm-up routine was conducted, comprising stationary cycling, dynamic lower body mobility exercises, stretching, and submaximal body-weight exercises. Subsequently, participants underwent knee isokinetic dynamometry involving familiarization trials and 5 maximal voluntary contractions of concentric knee flexion and extension per limb. The knee extensors isokinetic strength symmetry index was calculated using the following formula:

$$\frac{\begin{array}{c} The\ average\ of\ 5\ maximal\ contractions\ of\ knee\ extensors\ in\ the\ involved\ (ACLR)\ or \\ non-dominant\ (Healthy\ Controls)\ limb \end{array}}{The\ average\ of\ 5\ maximal\ contractions\ of\ knee\ extensors\ in\ the\ contralateral\ limb} \times 100$$

Participants who scored 80% or more on the isokinetic strength symmetry index moved on to the jump testing. Participants who scored less than 80% were allowed another assessment within one month to re-test their strength stability indices to allow them to participate in the evaluation. If they were unsuccessful on the second attempt, they were excluded from the study.

Jump Testing

Participants were asked to perform a barefoot jump-specific warm-up protocol including 10 CMJs, 10-15 calf hops, and 10 CMJ rebound jumps. Participants were then asked to stand barefoot with each foot on a force plate. They were asked to stand tall placing hands on hips maintaining this position over the respective force plate motionless for at least three seconds before jumping.

At the time of hearing the word “jump“, participants would rapidly perform a CMJ, which involves downward motion/squat to approximately 90 degrees of knee flexion, followed by rapid triple extension of the ankles, knees, and hips, jumping as high as possible, while maintaining hands on hips and landing with each foot completely on a the respective force plate. Participants were required to maintain their landing position, without any movement, for a duration of 10 seconds after landing.

Participants were instructed to perform 5 CMJ trials, taking a minimum break of five seconds between each jump. Participants would repeat trials if jumps failed to meet the established criteria, such as any movement occurring before 10 seconds post-landing, incorrect execution of the jump, or landing with part of a foot off the force plates. To count for learning effect and fatigue, data from the first and last trials were excluded from data analysis.[38]

Outcomes

We assessed TTS and PSI using four distinct measures for each outcome. For TTS, we evaluated anterior-posterior time to stabilization (APTTS), medial-lateral time to stabilization (MLTTS), vertical time to stabilization (VTTS), and resultant vector time to stabilization (RVTTS), which assesses TTS in both horizontal planes.[12] Similarly, for PSI, we examined anterior-posterior stability index (APSI), medial-lateral stability index (MLSI), vertical stability index (VSI), and dynamic postural stability index (DPSI).

We compared the combined TTS (TTS-C) and combined PSIs (PSI-C) measured from both force plates (i.e., both limbs) between the ACLR and control groups. TTS-C and PSI-C were calculated from the combined forces (FC) from the forces in the right (FR) and left (FL) force plates using the following formula: FC= FR + FL. Additionally, we compared these variables from the operated leg (op) in the ACLR group with the corresponding (right or left) sides in the Healthy Control group, and repeated the comparison for the non-operative (nop) sides. In the ACLR group, there were 5 males and 5 females with right ACLR and 6 males and 5 females with left ACLR. To ensure balanced comparisons, Healthy Control participants' data were randomly allocated to match the sex and side (op or nop) of the ACLR participants. This involved comparing the right operative legs of ACLR participants to the right legs of sex-matched Healthy Controls, and the left operative legs of ACLR participants to the left legs of sex-matched Healthy Controls. The same approach was applied to the non-operative sides, where the non-operative legs of ACLR participants were compared to the corresponding legs of sex-matched Healthy Controls.

Furthermore, we assessed the asymmetry in TTS and PSI between the two legs in the ACLR group and compared it with the asymmetry observed in the Healthy Control group. The full list of TTS and PSI outcomes and nomenclature are listed in Table 5.1.

Table 5.9 List of TTS and PSI outcomes

Time to stabilization		**Postural stability indices**	
Abbreviations	**Outcomes**	**Abbreviations**	**Outcomes**
APTTS-C	Anterior posterior time to stabilization-combined	**APSI-C**	Anterior posterior postural stability index - combined
MLTTS-C	Medial lateral time to stabilization-combined	**MLSI-C**	Medial lateral postural stability index - combined
VTTS-C	Vertical time to stabilization-combined	**VSI-C**	Vertical postural stability index - combined
RVTTS-C	Resultant vector time to stabilization-combined	**DPSI-C**	Dynamic postural stability index - combined
APTTS-op	Anterior posterior time to stabilization in operated leg (or matched leg in Healthy Control)	**APSI-op**	Anterior posterior postural stability index in operated leg (or matched leg in Healthy Control)
MLTTS-op	Medial lateral time to stabilization in operated leg (or matched leg in Healthy Control)	**MLSI-op**	Medial lateral postural stability index in operated leg (or matched leg in Healthy Control)
VTTS-op	Vertical time to stabilization in operated leg (or matched leg in Healthy Control)	**VSI-op**	Vertical postural stability index in operated leg (or matched leg in Healthy Control)

RVTTS-op	Resultant vector time to stabilization in operated leg (or matched leg in Healthy Control)	**DPSI-op**	Dynamic postural stability index in operated leg (or matched leg in Healthy Control)
APTTS-nop	Anterior posterior time to stabilization in non-operated leg (or matched leg in Healthy Control)	**APSI-nop**	Anterior posterior postural stability index in non-operated leg (or matched leg in Healthy Control)
MLTTS-nop	Medial lateral time to stabilization in non-operated leg (or matched leg in Healthy Control)	**MLSI-nop**	Medial lateral postural stability index in non-operated leg (or matched leg in Healthy Control)
VTTS-nop	Vertical time to stabilization in non-operated leg (or matched leg in Healthy Control)	**VSI-nop**	Vertical postural stability index in non-operated leg (or matched leg in Healthy Control)
RVTTS-nop	Resultant vector time to stabilization in non-operated leg (or matched leg in Healthy Control)	**DPSI-nop**	Dynamic postural stability index in non-operated leg (or matched leg in Healthy Control)
APTTS-Asy	Asymmetry in anterior posterior time to stabilization	**APSI-Asy**	Asymmetry in anterior posterior postural stability index
MLTTS-Asy	Asymmetry in medial lateral time to stabilization	**MLSI-Asy**	Asymmetry in medial lateral postural stability index
VTTS-Asy	Asymmetry in vertical time to stabilization	**VSI-Asy**	Asymmetry in vertical postural stability index
RVTTS-Asy	Asymmetry in resultant vector time to stabilization	**DPSI-Asy**	Asymmetry in dynamic postural stability index

Data processing

A moving average filter with a 100 millisecond window was applied to the GRF traces to reduce random noise; then a subset of data trimmed from the time of landing and lasting 10 seconds was extracted for the calculations. Time of landing was determined from the filtered traces as the time after jumping when GRFv > 10 Newtons, and body weight was estimated as the median value over the last 2 seconds of the data subset. GRF data from each force plate was used to analyze the stability performance from each side (TTS-left, TTS-right, PSI-left, PSI-right), and combined data from both force plates was used to analyze the participant's overall stability (TTS-C, DPSI-C). Data from all the trials was processed offline using a custom-written program in R (R Core Team, 2023)[35] to calculate TTS variables [anterior-posterior TTS (APTTS), medio-lateral TTS (MLTTS), vertical TTS (VTTS)] and PSIs variables [anterior-posterior PSI (APSI), medio-lateral PSI (MLSI), vertical PSI (VSI), and dynamic PSI (DPSI)] based on the methods described by Colby et al. 1999[5] and Wikstrom et al., 2005[40] respectively. The resultant vector TTS (RVTTS) was calculated using the following formula $RVTTS = \sqrt{(APTTS)^2 + (MLTTS)^2}$ [29]

Statistical analysis

We estimated the power based on data from previous literature looking at TTS after forward jump landing in females.[39] Using the Satterthwaite's t test assuming unequal variances, 20 participants per group would acquire a power of 82%. All outcome variables were assessed for normality and homogeneity of variances using The Shapiro-Wilk's test and the Levene's tests, respectively.

As most of the TTS and PSI variables were not normally distributed, we applied the Mann-Whitney U test for all TTS and PSI comparisons regardless of their distribution to provide homogeneity of data reporting for these variables. Therefore, we used the median and the interquartile range (IQR) to examine potential differences between the ACLR and Healthy Control group, for all the TTS and PSI outcomes. A sensitivity analyses was performed using parametric tests to ensure that there was no impact on reported outcomes (see Appendices 5.2 and 5.3). For the participant characteristics, we applied parametric or non-parametric tests as appropriate based on data distribution. Significance was set at $p < 0.05$.

When significant differences were identified, we estimated effect sizes using Cliff's Delta with the corresponding 95% confidence intervals. Cliff's Delta was interpreted as trivial ($\delta < 0.11$), small ($0.11 \leq \delta < 0.28$), medium ($0.28 \leq \delta < 0.43$), and large ($\delta \geq 0.43$).[36] Cliff's Delta effect sizes were calculated using an Excel sheet (website: Real Statistics Using Excel, 2023),[41] while the rest of the statistical analysis were performed using Stata (StataCorp LLC, version 15.1, USA).

To examine the effect of sex and the ACLR status, we employed the Kruskal Wallis test. The Dunn's post hoc test with Bonferroni adjustment was used for pair-wise comparisons, followed by effect size estimation for the significant comparisons.

RESULTS

A total of 43 participants were recruited, comprising 23 individuals with ACLR and 20 Healthy Controls. Among the ACLR group, two participants did not meet the criterion of 80% on the quadriceps strength symmetry index at either their initial or secondary assessment. Consequently, our final dataset comprised 41 participants, including 20 Healthy Controls (10 females and 10 males) and 21 individuals in the ACLR group (10 females and 11 males). The participants' characteristics are detailed in Table 5.2. Individuals in both groups exhibited similarities across numerous characteristics; however, Healthy Controls consistently outperformed individuals with ACLR across various functional measures such as Tegner (p=0.002), the Marx Activity Rating Scale (MARS) (p = 0.03), and the International Knee Documentation Committee (IKDC) (p < 0.001).

Table 5.10 – Participant Characteristics

Participants' Characteristics	**ACLR (n=21)**	**Healthy Controls (n=20)**	**P-value**
Sex (Mean ± SD)	F=10 / M=11	F=10 / M=10	
Age (year) (Median ± IQR)	22.17 (8.5)	22.63 (3.54)	0.97
Height (cm) (Mean ± SD)	170.18 ± 9.15	168.85 ± 11.84	0.69
Weight (kg) (Mean ± SD)	75.32 ± 13.07	70.38 ± 11.70	0.21
Total muscle mass (kg) (Median ± IQR)	53.8 (16.9)	48.7 (19.85)	0.74
Trunk muscle mass (kg) (Median ± IQR)	29.3 (5.4)	28.4 (8.05)	0.97
Right leg muscle mass (kg)(Median ± IQR)	9.5 (3.6)	9.0 (4.2)	0.91
Left leg muscle mass (kg) (Median ± IQR)	9.3 (3.7)	8.9 (4.15)	0.93
Total fat mass (kg) (Mean ± SD)	17.96 ± 6.62	14.86 ± 4.39	0.09
Total fat % (Mean ± SD)	23.58 ± 6.68	19.59 ± 6.11	0.053
Trunk fat % (Mean ± SD)	22.06 ± 6.53	17.79 ± 5.41	**0.03***
Right leg fat % (Mean ± SD)	25.43 ± 10.11	22.86 ± 10.37	0.43
Left leg fat % (Mean ± SD)	25.62 ± 9.90	23.28 ± 10.32	0.49
Total body water % (Median ± IQR)	55.4 (7.2)	56.85 (8.35)	0.14
Tegner (Median ± IQR)	5 (1)	7 (3)	**0.002***
MARS (Mean ± SD)	7.43 ± 4.48	10.35 ± 3.90	**0.032***
IKDC% (Median ± IQR)	86.2 (10.3)	99.5 (2.9)	**<0.001***
Quadriceps strength SI% (Median ± IQR)	91 (12)	93 (11.5)	0.39
ACL-RSI (Mean ± SD)	69.62 ± 29.90	NA	
TSK-11 (Mean ± SD)	17.52 ± 4.99	NA	
Time since surgery (month) (Median ± IQR)	12.12 (5.02)	NA	

Hamstring autograft, n (%)(Mean ± SD)	19 (90.48)	NA
Quadriceps autograft, n (%) (Mean ± SD)	2 (9.52)	NA
Co-injuries, n (%) (Mean ± SD)	12 (57.14)	NA
Meniscus, n (%) (Mean ± SD)	10 (47.62)	NA
Meniscus & chondral, n (%) (Mean ± SD)	1 (4.76)	NA
Meniscus & MCL sprain, n (%) (Mean ± SD)	1 (4.76)	NA

SD: Standard deviation, IQR interquartile range, MARS: Marx Activity Rating Scale, IKDC: International Knee Documentation Committee, SI: symmetry index, ACLR-RSI: Anterior Cruciate Ligament-Return to Sport after Injury, TSK: Tempa Scale of Kinesiophobia, MCL: Medial Collateral Ligament.

Time to stabilization

When comparing the ACLR group to the Healthy Control group, the RVTTS-C and VTTS-op were significantly longer in the ACLR group, with p-values of 0.03 and 0.02, respectively. Effect sizes were moderate for RVTTS-C ($\delta = 0.4$, 95% CI [0.04, 0.67]) and large for VTTS-op ($\delta = 0.96$, 95% CI [0.84, 0.99]). No other significant differences were found between the groups (see Table 5.3).

The Kruskal Wallis test revealed significant differences between the subgroups (female ACLR, female Healthy Control, male ACLR and male Healthy Control) for the combined vertical time to stabilization VTTS-C ($p = 0.01$), RVTTS-C ($p = 0.02$), and VTTS-op ($p < 0.01$). (see Table 5.4) Subsequent pairwise Dunn's tests, with Bonferroni adjustment, demonstrated that males in the ACLR group exhibited significantly higher VTTS-C compared to females in the ACLR group ($p = 0.03$, $\delta = -0.69$; 95% CI [-0.89, -0.26]) and females in the control group ($p < 0.01$, $\delta = -0.74$; 95% CI [-0.93, -0.25]) (see Figure 5.1). Similarly, males with ACLR displayed elevated RVTTS-C compared to healthy females ($p = 0.01$, $\delta = -0.73$; 95% CI [-0.91, -0.31]) (see Figure 5.2). Pairwise analysis on VTTS-op showed that males with ACLR exhibited significantly higher values than females with ACLR ($p < 0.01$, $\delta = -0.82$; 95% CI [-0.96, -0.39]) and healthy females ($p < 0.01$, $\delta = -0.92$; 95% CI [-0.98, -0.64]), as well as compared to healthy males ($p = 0.03$, $\delta = -0.71$; 95% CI [-0.90, -0.28]) (see Figure 5.3). No other pairwise comparisons reached statistical significance.

Table 5.11 - Comparisons of TTS variables between ACLR and Healthy Control groups

OUTCOMES	ACLR (n = 21)	Healthy Control (n = 20)	P-value	ES (95% CI)
APTTS-C	2.01 (0.28)	2.04 (0.23)	0.80	
MLTTS-C	2.29 (0.27)	2.16 (0.42)	0.38	
VTTS-C	1.61 (0.16)	1.57 (0.1)	0.07	
RVTTS-C	2.31 (1.02)	2.03 (0.26)	**0.03***	**0.40 (0.04 - 0.67)**
APTTS-op	1.97 (0.29)	1.87 (0.27)	0.28	
MLTTS-op	1.93 (0.39)	1.83 (0.47)	0.30	
VTTS-op	1.76 (0.27)	1.6 (0.19)	**0.02***	**0.96 (0.84 - 0.99)**
RVTTS-op	2.87 (0.35)	2.87 (0.35)	1.00	
APTTS-nop	2.12 (0.24)	2.19 (0.46)	0.56	
MLTTS-nop	1.95 (0.4)	1.84 (0.4)	0.16	
VTTS-nop	1.66 (0.18)	1.63 (0.16)	0.53	
RVTTS-nop	2.97 (0.47)	2.94 (0.56)	0.47	
APTTS-Asy	-0.01 (0.20)	0.01 (0.27)	0.71	
MLTTS-Asy	0.06 (0.23)	0.02 (0.19)	0.80	
VTTS-Asy	0.03 (0.27)	0.07 (0.20)	0.90	
RVTTS-Asy	0.02 (0.35)	0.01 (0.18)	0.72	

Data reported in median and inter-quartile range (IQR). ES: effect size. APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APTTS-Asy: asymmetry in anterior-posterior time to stabilization between the two legs. MLTTS-Asy: asymmetry in medial-lateral time to stabilization between the two legs. VTTS-Asy: asymmetry in vertical time to stabilization between the two legs. RVTTS-Asy: asymmetry in resultant vector time to stabilization between the two legs. Bonferroni adjustment was not made.[23, 27]

Table 5.12 – Sex differences within and between ACLR and Healthy Control groups - TTS outcomes

OUTCOMES	ACLR		Healthy Controls		df	X^2	p-value
	Female (n=10)	Male (n=11)	Female (n=10)	Male (n=10)			
APTTS-C	1.93 (0.13)	2.12 (0.40)	2.04 (0.27)	2.05 (0.23)	3	3.78	0.29
MLTTS-C	2.33 (0.27)	2.27 (0.35)	2.35 (0.66)	2.09 (0.31)	3	4.72	0.19
VTTS-C	1.56 (0.12)	1.71 (0.15)	1.53 (0.10)	1.56 (0.14)	3	12.76	**0.01***
RVTTS-C	2.09 (0.91)	3.03 (1.03)	2.04 (0.52)	2.02 (0.27)	3	9.87	**0.02***
APTTS-op	2.13 (0.42)	1.97 (0.70)	2.15 (0.21)	2.22 (0.40)	3	3.05	0.38
MLTTS-op	1.86 (0.31)	2.12 (0.47)	1.83 (0.45)	1.81 (0.60)	3	3.07	0.38
VTTS-op	1.59 (0.13)	1.87 (0.26)	1.58 (0.13)	1.68 (0.25)	3	16.94	**<0.01***
RVTTS-op	2.76 (0.33)	2.87 (0.73)	2.85 (0.23)	2.87 (0.51)	3	0.01	1.00
APTTS-nop	2.02 (0.52)	2.19 (0.16)	2.18 (0.28)	2.36 (0.61)	3	1.20	0.75
MLTTS-nop	1.80 (0.55)	2.03 (0.38)	1.86 (0.24)	1.80 (0.62)	3	3.94	0.27
VTTS-nop	1.59 (0.15)	1.72 (0.11)	1.59 (0.11)	1.66 (0.15)	3	5.99	0.11
RVTTS-nop	2.93 (0.37)	2.99 (0.45)	2.92 (0.21)	2.98 (0.85)	3	1.87	0.60
APTTS-Asy	0.03 (0.19)	-0.01 (0.44)	0.01 (0.12)	0.01 (0.44)	3	0.62	0.89
MLTTS-Asy	0.08 (0.23)	0.05 (0.27)	0.06 (0.26)	-0.01 (0.13)	3	0.43	0.93
VTTS-Asy	0.03 (0.16)	0.05 (0.40)	0.06 (0.18)	0.07 (0.23)	3	0.08	0.99
RVTTS-Asy	0.05 (0.37)	-0.07 (0.53)	0.01 (0.10)	0.01 (0.37)	3	0.79	0.89

Data reported in median and inter-quartile range (IQR). APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APTTS-Asy: asymmetry in anterior-posterior time to stabilization between the two legs. MLTTS-Asy: asymmetry in medial-lateral time to stabilization between the two legs. VTTS-Asy: asymmetry in vertical time to stabilization between the two legs. RVTTS-Asy: asymmetry in resultant vector time to stabilization between the two legs. Bonferroni adjustment was not made.[23, 27]

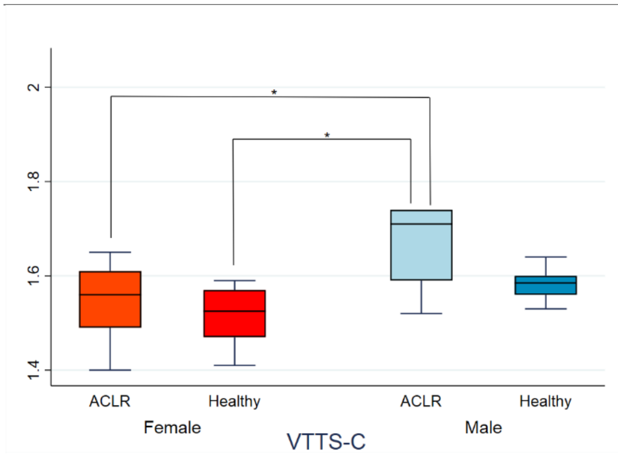

Figure 5.10 Pair-wise comparison results for VTTS-C in seconds

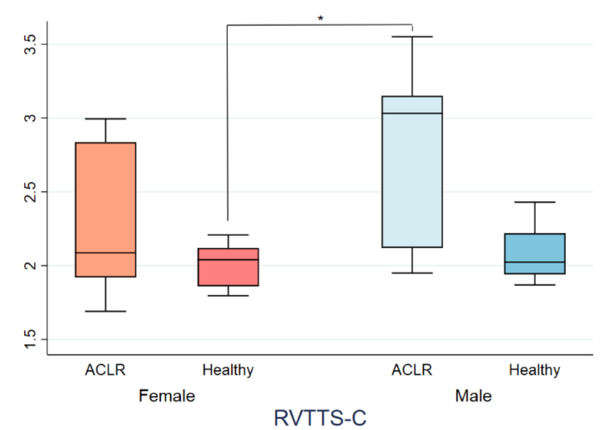

Figure 5.11 Pair-wise comparison results for RVTTS-C in seconds

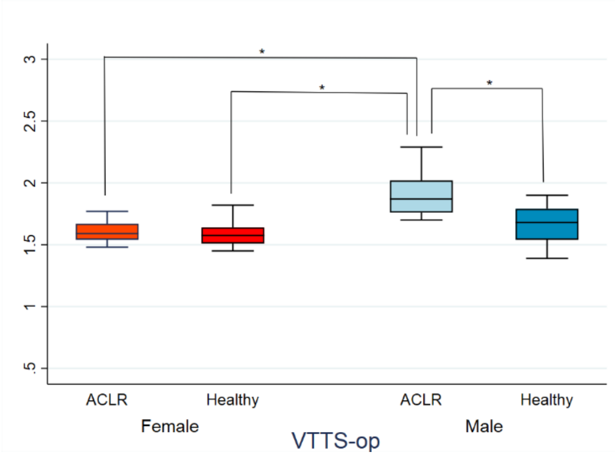

Figure 5.12 Pair-wise comparison results for VTTS-op in seconds

Postural stability indices

No differences were found between the ACLR and control groups in any of the PSI variables. (see Appendix 5.3 - *Table 1*). However, when examining sex and ACLR status, we identified a significant difference among the four subgroups for the VSI-nop with p=0.05. (see Appendix 5.3 - *Table 2*) Pair-wise analysis revealed that female participants with ACLR demonstrated higher VSI-nop values when compared to Healthy Control males only (p = 0.04, δ = -0.63; 95% CI [-0.88, -0.11]). (see Figure 5.4) No interaction between sex and other PSI variables were identified.

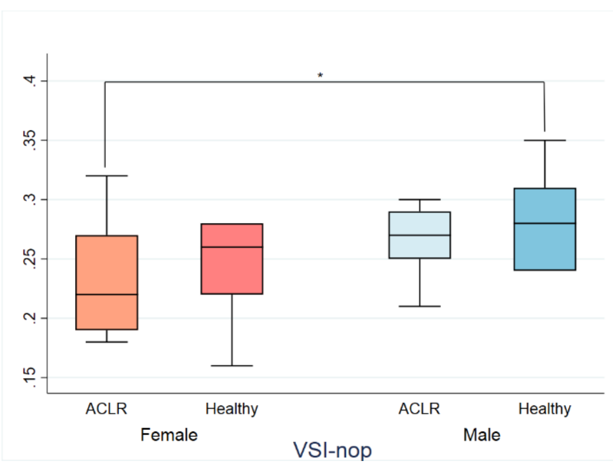

Figure 5.13 Pair-wise comparison results for the VSI-nop

DISCUSSION

Our study evaluated the differences in TTS and PSIs outcomes between individuals post-ACLR and Healthy Controls, as well as exploring sex differences. We examined our participants' dynamic postural stability after double-leg CMJ landing which allowed us to better capture the complex biomechanical and neuromuscular strategies individuals follow after ACLR.[4] Our results demonstrated that individuals with ACLR took a longer time to stabilize as indicated by the significantly higher RVTTS-C and VTTS-op values when compared to Healthy Controls. The findings also showed significant differences between sex and the ACLR status in VTTS-C, RVTTS-C, VTTS-op and VSI-nop. Specifically, males post-ACLR demonstrated higher values in VTTS-C and VTTS-op when compared to females with ACLR, and higher VTTS-op compared to healthy males and healthy females.

Similar to our findings, previous studies demonstrated higher TTS outcomes among individuals post-ACLR. [5, 26, 39]. Patterson and Delahunt (2013) compared APTTS, MLTTS and RVTTS between female participants with and without ACLR while performing single-leg forward landing and single-leg diagonal landing. They reported higher values in all parameters among the ACLR group with diagonal landing but not with forward landing.[26] Webster et al (2010) reported an increased RVTTS of 0.11 seconds among elite female athlete with ACLR when compared to a matched control group while performing a single-leg drop jump.[39] However, more recent studies reported contradictory findings. Aghdam et al (2024) studied VTTS in a group of males (15 with ACLR, and 15 control) while performing single-leg drop jump landing, and found no differences between the two groups. However, all the ACLR participants in that study had already returned to sports and were at least two years post-surgery, so it is possible that our results may only be applicable to the recovery period. Similarly, Chaput et al (2022) reported no difference in the RVTTS between the ACLR group (n=16, female=10) and the control group (n=15, female=9) when they performed forward jump landing on a single-leg.[3] The conflicting results in the previous studies could be due to the timing of the jumps relative to their surgery, heterogeneity in jump types, population characteristics, TTS outcomes being studied as well as the methods of calculations.[11] Our study found no differences in the RVTTS-op and the RVTTS-nop between the ACLR and the corresponding limbs in the Healthy Control group. However, the RVTTS-C was significantly higher in the ACLR group ($p=0.03$) with a moderate effect size $\delta=0.40$, 95% CI (0.04, 0.67). This finding suggest that the RVTTS-C is more sensitive in detecting between-group differences and highlights the complexity of postural stability, particularly after double-leg CMJ.

Furthermore, our study identified significant differences in sex and ACLR status in specific TTS outcomes: VTTS-C, RVTTS-C and VTTS-op. No previous studies have examined the impact of sex and ACLR status on postural stability. However, given that secondary ACL injuries are more common in females [20–22] and that deficits in postural stability, measured on a balance platform, can predict a secondary ACL injury,[25] one would expect higher TTS values among females. Contrary to these expectations, our findings suggest that males post-ACLR exhibited higher TTS values across various measures compared to females in both the ACLR and Healthy Control groups. This challenges the notion that reduced postural stability is a risk factor for secondary ACL injuries and highlights postural stability as a complex phenomenon that requires further sex-specific investigations, particularly in the ACLR population.

Interestingly, no significant differences were observed between the ACLR and Healthy Control groups across PSI variables. Our findings agree with previous literature studying PSI in the ACLR population. Robey et al (2021) reported no significant differences in DPSI and no association between sex and ACLR status during a jump landing task. Similarly, Head et al (2019) compared DPSI between 15 individuals with ACLR and 15 controls and reported no differences while performing forward jump-landing, lateral jump-landing and diagonal jump-landing. Our study identified a significant difference for the VSI-nop between sex and ACLR status with the pairwise analysis demonstrating that Heathy Control males had a significantly higher VSI-nop compared females with ACLR.

This study is not without limitations. The cross-sectional study design prevents causal inferences. Our first objective was to comprehensively explore differences between people with and without ACLR comparing a total of 32 parameters. We didn't employ Bonferroni adjustment for those comparison, which may have increased the risk of type 1 error. However, we did imbed the Bonferroni adjustment for all pairwise comparisons. Furthermore, we did not control for other covariates that could have influenced our results, such as concomitant meniscus injuries or graft type, due to the small sample size.

With the observed sex differences in TTS outcomes, further research is needed to elucidate the underlying mechanisms contributing to differences between males and females. Longitudinal studies examining the changes of postural stability post-ACLR compared to Healthy Controls could provide valuable insights into their impact on long-term functional outcomes. Additionally, exploring the role of psychological factors, such as fear of re-injury, could further refine our understanding of recovery and return-to-sport decisions.

CONCLUSION

Our study underscores significant differences in TTS outcomes between individuals post-ACLR and Healthy Controls, with notable differences between sex and ACLR status. Despite no significant differences in postural stability indices (PSIs) between ACLR and control groups, our study highlights the complexity of postural stability following ACLR and suggests further investigation into sex-specific differences in this population. Future research should focus on exploring the underlying mechanisms contributing to these sex-differences to inform tailored rehabilitation strategies for optimal recovery post-ACLR.

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CHAPTER 6: DUAL-TASK POSTURAL STABILITY: DO INDIVIDUALS WITH AND WITHOUT ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION PERFORM DIFFERENTLY UNDER COGNITIVE LOADING?

This chapter has been formatted for submission to Clinical Biomechanics:

Labban W, Sommerfeldt M, Westover L, Forero JM, Nathanail S, Beaupre LA: Dual-task Postural Stability: Do Individuals with and without ACLR Perform Differently under Cognitive Loading?

ABSTRACT

Objective: To examine differences in postural stability immediately after a double-leg countermovement jump (CMJ) landing between single- and dual-task conditions within groups of males and females with and without anterior cruciate ligament reconstruction (ACLR). Additionally, to compare the dual-task effect on postural stability immediately after a double-leg CMJ landing between the ACLR and the Healthy Control groups.

Design: Cross-sectional

Setting: Laboratory

Participants: Twenty-one participants (10 females) who were 9-24 months post-ACLR, and 20 Healthy Controls (10 females) were instructed to perform two sets of five double-leg CMJ on force plates. They were required to land and maintain the landing position for 10 seconds. In the second set, participants were additionally asked to answer a Stroop test as they simultaneously initiated the jump, landed, and maintained the landing position for 10 seconds.

Main outcome measures: Time to stabilization (TTS) and postural stability indices (PSI) variables were calculated after landing and compared between groups.

Results: Both groups showed longer resultant vector time to stabilization-combined (RVTTS-C) under Stroop conditions. In the ACLR group, RVTTS-C was 0.61±0.14 seconds longer under the Stroop condition compared to the no-Stroop condition ($p<0.01$). Among Healthy Controls, RVTTS-C was 0.98±0.12 seconds longer under the Stroop condition compared to the no-Stroop condition ($p<0.01$). Significant increases in PSI variables between conditions were observed in the ACLR group in medial-lateral stability index-combined (MLSI-C) (0.05±0.02, $p=0.01$) and dynamic postural stability index-combined (DPSI-C) (0.06±0.02, $p=0.03$) under Stroop conditions. Among Healthy Controls, significant increases were found in anterior posterior stability index-combined (APSI-C) (0.05±0.01, $p=0.02$), MLSI-C (0.07±0.01, $p<0.01$), DPSI-C (0.08±0.01, $p<0.01$), and matched medial lateral stability index to operated leg (MLSI-op) (0.08±0.03, $p=0.02$) under Stroop conditions. When comparing the Stroop effect, RVTTS-C was the only higher outcome among Healthy Controls by 0.37±0.76 seconds ($p=0.03$); no other variables were significantly different.

Conclusion: Our study highlights the impact of dual-task conditions on postural stability. The findings emphasize reduced stability under cognitive load, especially in those with better baseline stability, and suggest the need for further investigation into compensatory mechanisms. Future longitudinal studies with detailed biomechanical analyses are needed to develop tailored rehabilitation/training protocols and potentially reduce the risk of primary and secondary ACL injuries.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries frequently occur in sports [7] and account for 50% or more of all knee injuries.[7, 28] Most ACL injuries occur when the limb decelerates during activities of landing or change of direction such as cutting and pivoting.[14] Due to the important role of the ACL in the knee joint stabilization,[21] anterior cruciate ligament reconstruction (ACLR) is frequently indicated to restore knee joint stability. Yet, individuals following ACLR often exhibit changes in lower extremity movement variability,[27] and deficits in joints kinesthesia, affecting their postural stability.[12] It is important to address those deficits when planning rehabilitation strategies following ACLR to enhance functional outcomes.

Postural stability, the ability to maintain posture against gravity in response to internal and/or external perturbation,[20] plays a vital role in movement control and injury prevention. After ACLR, individuals encounter challenges in achieving optimal postural stability, which may impact their functional performance and elevate the risk of having secondary injuries.[9] In a clinical setting, postural stability is usually tested statically where patients are instructed to stand on a single-leg while maintaining their balance on a stationary platform.[17] However, static postural stability measures have been characterized as non-functional, insensitive, and lacking correlation with dynamic values.[31] Therefore, measuring more difficult and dynamic aspects of postural control that resemble sports-related activities could offer valuable information about athletes' functional abilities both with and without ACLR.[1, 11]

Athletes frequently multitask or perform dual tasks while engaging in athletic activities to make deliberate movements, assess their surroundings, and make cognitive-motor decisions. Dual-task performance is defined as "the ability to perform two separate tasks simultaneously."[22] Despite being challenging, this ability is crucial for athletes to perform effectively. The human body can process multiple tasks with limited attentional resources, and task difficulty can affect how these attentional resources are allocated.[30] Research indicates that individuals with ACLR show slower reaction times during dynamic postural tasks, suggesting potential neuromuscular adaptations following surgery.[2] Additionally, changes in cortical connectivity have been observed in post-ACLR patients, implying alterations in the neural mechanisms associated with postural control.[19] Accordingly, the measurement of postural stability while performing dual tasks may provide critical information on neuromuscular deficits, especially in individuals with ACLR.

Several cognitive tasks have been applied under the dual-task paradigm. The Stroop test is one of the most widely used secondary cognitive tasks.[32] It is a cognitive exercise designed to assess an individual's capacity to prevent cognitive interference.[33] The primary version of the Stroop test involves a list of five colors' names printed in various ink colors. The task requires participants to name the color of the ink rather than reading the word. The mismatch between the color of the ink and the word, causes a delay in reaction time known as the Stroop effect.[33] It has proven high internal consistency ($\alpha=0.88$) and reliability ($r=0.87$).[32]

Several studies have examined standing postural stability while performing a cognitive task, but very few have reported on dynamic postural stability under dual-task conditions,[25] particularly during dynamic activities such as jumping-landing. Imai et al (2020) investigated the effect of dual tasks on landing biomechanics in healthy female athletes, revealing kinematic and kinetic changes when cognitive tasks were introduced.[13] However, as many ACL injuries are non-contact injuries, and occur with dynamic activities, it is important to study the dynamic postural stability while performing those activities to better understand the potential neuromuscular deficit and see how they compare to healthy athletes.

Assessing postural stability after performing a jump task, such as the CMJ, provides valuable insights into lower limb function and dynamic stability. While previous studies have predominantly focused on single-leg CMJ tasks, examining postural stability immediately after double-leg CMJ landing offers a comprehensive evaluation of bilateral weight-bearing capabilities and control mechanisms of both lower limbs.[3] Various methods exist to calculate and report parameters to estimate postural stability, each with its own advantages and limitations.[36] Time to stabilization (TTS) and the postural stability index (PSI) are suggested metrics for evaluating postural stability.[5, 36] TTS measures the duration required for the ground reaction force (GRF) signal to stabilize, in several directions, following a landing on a force plate,[5] while PSI quantifies deviations around a central point to assess fluctuations in stability across various directions.[36]

Assessing postural stability after a double-leg CMJ landing mimics real-life movements and provides insights into balance and control in dynamic scenarios. The addition of a cognitive task, like the Stroop task, during the CMJ, adds a cognitive challenge reflecting real-world multitasking demands for maintaining balance and performing tasks. Therefore, this study aimed to understand the differences in postural stability immediately after a double-leg CMJ landing between the single and dual-task conditions within groups of individuals with and without ACLR. Additionally, it compared the dual-task effect on postural stability immediately after a double-leg CMJ landing between the ACLR and the Healthy Control groups.

METHODS

Study design

This cross-sectional study was conducted and reported according to the Strengthening the Reporting of Observational studies in Epidemiology (STROBE) guidelines[8] and the considerations for methodological reporting suggested in our previous work.[17] The study protocol received approval by the Research Ethics Board at the University of Alberta (Pro00111475). (see Appendix B)

Setting

Testing procedures took place at the Human Movement Laboratory at the University of Alberta in Edmonton, AB, Canada. We recruited a convenience sample of participants with and without ACLR through study posters displayed at the University of Alberta and local community sports centers. Additionally, a digital version of the poster was emailed to all students in the Faculty of Rehabilitation Medicine and the Department of Mechanical Engineering at the University of Alberta. Most participants with ACLR were recruited from the Glen Sather Sport Medicine Clinic, University of Alberta. Furthermore, we included data from 10 participants who were 9-12 months post-ACLR participating in an ongoing cohort study that employed the same testing protocol, equipment and laboratory setting.

Inclusion and Exclusion Criteria

Participants in the ACLR group were recruited if they had undergone primary unilateral ACLR within the past 9-24 months, had no significant concomitant ligament injuries, no bilateral lower limb pathologies or recent orthopedic surgeries, and reported regular participation in sports/activities involving jumping, cutting, pivoting, and lateral movements before their ACL injury. Additionally, they were either planning to return to these activities or had already done so and had begun dynamic activities during their ACL rehabilitation. Participants in the Healthy Control group were recruited if they were engaged in sports/activities involving jumping, cutting, pivoting, and lateral movements. Both groups included individuals aged 18 to 35 years old who had no medical conditions affecting participation.

Participants were excluded if they had back pain, a recent concussion, a balance disorder, or color blindness, scored less than 80% on the knee extensors isokinetic strength symmetry index, or were found unfit for jumping/landing activities based on knee clinical examinations conducted by qualified research staff. All participants provided informed consent, approved by the Research Ethics Board. (Appendix C)

Instrumentation:

Ground reaction forces (GRF) data were collected separately for each leg by means of two 46.5 centimeter (cm) wide × 51 cm long force plates (model AMTI OR6-7-1, AMTI, Watertown, MA, USA) located side-by-side mounted in the center of a custom-built 122 cm wide x 173 cm long platform. A 19-inch monitor (Dell 1907FP) connected to a Raspberry Pi Model B+ running a custom-written program in Python (Van Rossum & Drake, 2009) was located at 110 cm above ground, 125 cm in front of the force plates and tilted 15 degrees to provide the participant, when needed, with visual cues for the Stroop test (cognitive task). Data for the GRF (sampled at 1000 Hz) and the visual cues (sampled at 60 Hz) were synchronized, recorded, and processed using the Motion Monitor xGen v3.80.3.0 system (Innovative Sports Training, Inc, Chicago, IL, USA) to output the vertical (GRFv), medial-lateral (GRFml) and anterior-posterior (GRFap) force component traces three seconds before the jump and 15 seconds after the landing. The knee isokinetic dynamometry testing was done using the PrimusRS system (BTE PrimusRS (PR30); BTE Technologies, Hanover, MD, USA). Overall body composition was estimated using the bioelectrical impedance analysis (BIA) device (Tanita MC-780U).

Procedure:

Participants underwent a standardized laboratory procedure to assess various aspects of knee function and postural stability. Anthropometric measurements, such as height, weight, and bilateral thigh circumference, were recorded. The warm-up routine included stationary cycling, dynamic lower body mobility exercises, stretching, and submaximal body-weight exercises. Following the warm-up, participants performed knee isokinetic dynamometry, which involved familiarization trials and five maximal voluntary contractions of concentric knee flexion and extension for each limb. The knee extensors isokinetic strength symmetry index was calculated using the following formula:

$$\frac{\begin{array}{c}\mathit{The\ average\ of\ }5\ \mathit{maximal\ contractions\ of\ knee\ extensors\ in\ the\ involved\ }(ACLR)\\ \mathit{or\ non-dominant\ }(\mathit{Healthy\ Control})\ \mathit{limb}\end{array}}{\mathit{The\ average\ of\ }5\ \mathit{maximal\ contractions\ of\ knee\ extensors\ in\ the\ contralateral\ limb}} \times 100$$

Participants who scored 80% or higher on the isokinetic strength symmetry index proceeded to the jump testing phase. Those who scored below 80% were given the opportunity to retest their strength stability indices within one month to qualify for participation in the evaluation. If they were unsuccessful on the second attempt, they were excluded from the study.

Jump Testing:

Participants were asked to perform a barefoot jump-specific warm up protocol including 10 CMJs, 10-15 calf hops, and 10 CMJ rebound jumps. Participants were then asked to stand barefoot with each foot on a force plate. They were asked to stand tall placing hands on hips maintaining this position over the respective force plate motionless for at least three seconds before jumping.

Single task

At the time of hearing the word “jump“, participants rapidly performed a CMJ, which involves downward motion/squat to approximately 90 degrees of knee flexion, followed by rapid triple extension of the ankles, knees, and hips, jumping as high as possible, while maintaining hands on hips and landing with each foot completely on a the respective force plate. Participants were required to maintain their landing position, without any movement, for a duration of ten seconds after landing.

Dual task

Participants were instructed to perform maximum effort CMJs, similar to those they had already completed, with the addition of the Stroop task. The Stroop task involved a computer monitor displaying words representing colors, with the words themselves shown in different colors. Participants were instructed to say the color of the word aloud while jumping, rather than reading the word as displayed on the screen. The words changed every two seconds, and participants had to say the word colors while maintaining their landing position over a ten-second period.

They began the CMJ when the first word appeared on the screen and continued to answer the Stroop task (with different words appearing on the screen) while holding the landing position for 10 seconds. Participants were advised to jump as high as they could while ensuring a soft landing by bending their knees into a squat position upon landing. They were instructed to keep their knee bend aligned with their foot position, avoiding inward collapse of the knees. Upon landing, participants were to continue saying the colors out loud while maintaining their landing position without moving for 10 seconds.

Participants were instructed to perform five CMJ trials under single-task conditions and five CMJ trials under dual-task conditions, with a break of minimum five seconds between each jump. Participants would repeat trials if jumps failed to meet the established criteria, such as any movement occurring before 10 seconds post-landing, incorrect execution of the jump, or landing with part of a foot off the force plates. To count for learning effect and fatigue, data from the first and last trials were excluded from data analysis.[35]

Outcomes:

We assessed time to stabilization (TTS) and postural stability indices (PSIs) using four distinct measures for each outcome. For TTS, we evaluated anterior-posterior time to stabilization (APTTS), medial-lateral time to stabilization (MLTTS), vertical time to stabilization (VTTS), and resultant vector time to stabilization (RVTTS). The RVTTS has been recommended to provide postural stability assessment of both horizontal coordinate directions.[10] Similarly, for PSIs, we examined anterior-posterior stability index (APSI), medial-lateral stability index (MLSI), vertical stability index (VSI), and dynamic postural stability index (DPSI).

We examined the combined TTS (TTS-C) and combined PSIs (PSI-C) obtained from both force plates (i.e., both limbs) and compared them between the ACLR and control groups. TTS-C and PSI-C were calculated from the combined forces (FC) from the forces in the right (FR) and left (FL) force plates using the following formula: FC= FR + FL. Also, we compared these variables from the operated (op) and non-operated (nop) legs in the ACLR group to the corresponding (left or right) sides in the control group. In the ACLR group, there were 5 males and 5 females with right ACLR and 6 males and 5 females with left ACLR. To ensure balanced comparisons, Healthy Control participants' data were randomly allocated to match the sex and side (operative or non-operative) of the ACLR participants. This involved comparing the right operative legs of ACLR participants to the right legs of sex-matched Healthy Controls, and the left operative legs of ACLR participants to the left legs of sex-matched Healthy Controls. The same approach was applied to the non-operative sides, where the non-operative legs of ACLR participants were compared to the corresponding legs of sex-matched Healthy Controls. The full list of TTS and PSI outcomes and nomenclature are listed in Table 6.1

Table 6.13 List of TTS and PSI outcomes

Time to stabilization		**Postural stability indices**	
Abbreviations	**Outcomes**	**Abbreviations**	**Outcomes**
APTTS-C	Anterior posterior time to stabilization-combined	**APSI-C**	Anterior posterior postural stability index - combined
MLTTS-C	Medial lateral time to stabilization-combined	**MLSI-C**	Medial lateral postural stability index - combined
VTTS-C	Vertical time to stabilization-combined	**VSI-C**	Vertical postural stability index - combined
RVTTS-C	Resultant vector time to stabilization-combined	**DPSI-C**	Dynamic postural stability index - combined
APTTS-op	Anterior posterior time to stabilization in operated leg (or matched leg in Healthy Control)	**APSI-op**	Anterior posterior postural stability index in operated leg (or matched leg in Healthy Control)

MLTTS-op	Medial lateral time to stabilization in operated leg (or matched leg in Healthy Control)	**MLSI-op**	Medial lateral postural stability index in operated leg (or matched leg in Healthy Control)
VTTS-op	Vertical time to stabilization in operated leg (or matched leg in Healthy Control)	**VSI-op**	Vertical postural stability index in operated leg (or matched leg in Healthy Control)
RVTTS-op	Resultant vector time to stabilization in operated leg (or matched leg in Healthy Control)	**DPSI-op**	Dynamic postural stability index in operated leg (or matched leg in Healthy Control)
APTTS-nop	Anterior posterior time to stabilization in non-operated leg (or matched leg in Healthy Control)	**APSI-nop**	Anterior posterior postural stability index in non-operated leg (or matched leg in Healthy Control)
MLTTS-nop	Medial lateral time to stabilization in non-operated leg (or matched leg in Healthy Control)	**MLSI-nop**	Medial lateral postural stability index in non-operated leg (or matched leg in Healthy Control)
VTTS-nop	Vertical time to stabilization in non-operated leg (or matched leg in Healthy Control)	**VSI-nop**	Vertical postural stability index in non-operated leg (or matched leg in Healthy Control)
RVTTS-nop	Resultant vector time to stabilization in non-operated leg (or matched leg in Healthy Control)	**DPSI-nop**	Dynamic postural stability index in non-operated leg (or matched leg in Healthy Control)

Data processing

A moving average filter with a 100-millisecond window was applied to the GRF traces to reduce random noise. A subset of data, starting from the time of landing and lasting 10 seconds, was then trimmed and extracted for calculations. Time of landing was determined from the filtered traces as the time after jumping when vertical GRF >10N, and body weight was estimated as the median value over the last 2 seconds of this subset. GRF data from each force plate was used to analyze the stability performance for each side (TTS-left, TTS-right, PSIs-left, PSIs-right), while combined data from both force plates was used to analyze the participant's overall stability (TTS-C, DPSI-C). Data from all the trials was processed offline using a custom-written program in R (R Core Team, 2023)[34]. The program calculated TTS variables [anterior-posterior TTS (APTTS), medio-lateral TTS (MLTTS), vertical TTS (VTTS)] and PSIs variables [anterior-posterior PSI (APSI), medio-lateral PSI (MLSI), vertical PSI (VSI), and dynamic PSI (DPSI)] based on the methods described by Colby et al. 1999[5] and Wikstrom et al., 2005[36] respectively. The resultant vector TTS (RVTTS) was calculated using the following formula $RVTTS = \sqrt{(APTTS)^2 + (MLTTS)^2}$ [29].

Statistical analysis

We estimated the power based on data from previous literature looking at TTS after forward jump landing in females.[39] Using the Satterthwaite's t-test assuming unequal variances, 20 participants per group would acquire a power of 82%. All outcome variables were assessed for normality and homogeneity of variances using The Shapiro-Wilk's test and the Levene's tests, respectively.

As most of the TTS and PSI variables were normally distributed, we applied parametric statistical tests for all TTS and PSI comparisons regardless of their distribution to provide homogeneity of data reporting for those variables; sensitivity analyses were performed to ensure that this decision did not significantly impact reported results (see Appendix 6.1-6.3). Therefore, we reported only the means and the standard deviations (SD) for all the TTS and PSI outcomes. For participants' characteristics, we applied the parametric and non-parametric tests as appropriate based on data distribution. Significance was set at $p < 0.05$.

We used paired t-tests to examine the within group differences in postural stability between the single and dual-task conditions in individuals with and without ACLR. Additionally, we used the independent t-test to compare the dual-task effect between the ACLR and the Healthy Control groups. When significant differences were identified, we estimated effect sizes (ES) using Cohen's *d*, interpreted as trivial ($d < 0.2$), small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$), and large ($d \geq 0.8$).[4, 18] Statistical analysis were performed using Stata (StataCorp LLC, version 15.1, USA).

RESULTS

A total of 43 participants were recruited, comprising 23 individuals with ACLR and 20 Healthy Controls. Among the ACLR group, two participants did not meet the criterion of 80% on the quadriceps strength symmetry index at either their initial or secondary assessment. Consequently, our final dataset comprised 41 participants, including 20 healthy individuals (10 females and 10 males) and 21 individuals in the ACLR group (10 females and 11 males). The participants' characteristics are detailed in Table 6.2. Individuals in both groups exhibited similarities across numerous characteristics; however, Healthy Controls consistently outperformed individuals with ACLR across various functional measures such as Tegner (p=0.002), the Marx Activity Rating Scale (MARS) (p = 0.03), and the International Knee Documentation Committee (IKDC) (p < 0.001).

Table 6.14 Participant characteristics

Participants' Characteristics	ACLR (n=21)	Healthy Control (n=20)	P-value
Sex (Mean ± SD)	F=10 / M=11	F=10 / M=10	
Age (year) (Median ± IQR)	22.17(8.5)	22.63 (3.54)	0.97
Height (cm) (Mean ± SD)	170.18 ± 9.15	168.85 ± 11.84	0.69
Weight (kg) (Mean ± SD)	75.32 ± 13.07	70.38 ± 11.70	0.21
Total muscle mass (kg) (Median ± IQR)	53.8 (16.9)	48.7 (19.85)	0.74
Trunk muscle mass (kg) (Median ± IQR)	29.3 (5.4)	28.4 (8.05)	0.97
Right leg muscle mass (kg)(Median ± IQR)	9.5 (3.6)	9.0 (4.2)	0.91
Left leg muscle mass (kg) (Median ± IQR)	9.3 (3.7)	8.9 (4.15)	0.93
Total fat mass (kg) (Mean ± SD)	17.96 ± 6.62	14.86 ± 4.39	0.09
Total fat % (Mean ± SD)	23.58 ± 6.68	19.59 ± 6.11	0.053
Trunk fat % (Mean ± SD)	22.06 ± 6.53	17.79 ± 5.41	**0.03***
Right leg fat % (Mean ± SD)	25.43 ± 10.11	22.86 ± 10.37	0.43
Left leg fat % (Mean ± SD)	25.62 ± 9.90	23.28 ± 10.32	0.49
Total body water % (Median ± IQR)	55.4 (7.2)	56.85 (8.35)	0.14
Tegner (Median ± IQR)	5 (1)	7 (3)	**0.002***
MARS (Mean ± SD)	7.43 ± 4.48	10.35 ± 3.90	**0.032***
IKDC% (Median ± IQR)	86.2 (10.3)	99.5 (2.9)	**<0.001***
Quadriceps strength SI% (Median ± IQR)	91 (12)	93 (11.5)	0.39
ACL-RSI (Mean ± SD)	69.62 ± 29.90	NA	
TSK-11 (Mean ± SD)	17.52 ± 4.99	NA	
Time since surgery (month) (Median ± IQR)	12.12 (5.02)	NA	
Hamstring autograft, n (%)(Mean ± SD)	19 (90.48)	NA	
Quadriceps autograft, n (%) (Mean ± SD)	2 (9.52)	NA	
Co-injuries, n (%) (Mean ± SD)	12 (57.14)	NA	
Meniscus, n (%) (Mean ± SD)	10 (47.62)	NA	
Meniscus & chondral, n (%) (Mean ± SD)	1 (4.76)	NA	
Meniscus & MCL sprain, n (%) (Mean ± SD)	1 (4.76)	NA	

SD: Standard deviation, IQR: Interquartile range, MARS: Marx Activity Rating Scale, IKDC: International Knee Documentation Committee, SI: symmetry index, ACLR-RSI: Anterior Cruciate Ligament-Return to Sport after Injury, TSK: Tempa Scale of Kinesiophobia, MCL: Medial Collateral Ligament.

Within group comparisons of single versus dual task conditions revealed that only the RVTTS-C reached significance in both groups. The RVTTS-C was 0.61±0.14 seconds longer under the Stroop condition compared to the no-Stroop condition in individuals with ACLR (p<0.01) with a large ES (*d*=1.01, 95%CI [0.49, 1.54]). Among Healthy Controls, the RVTTS-C was 0.98±0.12 seconds longer under the Stroop condition compared to the no-Stroop condition (p<0.01) with a large effect size (*d*=2.16, 95%CI [1.36, 2.96]). See Table 6.3

Table 6.15- Between conditions (Stoop vs. no-Stroop) differences of TTS outcomes in ACLR and Healthy Control individuals

TTS Variables	**ACLR (n=21)**				**Healthy Control (n=20)**			
	No-Stroop	**Stroop**	**p-value**	**ES (95% CI)**	**No-Stroop**	**Stroop**	**p-value**	**ES (95% CI)**
APTTS-C	2.07±0.23	2.09±0.19	0.66		2.08±0.22	2.06±0.20	0.67	
MLTTS-C	2.30±0.17	2.34±0.27	0.51		2.29±0.39	2.33±0.39	0.71	
VTTS-C	1.64±0.16	1.69±0.27	0.26		1.56±0.10	1.58±0.12	0.67	
RVTTS-C	2.53±0.58	3.14±0.24	**<0.01***	1.01 (0.49, 1.54)	2.13±0.37	3.11±0.38	**<0.01***	2.16 (1.36, 2.96)
APTTS-op	2.19±0.40	2.11±0.32	0.33		2.21±0.25	2.21±0.25	0.85	
MLTTS-op	1.97±0.29	1.87±0.31	0.17		1.87±0.27	1.83±0.26	0.49	
VTTS-op	1.77±0.43	1.71±0.34	0.25		1.62±0.14	1.66±0.15	0.31	
RVTTS-op	2.96±0.41	2.84±0.33	0.18		2.91±0.30	2.88±0.27	0.60	
APTTS-nop	2.15±0.28	2.15±0.22	0.91		2.19±0.30	2.11±0.32	0.39	
MLTTS-nop	2.02±0.31	1.93±0.36	0.26		1.87±0.27	1.84±0.26	0.55	
VTTS-nop	1.68±0.15	1.64±0.24	0.55		1.66±0.14	1.69±0.19	0.47	
RVTTS-nop	2.97±0.29	2.90±0.30	0.38		2.89±0.36	2.80±0.36	0.38	

Data reported in means and standard deviation (SD), and effect size (ES) is reported with 95% confidence interval (CI). APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. Bonferroni adjustment was not made.[23, 26]

The results indicated several significant differences in PSI variables between the no-Stroop and Stroop conditions within both groups, but particularly in the Healthy Control group. In the ACLR group, significant differences were only observed in the MLSI-C and the DPSI-C. Specifically, the MLSI-C increased by 0.05±0.02 under the Stroop condition compared to the no-Stroop condition (p=0.01) with a moderate ES (*d*=0.62, 95%CI [0.16, 1.09]) while the DPSI-C increased by 0.06±0.02 under the Stroop condition compared to the no-Stroop condition (p=0.03) and an ES (*d*=0.51, 95%CI [0.05, 0.96]).

Among Healthy Controls, significant differences were found in the APSI-C, MLSI-C, DPSI-C, and the matched MLSI-op. APSI-C increased by 0.05±0.01 under the Stroop condition compared to the no-Stroop condition (p=0.02) and a moderate ES (*d*=0.59, 95%CI [0.12, 1.07]). MLSI-C increased by 0.07±0.01 under the Stroop condition compared to the no-Stroop condition (p<0.01) and a moderate ES (*d*=0.77, 95%CI [0.27, 1.27]). DPSI-C increased by 0.08±0.01 under the Stroop condition compared to the no-Stroop condition (p<0.01) and a large ES (*d*=0.88, 95%CI [0.36, 1.40]). Additionally, the matched MLSI-op increased by 0.08±0.03 under the Stroop condition compared to the no-Stroop condition (p=0.02) and a moderate ES (*d*=0.57, 95%CI [0.10, 1.04]). See Table 6.4

Table 6.16- Between conditions (Stoop vs. no-Stroop) differences of PSI outcomes in ACLR and Healthy Control individuals

Postural Stability Indices	**ACLR (n=21)**				**Healthy Control (n=20)**			
	No-Stroop	**Stroop**	**p-value**	**ES (95% CI)**	**No-Stroop**	**Stroop**	**p-value**	**ES (95% CI)**
APSI-C	0.69±0.19	0.71±0.23	0.43		0.71±0.16	0.76±0.15	**0.02***	0.59 (0.12, 1.07)
MLSI-C	0.60±0.18	0.65±0.20	**0.01***	0.62 (0.16, 1.09)	0.68±0.15	0.75±0.16	**<0.01***	0.77 (0.27, 1.27)
VSI-C	0.24±0.04	0.24±0.04	0.49		0.25±0.03	0.25±0.04	0.69	
DPSI-C	0.95±0.22	1.01±0.23	**0.03***	0.51 (0.05, 0.96)	1.03±0.17	1.11±0.17	**<0.01***	0.88 (0.36, 1.40)
APSI-op	0.65±0.21	0.70±0.25	0.13		0.71±0.18	0.73±0.17	0.34	
MLSI-op	0.64±0.34	0.68±0.35	0.10		0.67±0.29	0.75±0.34	**0.02***	0.57 (0.10, 1.04)
VSI-op	0.23+0.07	0.23±0.07	0.75		0.25±0.07	0.25±0.07	0.95	
DPSI-op	0.97±0.32	1.05±0.33	**0.01***	0.59 (0.12, 1.05)	1.04±0.26	1.12±0.29	**0.04***	0.49 (0.03, 0.96)
APSI-nop	0.72±0.24	0.72±0.22	0.91		0.71±0.17	0.80±0.18	**0.02***	0.60 (0.12, 1.07)
MLSI-nop	0.66±0.29	0.73±0.32	**0.02***	0.54 (0.09, 1.00)	0.74±0.30	0.80±0.37	0.11	
VSI-nop	0.26±0.05	0.26±0.05	0.80		0.26±0.04	0.27±0.06	0.69	
DPSI-nop	1.05±0.28	1.09±0.31	0.33		1.08±0.28	1.20±0.31	**0.01***	0.64 (0.16, 1.12)

Data reported in means and standard deviation (SD), and effect size (ES) is reported with 95% confidence interval (CI). APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. Bonferroni adjustment was not made.[23, 26]

When comparing the dual task effect (Stroop effect) between the ACLR and Healthy Control groups, only the RVTTS-C was significantly higher among Healthy Controls compared to those with ACLR with a mean difference of 0.37±0.76 seconds (p=0.03) and a moderate ES (*d*=0.71, 95%CI [0.07, 1.33]). No other dual-task effect TTS or PSI comparisons were significantly different between the two groups (Table 6.5).

Table 6.17- Dual-task effect

TTS Variables	ACLR (n=21)	Healthy Control (n=20)	p-value
APTTS-C	0.02±0.20	-0.02±0.25	0.55
MLTTS-C	0.04±0.27	0.03±0.37	0.94
VTTS-C	0.05±0.20	0.01±0.13	0.50
RVTTS-C	0.61±0.60	0.98±0.46	**0.03***
APTTS-op	-0.07±0.34	-0.01±0.24	0.49
MLTTS-op	-0.1±0.32	-0.04±0.26	0.52
VTTS-op	-0.06±0.22	0.04±0.17	0.13
RVTTS-op	-0.12±0.39	-0.03±0.27	0.42
APTTS-nop	-0.01±0.32	-0.09±0.44	0.52
MLTTS-nop	-0.09±0.34	-0.03±0.25	0.58
VTTS-nop	-0.04±0.28	0.03±0.19	0.36
RVTTS-nop	-0.05±0.40	-0.11±0.43	0.68
APSI-C	0.02±0.12	0.05±0.09	0.31
MLSI-C	0.05±0.08	0.07±0.09	0.46
VSI-C†	0.00±0.02	0.00±0.01	0.57
DPSI-C	0.06±0.11	0.09±0.10	0.37
APSI-op	0.05±0.16	0.02±0.11	0.48
MLSI-op†	0.04±0.10	0.08±0.14	0.40
VSI-op†	0.00±0.03	0.00±0.03	0.78
DPSI-op†	0.08±0.13	0.08±0.16	0.97
APSI-nop	0.00±0.16	0.09±0.16	0.06
MLSI-nop	0.06±0.11	0.06±0.17	0.91
VSI-nop	0.00±0.04	0.00±0.04	0.93
DPSI-nop	0.03±0.16	0.12±0.18	0.14

APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. Bonferroni adjustment was not made.[23, 26]

DISCUSSION

Our study investigated the differences in postural stability following a double-leg CMJ landing between single and dual-task conditions within groups of individuals with and without ACLR, and compared the dual-task effect on postural stability between ACLR and Healthy Control groups. Overall, postural stability was compromised under the dual-task conditions as indicated by the increase of several TTS and PSI variables. Additionally, the Stroop effect on RVTTS-C was higher among the Healthy Controls compared to those with ACLR. Our finding highlight the importance of considering cognitive loading in rehabilitation and training program to improve postural stability, which may reduce the risk of sustaining a secondary ACL injury.

Limited previous literature demonstrated that lower extremity biomechanics were altered when motor tasks were combined with cognitive tasks in healthy populations,[6] and individuals following ACLR.[25] Similarly, our findings demonstrated that postural stability indicated by RVTTS-C was significantly longer under the dual task condition relative to the single task condition in both groups. The large effect sizes indicate that the Stroop task significantly decreased postural stability compared to the no-Stroop condition. Our previous work in showed that RVTTS-C and VTTS-op could differentiate between individuals with ACLR and Healthy Controls under single task conditions.[15] Similarly, the RVTTS was also sensitive to task complexity in the current study. Accordingly, RVTTS-C should be considered in future studies when postural stability under dual-task conditions in the ACLR population to Healthy Controls.

When examining the PSI variables, our study demonstrated several differences between the single and dual-task conditions showing consistently higher values under the Stroop condition, indicating more deviations from the stable positions and poorer postural stability. Notably, there were more significant differences in PSIs among the Healthy Controls compared to those with ACLR. This finding may be related to the increased variation in postural stability performances among the ACLR group compared to the Healthy Controls, leading to larger standard deviations in the ACLR group, and therefore fewer significant findings. Moreover, our previous systematic review indicated that Healthy Controls jump significantly higher than those with ACLR.[16] While we did not measure or control for jump height in our study, it is plausible that Healthy Controls performed higher jumps (i.e. a more challenging motor task) that compromised their postural stability upon landing under dual-task condition.[30] Further research is required to understand these different findings between those with and without ACLR.

Interestingly, the dual-task effect was significantly higher among Healthy Controls as indicated by the RVTTS-C. Our previous work reported longer RVTTS-C among the ACLR group indicating poorer postural stability compared to Healthy Controls.[15] Thus, the ACLR group might start with lower postural stability following surgery, so the addition of a cognitive task may not further reduce their stability. In contrast, the Healthy Control individuals, who had better stability baseline, might have experienced a larger decline in stability when a cognitive task was introduced. Understanding these dynamics is important for designing and implementing effective rehabilitation and training programs following ACLR. The lack of differences between the two groups when looking at the other postural stability metrics may be related to the fact that all participants in the ACLR group were already between 9-24 months post ACLR with some participants having already returned to sport. In addition, the double-leg CMJ is a less challenging motor task than the single-leg CMJ or drop jump, which also could have contributed to the lack of differences seen between the two groups.

This study is not without limitations. While we applied a dual task environment, we did not test the accuracy of the responses on the Stroop task. Negahban et al (2009) postulated that people with ACL injuries or reconstruction scarify cognitive test performance to maintain postural stability.[24] Thus, it is possible that Stroop task accuracy could play a role in our reported findings. In addition, while there is no current published evidence regarding the relationship between CMJ height and postural stability, exploring the impact of jump height on reported outcomes in future studies might further explain the dynamics of the motor and cognitive tasks' influences on postural stability. We also did not control for other covariates that could have influenced our results, such as concomitant meniscus injuries or graft type, due to the small sample size. Finally, to comprehensively explore differences between the single and dual task condition, we compared several parameters of postural stability. As we did not employ Bonferroni adjustment for those comparison, we may have increased the risk of type 1 error.

Future research with larger sample sizes should employ longitudinal designs to better understand causality, and use different cognitive tasks while measuring responses to determine if people with ACLR compromise cognitive performance for stability. Additionally, investigating the effectiveness of dual-task training that can mimic real scenarios in sport may augment rehabilitation programs and assessments for return to sport. Detailed biomechanical analysis using kinetic, kinematic and electromyography measurement might also offer better understanding of factors affecting postural stability, and inform tailored rehabilitation protocols that can enhance functional outcomes for people after ACLR.

CONCLUSION:

Our study highlights the impact of dual-task conditions on postural stability in individuals with and without ACLR, with several within group differences found, but a more noticeable effect of the impact of dual task seen in Healthy Controls. Our findings emphasize the reduction of stability under cognitive load, particularly in those with better baseline stability. The observed dual-task effect suggests a need for further investigation into compensatory mechanisms and the specific challenges faced by healthy and ACLR individuals under different motor and cognitive task conditions. Future longitudinal studies that incorporate detailed biomechanical analyses are needed to develop tailored rehabilitation strategies that improve postural stability and reduce the risk of secondary ACL injuries.

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CHAPTER 7: DISCUSSION AND CONCLUSION

INTRODUCTION:

ACLR is a common procedure due to a high incidence of ACL injuries.[15] Preventing these injuries and re-injuries remains challenging due to the complex interplay of neuromuscular, biomechanical as well as psychological factors. The decision to RTS is a complex process, often relying on subjective assessments and criteria that may not fully capture a person's readiness. The use of objective measurements, particularly with force plates, has grown substantially in recent years to facilitate return to sport decisions.[10] These tools provide detailed insights into kinetic and postural stability parameters, offering a more precise evaluation of an individual's functional status. Despite these advancements, significant gaps remain in standardizing methodologies, identifying key force plate parameters, and evaluating function under conditions that mimic real life scenarios.

In this dissertation, we explored dimensions of kinetic measurement and postural stability using force plates in individuals who had undergone ACLR, comparing their results to a group of Healthy Control participants. This work includes four interconnected original papers starting with 2 reviews of the current status of force plate measurements in our population of interest, followed by evaluations of postural stability under single and dual task conditions in both participants recovering from ACLR and Healthy Controls. The overarching goal of the prospective evaluation was to build on current published evidence to determine how dynamic postural stability, a critical aspect of movement control and injury prevention[20], differs in individuals recovering from ACLR compared to Healthy Controls.

SYNOPSIS OF THE FINDINGS

Paper 1: Kinetic measurement system use in individuals following anterior cruciate ligament reconstruction: a scoping review of methodological approaches

We conducted a scoping review on the methodological approaches used in kinetic measurement systems for individuals following ACLR. The study explored various approaches and tools used to assess kinetic outcomes in individuals with ACLR, to explore the variation in approaches across studies. Including 158 original papers, the review identified that there was a substantial increase in the evaluation of the kinetic outcomes among the ACLR patient population in recent years. However, the review reported marked heterogeneity in parameters evaluated and methodological protocols across studies. Therefore, we suggested methodological considerations to enhance the reporting quality in future studies to facilitate comparisons across studies, which will help to advance the field in an efficient and effective manner. The review also explored the available evidence on the potential association between kinetic measures and patient reported outcome measures (PROMs), identifying only a small number of papers investigating this relationship. This initial review underscored a) the need for further research to understand the potential association between kinetic measures and PROMs in people following ACLR and b) enhanced our understanding of the complexity, challenges and advancements in kinetic measurements of individuals following ACLR.

Paper 2: Jumping into recovery: A systematic review and meta-analysis of discriminatory and responsive force plate parameters in individuals following anterior cruciate ligament reconstruction during countermovement and drop jumps.

Building on our initial review, the subsequent systematic review identified which kinetic parameters were most discriminative between individuals with ACLR and Healthy Controls performing CMJ. In addition, this review looked at parameters that were most responsive to changes over time, providing insights into the most effective measures for monitoring recovery and rehabilitation progress after ACLR, contributing to the ongoing advancement in this area of inquiry. The findings from 33 studies indicated that certain force plate parameters such as jump height during single and double-leg CMJs and peak vGRF (normalized) during DJs, showed significant differences between individuals with and without ACLR. However, the discriminative ability of those parameters were influenced by the type of jump (i.e. single vs. double-leg) and the limb side involved. Specifically, jump height was significantly lower in individuals post-ACLR compared to Healthy Controls. In addition, eccentric peak vGRF was significantly higher in the uninvolved side and significantly lower in the involved side in individuals with ACLR compared to Healthy Controls. Further, sensitivity analyses revealed heterogeneity in the discriminative ability of other parameters, highlighting the potential necessity of using multiple parameters to more accurately detect functional deficits after ACLR. Peak vGRF (normalized) was lower at 6 months compared to 3 years while performing double-leg DJs according to meta-analysis of three studies showing responsiveness to change characteristics. The findings from this systematic review underscore the importance of using force plate parameters, such as jump height and vGRF, to assess and tailor rehabilitation programs for individuals post-ACLR. In addition, long-term monitoring using peak vGRF (normalized) is crucial for addressing functional deficits and ensuring a safe return to sport.

Paper 3: Dynamic postural stability in individuals with and without ACLR, with insights into sex differences

The third paper aimed to build on published evidence, shifting the focus to evaluate postural stability, measuring the differences in TTS and PSI variables between individuals with ACLR and Healthy Controls, along with exploring sex-specific differences. We evaluated dynamic postural stability following double-leg CMJ landings in individuals with and without ACLR aiming to capture the intricate biomechanical and neuromuscular strategies used by participants who were post-ACLR and Healthy Controls. Our findings revealed that individuals with ACLR took significantly longer to stabilize, as shown by the higher combined resultant vector TTS (RVTTS-C) and the vertical TTS in the operated leg (VTTS-op) values compared to Healthy Controls. Additionally, we observed significant sex differences with males with ACLR exhibiting higher VTTS-C and VTTS-op values than females with ACLR, and higher VTTS-op values compared to healthy males. There were no differences in PSIs between groups.

<u>Paper 4: Postural stability under dual-task: comparing individuals with and without ACLR.</u>

The fourth paper delved into the dual-task effect on postural stability in the ACLR population compared to Healthy Controls. Our study investigated the differences in postural stability following a double-leg CMJ landing between single- and dual-task conditions within groups of individuals with and without ACLR, and compared the dual-task effect on postural stability between ACLR and Healthy Control groups. We used the validated Stroop task as a cognitive task under the dual-task condition.[19] Over all, postural stability was compromised within both groups under the dual-task conditions as indicated by the increase of RVTTS-C and several PSI variables. Specifically, the ACLR group exhibited significant increases in MLSI-C, DPSI-C, DPSI-op, and MLSI-nop, while the Healthy Control group demonstrated significant increases across APSI-C, MLSI-C, DPSI-C, matched MLSI-op, matched DPSI-op, matched APSI-nop, and matched DPSI-nop, indicating that even individuals without ACLR experience reduced stability under cognitive load, with the effect being more pronounced and widespread compared to the ACLR group.

Additionally, the Stroop effect on RVTTS-C was higher among the Healthy Controls compared to those with ACLR. Our findings highlight the importance of considering cognitive loading in rehabilitation and training programs to improve postural stability, as it begins to replicate the field performance when patients return to sport. Enhancing complexity of performing rehabilitation tasks with cognitive loading may reduce the risk of sustaining a secondary ACL injury and facilitate safer return to sport after ACLR.

CLINICAL IMPLICATIONS OF THE DISSERTATION

Enhancing Assessment Methods

The scoping review highlighted the extensive use of kinetic measurement systems to assess functional outcomes post-ACLR. Despite the growing interest in this field, the review identified considerable heterogeneity in the methodologies and parameters used. Researchers and clinicians should consider standardizing assessment protocols to improve cross-study comparability and reliability of kinetic measurements. This will enhance the quality of data collected, facilitating better clinical decision-making and more consistent monitoring of patient progress. The suggested methodological reporting considerations may also facilitate cross-study comparisons and improve the clinical applicability of findings. Furthermore, the association between kinetic measures and patient-reported outcome measures (PROMs) remains underexplored. Clinicians should be encouraged to incorporate both objective kinetic assessments and PROMs in their evaluations to gain a more holistic understanding of patient outcomes.

Identifying Key Kinetic Parameters

The systematic review and meta-analysis pinpointed specific kinetic parameters that are most discriminatory and responsive in individuals post-ACLR. Jump height during single- and double-leg CMJ and peak vGRF during DJs emerged as critical measures. Clinicians may prioritize these key parameters in their assessment protocols to effectively monitor functional recovery. The findings also underscore the importance of considering the type of jump and the limb side involved, as these factors influence the discriminative ability of the parameters. Considering those findings during the evaluation process may enhance the precision of the assessment and accordingly inform tailored rehabilitation strategies. Additionally, understanding how these parameters change throughout different stages of recovery can also provide valuable insights into the effectiveness of interventions. However, our systematic review and meta-analysis underscored a need for further research to assess longitudinal changes over time as we identified only six studies that looked at how parameters changes over time. This will help establish benchmarks and improve the precision of assessments, ultimately informing tailored rehabilitation strategies and enhancing patient outcomes.

Addressing sex differences when evaluating postural stability

The third paper's investigation into postural stability revealed significant sex-specific differences in TTS and PSI post-ACLR. Clinicians should consider sex differences when designing and implementing rehabilitation protocols. Customizing interventions to address the unique needs of male and female patients can optimize recovery outcomes. Recognizing and addressing these differences may contribute to more effective and individualized rehabilitation strategies. Our study demonstrated that male participants with ACLR showed higher RVTTS-C, VTTS-C and VTTS-op compared to female participants with ACLR. This suggests that males may benefit more from protocols to improve their dynamic stability. These sex-differences findings are important to consider when assessing postural stability and designing rehabilitation protocols.

Integrating cognitive loading in assessment and rehabilitation

The final paper examined how simultaneous cognitive and physical tasks influence postural stability. The findings emphasized the importance of considering cognitive tasks when assessing postural stability. Accordingly, clinician may utilize dual-task training, which combines physical and cognitive challenges that may help patients improve their ability to maintain stability, similar to real-world conditions where cognitive distractions are common and patients are not focused on their lower body or knee bio-mechanics.

This may enhance functional performance and reduce the risk of secondary ACL injuries, facilitating a safer return to sport.

STRENGTHS AND LIMITATIONS OF THE RESEARCH

This dissertation is novel due to its comprehensive insight on the assessment of individuals with ACLR, encompassing kinetic measurements, discriminative and responsive parameters, postural stability, sex differences, and cognitive loading impacts. Starting with a assessment of the current state of the science in kinetic measures, the comprehensive scoping review underscored the need for standardized methodologies and the integration of patient-reported outcome measures (PROMs). Employing systematic reviews and meta-analyses ensures methodological rigor and evidence-based conclusions; the systematic review identified key kinetic parameters to facilitates effective monitoring of recovery after ACLR and guidance for tailored rehabilitation strategies by exploring sex-specific differences. The original research conducted on postural stability and the effects of cognitive loading advanced current published evidence. The two related investigations included both males and females with and without ACLR. Despite females having a higher incidence of ACLR, they have been under-represented in the published literature. Comparative studies of individuals with and without ACLR are still somewhat limited. The practical clinical applications and future research directions identified in this dissertation aim to enhance the field of rehabilitation and RTS decisions following ACLR.

However, there are overarching limitations across the four studies that should be acknowledged to ensure an accurate interpretation of the findings and to guide future research. These include the potential for selection bias, confounding bias, and the exclusive assessment of double-leg CMJ.

Inconsistent inclusion criteria related to meniscus problems.

Firstly, there was inconsistency regarding the presence or absence of meniscus pathologies/surgeries between the scoping review and the systematic review. In the scoping review, studies were excluded if more than 50% of the participants had meniscal procedures at the same time as the ACLR, whereas this criterion was not applied in the systematic review. This introduces potential selection bias in the scoping review, as it may not represent the broader ACLR population, which often includes individuals with concurrent meniscus injuries. However, the scoping review included 158 papers which enhanced the comprehensiveness and representativeness of the review. Additionally, the review was able to identify a large number of methodologies and outcomes which could provide a clear understanding of its scope. In addition, including papers with participants who had meniscus injuries in the systematic review presents its own challenges. The presence of meniscus problems could be a confounder for the force-plate results, but it was not possible to dis-aggregate the data of those with and without meniscus injuries in all papers.

No matching based on age and activity levels in the evaluations of postural stability

Another limitation was the lack of matching strategies between the individuals in ACLR groups and Healthy Controls based on the age and activity level or sport in the evaluations of postural stability. This discrepancy introduces potential confounding bias due to physical variations in sports demands and age-related physiological differences. This limitation may impact the internal validity of the findings. However, it is important to note that all participants in our studies were physically active individuals aged between 18 and 35, creating relatively homogeneous comparison groups. This may reduce the likelihood that differences in physiological characteristics or varying sport participation and level of physical activity would confound the results.

Limited sample size for sex-specific analyses.

Our sample size was determined to achieve over 80% power for comparisons between the overall ACLR and Healthy Control groups. However, when analyzing sex-specific differences, the smaller sample size within each subgroup may have reduced the statistical power, potentially limiting the ability to detect significant differences. This may affect the generalizability of the findings related to sex differences. Future studies should consider larger sample sizes to adequately explore sex-specific effects.

Exclusive assessment of double-leg CMJs

Another limitation is the exclusive use of double-leg CMJs when assessing postural stability, without incorporating single-leg CMJs. Single-leg CMJs are important when evaluating individual limb function and identifying unilateral deficits. Those deficits may be masked during double-leg CMJs due to compensatory strategies and load distribution between the two legs.[5] As a result, our findings may not by applicable to activities requiring single-leg performance. Including both single-leg and double-leg CMJs would have provided a more detailed and complete understanding of postural stability and neuromuscular function, enhancing the study's clinical relevance; however, we were limited by the large number of ACLR participants who were <12 months since surgery.

Quadriceps strength symmetry threshold

We used a threshold of 80% for quadriceps strength symmetry as an inclusion criterion, so our results may not apply to individuals who fall below this threshold. This limitation suggests that the findings may be more relevant to those with higher baseline strength symmetry and may not fully capture the variability in recovery among all individuals post-ACLR.

FUTURE DIRECTIONS

The investigations included in this dissertation contribute to the growing body of evidence examining kinetic measures and postural stability after ACLR. These investigations highlight several gaps that can be filled with future studies.

Standardizing reporting checklist

Several reporting checklists have been developed to improve the synthesis and translation of clinical knowledge, and encourage physician participation in research and data gathering. These included, but are not limited to, the Consolidated Standards of Reporting Trials (CONSORT),[17] the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE),[6] the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA),[11] Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT),[4] Standards for Reporting of Diagnostic Accuracy Studies (STARD), Reporting Items for Practice Guidelines in Healthcare (RIGHT),[22] Consolidated Criteria for Reporting Qualitative Research (COREQ),[9] and the REPORTing of quantitative Patello-Femoral Pain studies (REPORT-PFP).[1] Future research should develop a standardized reporting checklist for kinetic measurement using force plates. Such a development will improve transparency and comparability of data across studies facilitating the ability to conduct systematic reviews and meta-analyses as well as to further advance our understanding of how to use kinetic measurements to prepare athletes to return to sport and/or prevent lower-extremity injuries.

Investigating the association between kinetic measures and PROMs

The use of PROMs in clinical trials is highly recommended as they provide important data on patient perspectives of several aspects related to their health problems.[2] Our scoping review identified a scarcity of studies investigating possible relationships between PROMs and kinetic measures in individuals post

ACLR. Understanding this association can provide a more comprehensive view of patient recovery and functional status post-ACLR. Future studies should include both objective kinetic assessments and PROMs to identify correlations and potential predictive markers for rehabilitation outcomes.

Longitudinal Studies on Kinetic and Postural Stability Measures

According to our findings, most of the published data on kinetic and postural stability measures in individuals with ACLR were cross sectional in nature. It is important to understand how those measures change over time to help inform more valid return to sport strategies following ACLR. In addition, longitudinal research may help us identify other risk factors for sustaining secondary ACL injuries through monitoring those measures overtime, and better understanding the potential development of compensatory strategies.

Addressing confounders such as graft types and meniscus issues in research.

Graft type may influence certain kinetic or postural stability measures in people with ACLR. Previous studies suggest that bone-patellar tendon-bone (BPTB) grafts may offer better anterior knee stability compared to hamstring tendon.[21] Moreover, the choice of graft may impact the lower extremity function.[16] Therefore, the choice of graft type in ACLR may have implications for kinetic and postural stability measures. Investigating this plausible relationship between kinetic measures, postural stability and different graft types is crucial for optimizing patient outcomes and rehabilitation strategies following ACLR.

In addition, meniscus surgeries at the time of the ACLR can also influence function and recovery post ACLR.[3] This may also have an impact on kinetic measure and postural stability post ACLR. Therefore, future research should be powered to be able to perform subgroup analysis to compare outcomes in individuals with and without concurrent meniscus pathologies.

Exploring sex-specific rehabilitation protocols.

Since ACL injuries are more common in females,[18] several studies investigated the biomechanical differences between male and females, and postulated specific biomechanical differences that could have increased the risk of sustaining ACL injuries among females.[12] However, we are not aware of other studies investigating the effect of sex as confounder on dynamic postural stability. The sex-specific differences identified in our study warrant further investigation on this relationship to determine how sex influences postural stability throughout recovery. This finding may lead to the development of more effective and individualized rehabilitation strategies.

Integrating cognitive loading and a broader range of functional activities in rehabilitation

During athletic activities, postural stability is processed subconsciously since the focus of conscious attention is on the field of play rather than on maintaining upright posture. However, the typical assessment of postural stability mainly quantifies the conscious control of posture, and not the natural automatic postural correction.[13, 14] To mimic the real life scenarios, dual task paradigms are commonly used to better simulate the actual automatic maintenance of postural stability during athletic activities.

Therefore, future studies should continue to investigate the impact of dual task on postural stability in individuals with ACLR. Research should explore various dual tasks (cognitive and motor) and their effects on postural control, aiming to identify optimal dual-task training protocols. Future research should also include a broader range of functional activities beyond countermovement jumps and drop jumps to assess kinetic and postural stability. Evaluating a variety of movements and tasks can provide a more comprehensive understanding of functional deficits and recovery post-ACLR, informing more holistic rehabilitation approaches.

<u>Utilizing kinematic measurements and electromyography for a comprehensive analysis</u>

In this dissertation, we primarily measured kinetic parameters generated by force plates. However, future research should incorporate kinematic measurements and electromyography (EMG) to better understand how each body segment behaves in the ACLR population compared to healthy controls. This approach would provide a more detailed analysis of movement patterns and muscle activation, offering insights into compensatory mechanisms and aiding in the development of targeted rehabilitation strategies.

<u>Refining Methods for Calculating Time to Stabilization (TTS)</u>

We used Colby's method to calculate TTS variables in our study. However, other methods are also available for calculating TTS.[7] Future research should focus on identifying the most valid method for calculating TTS among the ACLR population to ensure the accuracy and reliability of postural stability assessments. This could enhance the interpretation of results and contribute to more effective rehabilitation protocols.

KNOWLEDGE TRANSLATION

In this dissertation we followed the "End of Grant" approach to knowledge translation, where we developed a plan for making knowledge users aware of the knowledge gained. The End of Grant approach uses typical knowledge dissemination and communication activities such as conference presentations, publications in peer-reviewed journals.[8]

Knowledge translation activities in this doctoral research included:

- Peer-reviewed journals: Both reviews within this dissertation have been published in the Journal of Experimental Orthopedics. The postural stability evaluations have been formatted for submission to Physical Therapy in Sport, and Clinical Biomechanics journals.
- Conference presentations: The scoping review has been presented in the Canadian Academy of Sports and Exercise Medicine Conference (2021), Physio UAE (2022) and during the Orthopedic Research day in Edmonton (2022). The findings of the dissertation will be presented in the International Federation of Sports Medicine (FIMS) World Congress of Sports Medicine - Dubai in Dubai in October, 2024. In addition, the findings will be presented at the Soft Tissue Knee Group Webinars.

CONCLUSION

This dissertation highlights the current status of kinetic measurement using force plates in patient with ALCR and Healthy Controls as well as the importance of dynamic postural stability assessment in individuals with ACLR. Through four original papers, we explored kinetic measurement systems and postural stability, emphasizing the need for comprehensive assessment protocols, including kinetic and postural stability measures, to provide a holistic view of patient recovery. The research identified key kinetic parameters and sex-specific differences, suggesting tailored rehabilitation protocols. Incorporating dual-task paradigms in assessments revealed the impact of cognitive loading on postural control, emphasizing its importance in rehabilitation programs to simulate real-world conditions and to potentially reduce secondary ACL injuries. This novel research provides practical recommendations for improving assessment that are important for informing rehabilitation practices. Future research are needed to further understand the influence of other factors that may impact postural stability in people with ACLR.

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APPENDIX A: Permission to Use Figure 2.2

University of Alberta Mail - Permission Request to Use Figure from "Which biomechanical models are currently used in standing posture analysis?" - Google Chrome

mail.google.com/mail/u/0/?ik=3887a1da57&view=pt&search=all&permthid=thread-a:r-1137951576386355677&simpl=msg-a:r-7999915...

To: armel.cretual@univ-rennes2.fr

Dear Dr. Cretual,

I hope this message finds you well. I am following up on my previous email regarding permission to use "Figure 2 Different models used in postural analysis" from your paper titled "Which biomechanical models are currently used in standing posture analysis?" for my dissertation at the University of Alberta.

I would greatly appreciate your assistance with this request.

Thank you very much for your time and consideration.

Sincerely,

Wasim Labban

[Quoted text hidden]

Armel Cretual <armel.cretual@univ-rennes2.fr> Mon, Jun 24, 2024 at 1:09 AM
To: Wasim Labban <wlabban@ualberta.ca>

Dear Wasim Labban

Thanks for your interest in my review article, and sorry for the delayed answer. As soon as the use of this figure goes along a proper citation of the article from which it comes from, you are allowed to include it in your dissertation.

Sincerely,

[Quoted text hidden]

--

UNIVERSITÉ RENNES 2
UFR STAPS
Armel CRETUAL
Directeur de l'UFR STAPS
Université Rennes 2
0299141760

APPENDIX B: Ethics Approval

University of Alberta Mail - ARISE: Amendment Approved as Administrative Change Pro00111475_AME4 - Google Chrome

mail.google.com/mail/u/0/?ik=3887a1da57&view=pt&search=all&permmsgid=msg-f:1769343778381073495&simpl=msg-f:17693437783...

UNIVERSITY OF ALBERTA

Wasim Labban <wlabban@ualberta.ca>

ARISE: Amendment Approved as Administrative Change Pro00111475_AME4

arise@ualberta.ca <arise@ualberta.ca>
Reply-To: arise@ualberta.ca
To: wlabban@ualberta.ca

Wed, Jun 21, 2023 at 2:01 PM

UNIVERSITY OF ALBERTA

Amendment/Renewal Approved

Amendment/Renewal ID:	Pro00111475_AME4
Study ID:	MS5_Pro00111475
Study Title:	FORCE-ACL
Study Investigator:	Mark Sommerfeldt
Description:	The PAA to the above study has been approved as administrative change. Click on the link(s) above to navigate to the workspace. Please do not reply to this message. This is a system-generated email that cannot receive replies.

APPENDIX C: Informed Consent Forms

PARTICIPANT INFORMATION AND CONSENT FORM (ACLR)

Title of Sub-Study: Utilizing Force Plates for Assessment of Dynamic Postural Stability in Anterior Cruciate Ligament Reconstruction Patients and Healthy Participants

FORCE-Stability

Principal Investigator: Dr. Mark Sommerfeldt, MD, MPH, FRCSC, BScPT, Dip. Sport Med. Tel: (780) 439-4945
Co-Investigators: Dr. Lauren Beaupre, PhD, PT;
Dr. Lindsey Westover, PhD, P.ENG;
Wasim Labban, PhD Candidate, PT Tel: (587) 936-6882
Surgeon Collaborators: Dr. Catherine Hui, MD, FRCSC; Dr. David Otto, MD, FRCSC

Study Coordinator: Stephanie Nathanail, MA (Kin), CAT© Tel: (780) 492-0830

This form contains information about the study. Before you read it, a member of the study team will explain the study to you in detail. You are free to ask questions about anything you do not understand. You will be given a copy of this form for your records.

WHY AM I BEING ASKED TO TAKE PART IN THIS RESEARCH STUDY?

You are being asked to be in this study because you have had surgery to reconstruct the anterior cruciate ligament (ACL) in your knee in the past 9-24 months and may meet our study requirements. If you agree to take part in the study, you would participate in jumping and knee strength testing in a research lab, and complete study questionnaires.

What is the reason for doing the study?

Despite improved surgery and rehabilitation techniques for patients with ACL injuries, there are ongoing challenges in measuring changes in lower body muscle function and control of posture in ACL patients over the course of their recovery after ACL reconstruction (ACLR) surgery. The decision of when patients should return to activity following ACLR is a complex process. There are many tests that can be used to assess knee function post-ACLR. Jump testing on bilateral force plates can provide objective results for how patients are creating and absorbing forces in their lower body.

Postural control is another important factor to acknowledge throughout recovery after ACLR. Postural control helps you to stay upright and balanced. It is affected by individuals' motor control, the activities they perform, and their surrounding environment. Postural stability happens during daily and sporting activities without you thinking about it. However, when we actually measure postural stability, we often focus on thinking about how we move and stay upright, instead of doing the task automatically. To assess more “real-world” responses, we can ask participants to complete two different tasks at the same time (dual task). Postural stability during dual task conditions has not been commonly measured, especially for participants who have undergone ACLR surgery.

We would like to assess your lower body muscle function and postural stability while doing a single task (jump) as well as doing a dual task (jump plus mental task) at one visit. Participants will also complete knee strength testing and questionnaires to provide more information on how these may relate to jump testing results. This sub-study is observational, and is part of a larger study examining recovery in post-ACLR over numerous time points. For this sub-study, we aim to recruit up to 20 participants with ACLR and another 20 healthy participants.

What will I be asked to do?

After your eligibility for the study is confirmed and you have provided informed consent, you will take part in study activities, as described in the information below. You will complete one study visit in a research laboratory (Human Movement Laboratory in the Clinical Sciences Building at the University of Alberta). No follow up testing sessions are required.

During your visit:

The study visit will take approximately 60-90 minutes. Your visit to the Human Movement Laboratory will include the following:

- You will provide your: contact information to communicate as needed regarding study activities; demographics (e.g., age, sex); medical history/comorbidities; sport/activity and work information as applicable; your dominant and affected leg; initial date of ACL injury; date of surgery; type of ACLR graft used (if possible); other concomitant injuries; and baseline rehabilitation information and healthcare provider-type(s).
- You will have your height, weight, bilateral thigh circumference, and body composition taken, followed by a standard warm-up period including 5-10 minutes of stationary cycling, light lower body movement and stretching, and sub-maximal body-weight exercises (squats, lunges, skips);
- The warm-up will be followed by knee strength testing on a specialized machine; you will complete 3 familiarization trials, followed by 3-5 trials of knee flexion (bending) and extension (straightening) against resistance applied at a set speed. Your uninjured side will be measured first. The resistance pad will be placed on your lower leg. You will be seated during testing; to prevent excess movement or compensation from other muscle groups, you will be strapped to the device at the waist and thighs.
    - Knee strength will be compared between your left and right legs. If the knee strength on your injured side is less than 80% of your un-injured side, you will not complete jump testing and your visit will be rescheduled to complete these activities again in about 4-6 weeks. This will help to reduce the risk of injury to either side (if there are large strength imbalances).

- Jump testing will follow knee strength testing after a 5-10 minute rest period. You will receive jump instructions from the research staff, then complete 3 familiarization jumps, followed by 5 maximum effort countermovement jumps.
    - Countermovement jumps will be performed by taking off and landing on both legs at the same time. You will be asked to place your hands on your hips, then quickly perform a downward motion/squat to 90 degrees of knee bend, followed by rapid straightening of the ankles, knees, and hips, jumping as high as possible while firmly maintaining your hands on your hips;
    - A cognitive task (called the Stroop test) will be added to a second set of 5 countermovement jumps on the same force plates. The Stroop test uses a computer monitor to display words of colours on the screen, with the written words displayed in a different colour. Participants will be asked to perform a countermovement jump when they see the first word appear on the screen in front of them, and will continue to answer the Stroop test (with different words appearing on the screen) while holding the countermovement jump landing for 10 seconds. Participants will be allowed 3 familiarization trials, followed by 5 maximal trials.
    - Note, jump testing will be recorded on video (no body markers needed); this will provide observable context to the jump and be synced to data output following session completion. Ankle, knee, and hip angles will be analyzed from the recordings. Due to the nature of the activity, video recordings may include your face, however, these recordings will be securely stored and only accessible to the study team.
- You will complete questionnaires on your knee function and symptoms, activity levels, and rehabilitation. This will take approximately 15 minutes. Questionnaires may be provided to you through a secure online system (called REDCap), so you can complete the questionnaires in advance of your visit to decrease the amount of time spent in person; your email address will be needed. If you are unable to attend in person, the research staff may contact you to complete portion(s) of the visit over the phone.

With your consent, you allow the researchers to store study information in a secure data repository to facilitate future research.

WHAT ARE THE RISKS AND DISCOMFORTS?

You will undergo maximal knee strength and jump testing. These activities may be associated with physical and psychological stress, physical fatigue, and potential injuries. There is wide variability in the risk of re-injury to either the surgical knee or unaffected knee after ACL surgery. Some studies report re-injury risk between 2-16% when patients return to their full sports/activities, although these rates do not refer to potential re-injury when performing controlled knee strength or jump testing in particular.

For this study, participants will need to pass certain criteria to be able to participate in the jumping and landing tasks; these include having full knee range, having no pain or significant swelling in the knee, and demonstrating no large strength differences between the injured and uninjured limb during knee strength testing. Trained research staff will also be present during your visit, and they will provide standard instructions to you to help improve knee strength and jump testing safety; research staff are also trained in human movement, and may terminate jump testing if they observe potentially risky movement patterns.

For added safety, your knees will be examined by a qualified rehabilitation professional on the study team prior to testing to make sure you are fit to participate. The controlled testing environment and included criteria will help to reduce the likelihood of injury.

You will be asked to complete questionnaires which may be psychologically fatiguing or stressing. If you decide to be in the study and are uncomfortable with any portion of the study visit such as the questionnaires, you can choose to omit that portion. As the main goal is to better understand lower body function following ACL surgery, ideally, participants would complete all physical assessments. However, you can choose to not participate in the study if you are uncomfortable with the strength or jumping and landing assessments. This study is associated with extra time burden, which may be physically and/or psychologically fatiguing.

Risks associated with COVID-19 and participation in this study include one study visit, associated with increased exposure to other people such as the study staff. Greater than 2-meter distance between participants and the researchers will not be able to be maintained when setting up and taking down the knee strength device. COVID-19 risk mitigation strategies include using hand sanitizer and frequent hand washing, sanitizing surfaces and study equipment before and after use, and using physical distancing as much as possible. Parties will wear face masks and be screened in accordance with current public health guidelines.

Study participation is voluntary and you can choose not to enroll in this study if you are uncomfortable with these potential risks and discomforts. It is not possible to know all of the risks that may happen in a study, but the researchers have taken all reasonable safeguards to minimize any known risks to a study participant.

WHAT ARE THE BENEFITS TO ME?

There may not be any direct benefit to you from participating in this study. However, this study will help the researchers learn more about lower body function and postural stability in patients following ACL surgery. Hopefully, this information will help to improve assessment, rehabilitation, and return to activity and play decisions for people like you in the future.
At the end of the study, we may provide you with the results from your jumping and knee strength tests.

DO I HAVE TO TAKE PART IN THE STUDY?

Being in this study is your choice. If you decide to be in the study, you can change your mind and stop being in the study at any time, and it will in no way affect the care that you are entitled to.

If you are considering withdrawing from the study, please contact the study coordinator. If you decide to withdraw from the study, we may analyze the information collected up to that point and include the data in the study results, unless you make a request to withdraw your data. Data withdrawal will be allowed up to the point of data analysis. If the research personnel feel that it is in the best interest to withdraw you from the study, you will be removed without your consent.

WILL I BE PAID TO BE IN THE RESEARCH?

You will not be paid for participating in this study, but we will cover your parking costs during the study visit to the Human Movement Laboratory. Your vehicle license plate number may be needed, dependent on parking location method.

To reimburse you for the time burden and physical exertion of attending one study visit, you will receive a food/beverage gift card in the amount of $10.00. The gift card will be provided at the end of your visit.

WHAT HAPPENS IF I AM INJURED BECAUSE OF THIS RESEARCH?

If you become ill or injured as a result of being in this study, you will receive necessary medical treatment, at no additional cost to you. By signing this consent form, you are not giving up any of your legal rights or releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities.

Will my information be kept private?

During the study, we will be collecting data about you. We will do everything we can to make sure that this data is kept private. No data relating to this study that includes your name will be released outside of the researcher's office or published by the researchers. Sometimes, by law, we may have to release your information with your name, so we cannot guarantee absolute privacy. However, we will make every legal effort to make sure that your information is kept private.

During research studies, it is important that the data we get is accurate. For this reason, your data, including your name, may be looked at by people from the University of Alberta, members of the University of Alberta Research Ethics Board, and/or other regulatory agencies.

After the study is done, we will still need to securely store your data that was collected as part of the study. At the University of Alberta, we keep data stored for a minimum of 5 years after the end of the study.

If you leave the study, we will not collect new information about you, but we may need to keep the data that we have already collected.

After the study is done, and with your consent, study data will be stored in a secure database (e.g., REDCap) to facilitate re-use of the data by approved researchers. Any personal information (i.e. your name, telephone number) that could identify you will be removed or changed prior to sharing study data with other researchers. Any researcher who wants to use this data must have the new project reviewed by an ethics board and sign an agreement ensuring your confidentiality and restricting data use only to the approved project. Your data may be linked with other data for research purposes only to increase the usefulness of the data, as subject to scientific and ethical oversight.

WHAT IF I HAVE QUESTIONS?

If you have any questions about the research now or later, please contact the study co-investigator, Wasim Labban at (587) 936-6882.

If you have any questions regarding your rights as a research participant, you may contact the University of Alberta Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

This study is supported by the University of Alberta, Edmonton (Canada) and Mirdif Center for Physiotherapy and Rehabilitation, Dubai (United Arab Emirates). You are entitled to request any details concerning this compensation from the study co-investigator, Wasim Labban.

How do I indicate my agreement to be in this study?

By signing below, you understand:

- That you have read the above information and have had anything that you do not understand explained to you to your satisfaction.
- That you will be taking part in a research study.
- That you may freely leave the research study at any time.
- That you do not waive your legal rights by being in the study
- That the legal and professional obligations of the investigators and involved institutions are not changed by your taking part in this study.

SIGNATURE OF STUDY PARTICIPANT

____

Name of Participant

________________________________ ______________________

Signature of Participant Date

SIGNATURE OF PERSON OBTAINING CONSENT

______________________________ ____________________

Name of Person Obtaining Consent Contact Number

______________________________ ____________________

Signature of Person Obtaining Consent Date

A copy of this consent form will be given to you to keep for your records and reference.

PARTICIPANT INFORMATION AND CONSENT FORM (Healthy)

Title of Sub-Study: Utilizing Force Plates for Assessment of Dynamic Postural Stability in Anterior Cruciate Ligament Reconstruction Patients and Healthy Participants

FORCE-Stability

<u>Principal Investigator:</u> Dr. Mark Sommerfeldt, MD, MPH, FRCSC, BScPT, Dip. Sport Med. Tel: (780) 439-4945

<u>Co-Investigators:</u> Dr. Lauren Beaupre, PhD, PT;
Dr. Lindsey Westover, PhD, P.ENG;
Wasim Labban, PhD Candidate, PT Tel: (587) 936-6882

<u>Study Coordinator:</u> Stephanie Nathanail, MA (Kin), CAT© Tel: (780) 492-0830

This form contains information about the study. Before you read it, a member of the study team will explain the study to you in detail. You are free to ask questions about anything you do not understand. You will be given a copy of this form for your records.

WHY AM I BEING ASKED TO TAKE PART IN THIS RESEARCH STUDY?

You are being asked to be in this study because you are between the age of (18-35) year old, and you are an active athlete who participate in a sport involving jumping, cutting, pivoting, and lateral movements). If you agree to take part in the study, you would participate in jumping and knee strength testing in a research lab, and complete study questionnaires.

What is the reason for doing the study?

Despite improved surgery and rehabilitation techniques for patients with ACL injuries, there are ongoing challenges in measuring changes in lower body muscle function and control of posture in ACL patients over the course of their recovery after ACL reconstruction (ACLR) surgery. The decision of when patients should return to activity following ACLR is a complex process. There are many tests that can be used to assess knee function post-ACLR. Jump testing on bilateral force plates can provide objective results for how patients are creating and absorbing forces in their lower body.

Postural control is another important factor to acknowledge throughout recovery after ACLR. Postural control helps you to stay upright and balanced. It is affected by individuals' motor control, the activities they perform, and their surrounding environment. Postural stability happens during daily and sporting activities without you thinking about it. However, when we actually measure postural stability, we often focus on thinking about how we move and stay upright, instead of doing the task automatically. To assess more “real-world” responses, we can ask participants to complete two different tasks at the same time (dual task). Postural stability during dual task conditions has not been commonly measured, especially for participants who have undergone ACLR surgery. Having people who have not experienced ACLR allows us to see how participants perform in the absence of knee injuries.

We would like to assess your lower body muscle function and postural stability while doing a single task (jump) as well as doing a dual task (jump plus mental task) at one visit. Participants will also complete knee strength testing and questionnaires to provide more information on how these may relate to jump testing results. This sub-study is observational, and is part of a larger study examining recovery in post-ACLR over numerous time points. For this sub-study, we aim to recruit up to 20 participants with ACLR and another 20 healthy participants.

What will I be asked to do?

After your eligibility for the study is confirmed and you have provided informed consent, you will take part in study activities, as described in the information below. You will complete one study visit in a research laboratory (Human Movement Laboratory in the Clinical Sciences Building at the University of Alberta). No follow up testing sessions are required.

During your visit:

The study visit will take approximately 60-75 minutes. Your visit to the Human Movement Laboratory will include the following:

- You will provide your: contact information to communicate as needed regarding study activities; demographics (e.g., age, sex); medical history/comorbidities; your dominant leg; and sport/activity and work information as applicable.
- You will have your height, weight, bilateral thigh circumference, and body composition taken, followed by a standard warm-up period including 5-10 minutes of stationary cycling, light lower body movement and stretching, and sub-maximal body-weight exercises (squats, lunges, skips);
- The warm-up will be followed by knee strength testing on a specialized machine; you will complete 3 familiarization trials, followed by 3-5 trials of knee flexion (bending) and extension (straightening) against resistance applied at a set speed. The resistance pad will be placed on your lower leg. You will be seated during testing; to prevent excess movement or compensation from other muscle groups, you will be strapped to the device at the waist and thighs.
    - Knee strength will be compared between your left and right legs. If you demonstrate a knee strength difference greater than 20% between sides, you will not complete jump testing and your visit will be rescheduled to complete these activities again in about 4-6 weeks. This will help to reduce the risk of injury to either side (if there are large strength imbalances).
- Jump testing will follow knee strength testing after a 5-10 minute rest period.
    - You will receive jump instructions from the research staff, then complete 3 familiarization jumps, followed by 5 maximum effort countermovement jumps. Countermovement jumps will be performed by taking off and landing on both legs at the

same time. You will be asked to place your hands on your hips, then quickly perform a downward motion/squat to 90 degrees of knee bend, followed by rapid straightening of the ankles, knees, and hips, jumping as high as possible while firmly maintaining your hands on your hips;

    - Drop jumps will be performed by having participants place their hands on their hips and 'drop' from a 30 cm box, landing with both feet on the force plate system at the same time, then quickly jumping up as high as possible, and landing back on the force plates with both legs at the same time. Participants will receive jump instructions from the research staff, then complete 3 familiarization jumps, followed by 3 maximum effort drop jumps;
    - A cognitive task (called the Stroop test) will be added to a second set of 5 regular countermovement jumps on the same force plates. The Stroop test uses a computer monitor to display words of colours on the screen, with the written words displayed in a different colour. Participants will be asked to perform a countermovement jump when they see the first word appear on the screen in front of them, and will continue to answer the Stroop test (with different words appearing on the screen) while holding the countermovement jump landing for 10 seconds. Participants will be allowed 3 familiarization trials, followed by 5 maximal trials.
    - Note, jump testing will be recorded on video (no body markers needed); this will provide observable context to the jump and be synced to data output following session completion. Ankle, knee, and hip angles will be analyzed from the recordings. Due to the nature of the activity, video recordings may include your face, however, these recordings will be securely stored and only accessible to the study team.
- You will complete questionnaires on your knee function and symptoms, activity levels, and rehabilitation. This will take approximately 15 minutes. Questionnaires may be provided to you through a secure online system (called REDCap), so you can complete the questionnaires in advance of your visit to decrease the amount of time spent in person; your email address will be needed. If you are unable to attend in person, the research staff may contact you to complete portion(s) of the visit over the phone.

With your consent, you allow the researchers to store study information in a secure data repository to facilitate future research.

WHAT ARE THE RISKS AND DISCOMFORTS?

You will undergo maximal knee strength and jump testing. These activities may be associated with physical and psychological stress, physical fatigue, and potential injuries.

For this study, participants will need to pass certain criteria to be able to participate in the jumping and landing tasks; these include having healthy knees with full range of motion, having no pain or significant swelling in the knees, and demonstrating no large strength differences between the dominant and the non-dominant limb during knee strength testing. Trained research staff will also be present during your visit, and they will provide standard instructions to you to help improve knee strength and jump testing safety; research staff are also trained in human movement, and may terminate jump testing if they observe potentially risky movement patterns.

For added safety, your knees will be examined by a qualified rehabilitation professional on the study team prior to testing to make sure you are fit to participate. The controlled testing environment and included criteria will help to reduce the likelihood of injury.

You will be asked to complete questionnaires which may be psychologically fatiguing or stressing. If you decide to be in the study and are uncomfortable with any portion of the study visit such as the questionnaires, you can choose to omit that portion. As the main goal is to better understand lower body function in ACLR and healthy participants, ideally, participants would complete all physical assessments. However, you can choose to not participate in the study if you are uncomfortable with the strength or jumping and landing assessments. This study is associated with extra time burden, which may be physically and/or psychologically fatiguing.

Risks associated with COVID-19 and participation in this study include a study visit, associated with increased exposure to other people such as the study staff. Greater than 2-meter distance between participants and the researchers will not be able to be maintained when setting up and taking down the knee strength device. COVID-19 risk mitigation strategies include screening participants and study staff, all parties wearing face masks at all times, using hand sanitizer and frequent hand washing, sanitizing surfaces and study equipment before and after use, and using physical distancing as much as possible.

Study participation is voluntary and you can choose not to enroll in this study if you are uncomfortable with these potential risks and discomforts. It is not possible to know all of the risks that may happen in a study, but the researchers have taken all reasonable safeguards to minimize any known risks to a study participant.

WHAT ARE THE BENEFITS TO ME?

There may not be any direct benefit to you from participating in this study. However, this study will help the researchers learn more about lower body function and postural stability in patients following ACL surgery and how this compares to healthy participants. Hopefully, this information will help to improve assessment, rehabilitation, and return to activity and play decisions for people in the future.
At the end of the study, we may provide you with the results from your jumping and knee strength tests.

DO I HAVE TO TAKE PART IN THE STUDY?

Being in this study is your choice. If you decide to be in the study, you can change your mind and stop being in the study at any time, and it will in no way affect the care that you are entitled to.

If you are considering withdrawing from the study, please contact the study coordinator. If you decide to withdraw from the study, we may analyze the information collected up to that point and include the data in the study results, unless you make a request to withdraw your data. Data withdrawal will be allowed up to the point of data analysis. If the research personnel feel that it is in the best interest to withdraw you from the study, you will be removed without your consent.

WILL I BE PAID TO BE IN THE RESEARCH?

You will not be paid for participating in this study, but we will cover your parking costs during the study visit to the Human Movement Laboratory. Your vehicle license plate number may be needed, dependent on parking location method.

To reimburse you for the time burden and physical exertion of attending one study visit, you will receive a food/beverage gift card in the amount of $10.00. The gift card will be provided at the end of your visit.

WHAT HAPPENS IF I AM INJURED BECAUSE OF THIS RESEARCH?

If you become ill or injured as a result of being in this study, you will receive necessary medical treatment, at no additional cost to you. By signing this consent form, you are not giving up any of your legal rights or releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities.

Will my information be kept private?

During the study, we will be collecting data about you. We will do everything we can to make sure that this data is kept private. No data relating to this study that includes your name will be released outside of the researcher's office or published by the researchers. Sometimes, by law, we may have to release your information with your name, so we cannot guarantee absolute privacy. However, we will make every legal effort to make sure that your information is kept private.

During research studies, it is important that the data we get is accurate. For this reason, your data, including your name, may be looked at by people from the University of Alberta, members of the University of Alberta Research Ethics Board, and/or other regulatory agencies.

After the study is done, we will still need to securely store your data that was collected as part of the study. At the University of Alberta, we keep data stored for a minimum of 5 years after the end of the study.

If you leave the study, we will not collect new information about you, but we may need to keep the data that we have already collected.

After the study is done, and with your consent, study data will be stored in a secure database (e.g., REDCap) to facilitate re-use of the data by approved researchers. Any personal information (i.e. your name, telephone number) that could identify you will be removed or changed prior to sharing study data with other researchers. Any researcher who wants to use this data must have the new project reviewed by an ethics board and sign an agreement ensuring your confidentiality and restricting data use only to the approved project. Your data may be linked with other data for research purposes only to increase the usefulness of the data, as subject to scientific and ethical oversight.

WHAT IF I HAVE QUESTIONS?

If you have any questions about the research now or later, please contact the study co-investigator, Wasim Labban at (587) 936-6882.

If you have any questions regarding your rights as a research participant, you may contact the University of Alberta Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

This study is supported by the University of Alberta, Edmonton (Canada) and Mirdif Center for Physiotherapy and Rehabilitation, Dubai (United Arab Emirates). You are entitled to request any details concerning this compensation from the study co-investigator, Wasim Labban.

How do I indicate my agreement to be in this study?

By signing below, you understand:

- That you have read the above information and have had anything that you do not understand explained to you to your satisfaction.
- That you will be taking part in a research study.
- That you may freely leave the research study at any time.
- That you do not waive your legal rights by being in the study
- That the legal and professional obligations of the investigators and involved institutions are not changed by your taking part in this study.

SIGNATURE OF STUDY PARTICIPANT

____

Name of Participant

________________________________ ______________________

Signature of Participant Date

SIGNATURE OF PERSON OBTAINING CONSENT

______________________________	______________________
Name of Person Obtaining Consent	Contact Number
______________________________	______________________
Signature of Person Obtaining Consent	Date

A copy of this consent form will be given to you to keep for your records and reference.

APPENDIX 3.1: Scoping review - Search Strategies

Ovid MEDLINE(R) ALL 1946 to June 04, 2020

Date searched: June 5, 2020

Results: 1194

1. exp anterior cruciate ligament reconstruction/

2. ((Anterior cruciate ligament or ACL) adj8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*)).mp.

3. 1 or 2

4. (forceplate* or force plate* or force platform* or balance platform* or balance board* or wii balance or unstable platform or KAT-2000 or KAT2000 or platform system or biodex stability system or biodex balance system or centre of gravity or center of gravity or Neruocom balance master or Kistler or GRF or GRFs or VGRF or VGRFs or ground reaction force* or kinetic* or center of pressure).mp.

5. (Reactive strength index-modified or RSImod or vertical impulse or rate of force development or force production or jump duration or flight time or peak force* or fatigue index or reactive strength index or limb-impulse* or phase specific or knee-extensor-power or muscle-power or time curve).mp.

6. (postural stability or postural instability or postural balance or postural control or postural sway or postural impairment* or dynamic balance or dynamic stability or dynamic control or static balance or static stability or static control or standing balance or balance impairment* or stabilometric).mp.

7. (functional-test* or quiet standing or hop test or single-leg hop or single-leg squat or landing or (jump adj2 height) or ((Bilateral or unilateral or countermovement or squat or drop or vertical) adj4 jump*) or

((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices) adj4 (asymmetr* or symmetr*))).mp.

8. 3 and (or/4-7)

9. limit 8 to (address or autobiography or bibliography or biography or clinical trial, veterinary or clinical trials, veterinary as topic or dictionary or directory or editorial or interview or news or newspaper article or observational study, veterinary)

10. 8 not 9

Embase 1974 to 2020 June 04 (OVID interface)

Date searched:June 5, 2020

Results: 1268

1. anterior cruciate ligament reconstruction/

2. ((Anterior cruciate ligament or ACL) adj8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*)).mp.

3. 1 or 2

4. (forceplate* or force plate* or force platform* or balance platform* or balance board* or wii balance or unstable platform or KAT-2000 or KAT2000 or platform system or biodex stability system or biodex balance system or centre of gravity or center of gravity or Neruocom balance master or Kistler or GRF or GRFs or VGRF or VGRFs or ground reaction force* or kinetic* or center of pressure).mp.

5. (Reactive strength index-modified or RSImod or vertical impulse or rate of force development or force production or jump duration or flight time or peak force* or fatigue index or reactive strength index or limb-impulse* or phase specific or knee-extensor-power or muscle-power or time curve).mp.

6. (postural stability or postural instability or postural balance or postural control or postural sway or postural impairment* or dynamic balance or dynamic stability or dynamic control or static balance or static stability or static control or standing balance or balance impairment* or stabilometric).mp.

7. (functional-test* or quiet standing or hop test or single-leg hop or single-leg squat or landing or (jump adj2 height) or ((Bilateral or unilateral or countermovement or squat or drop or vertical) adj4 jump*) or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices) adj4 (asymmetr* or symmetr*))).mp.

8. 3 and (or/4-7)

9. limit 8 to conference abstract status

10. 8 not 9

11. limit 10 to editorial

12. 10 not 11

CINAHL Plus with Full Text (EBSCOhose interface)

Date searched: June 5, 2020

Results: 966

S1 (MH "Anterior Cruciate Ligament Reconstruction") OR ((Anterior cruciate ligament or ACL) N8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*)))

S2 forceplate* or force-plate* or force-platform* or balance-platform* or balance-board* or wii-balance or unstable-platform or KAT-2000 or KAT2000 or platform-system or stability-system or balance-system or centre-of-gravity or center-of-gravity or balance-master or Kistler or GRF or GRFs or VGRF or VGRFs or ground-reaction-force* or kinetic* or center-of-pressure or centre-of-pressure or Reactive-strength-index-modified or RSImod or vertical-impulse or rate-of-force-development or force-production or jump-duration or flight-time or peak-force* or fatigue-index or reactive-strength-index or limb-impulse* or phase-specific or knee-extensor-power or muscle-power or time-curve or postural-stability or postural-instability or postural-balance or postural-control or postural-sway or postural-impairment* or dynamic-balance or dynamic-stability or dynamic-control or static-balance or static-stability or static-control or standing-balance or balance-impairment* or stabilometric or functional-test* or quiet-standing or hop-test or single-leg-hop or single-leg-squat or landing or (jump N2 height) or ((Bilateral or unilateral or countermovement or squat or drop or vertical) N4 jump*) or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices) N4 (asymmetr* or symmetr*))

S3 S1 AND S2

S4 S3 Limiters - Publication Type: Biography, Book Review, Editorial, Obituary, Pamphlet, Pamphlet Chapter, Proceedings

S5 S3 NOT S4

SPORTDiscus with Full Text (EBSCOhose interface)

Date searched: June 5, 2020

Results: 846

S1 (((Anterior cruciate ligament or ACL) N8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*))) AND (forceplate* or force-plate* or force-platform* or balance-platform* or balance-board* or wii-balance or unstable-platform or KAT-2000 or KAT2000 or platform-system or stability-system or balance-system or centre-of-gravity or center-of-gravity or balance-master or Kistler or GRF or GRFs or VGRF or VGRFs or ground-reaction-force* or kinetic* or center-of-pressure or centre-of-pressure or Reactive-strength-index-modified or RSImod or vertical-impulse or rate-of-force-development or force-production or jump-duration or flight-time or peak-force* or fatigue-index or reactive-strength-index or limb-impulse* or phase-specific or knee-extensor-power or muscle-power or time-curve or postural-stability or postural-instability or postural-balance or postural-control or postural-sway or postural-impairment* or dynamic-balance or dynamic-stability or dynamic-control or static-balance or static-stability or static-control or standing-balance or balance-impairment* or stabilometric or functional-test* or quiet-standing or hop-test or single-leg-hop or single-leg-squat or landing or (jump N2 height) or ((Bilateral or unilateral or countermovement or squat or drop or vertical) N4 jump*) or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices) N4 (asymmetr* or symmetr*)))

S2 S1 Limiters - Publication Type: Audio, Audiocassette, CD-ROM, Computer Disk or Diskette, Conference Proceeding, Newspaper, Newswire, Proceeding, Trade Publication, Video, Video Recording, Videocassette, URL

S3 S1 NOT S2

SCOPUS

Date searched:June 5, 2020

Results: 1395

TITLE-ABS-KEY ((anterior-cruciate-ligament OR acl) W/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND TITLE-ABS-KEY (forceplate* OR force-plate* OR force-platform* OR balance-platform* OR balance-board* OR wii-balance OR unstable-platform OR kat-2000 OR kat2000 OR platform-system OR stability-system OR balance-system OR centre-of-gravity OR center-of-gravity OR balance-master OR kistler OR grf OR grfs OR vgrf OR vgrfs OR ground-reaction-force* OR kinetic* OR center-of-pressure OR centre-of-pressure OR reactive-strength-index-modified OR rsimod OR vertical-impulse OR rate-of-force-development OR force-production OR jump-duration OR flight-time OR peak-force* OR fatigue-index OR reactive-strength-index OR limb-impulse* OR phase-specific OR knee-extensor-power OR muscle-power OR time-curve OR postural-stability OR postural-instability OR postural-balance OR postural-control OR postural-sway OR postural-impairment* OR dynamic-balance OR dynamic-stability OR dynamic-control OR static-balance OR static-stability OR static-control OR standing-balance OR balance-impairment* OR stabilometric OR functional-test* OR quiet-standing OR hop-test OR single-leg-hop OR single-leg-squat OR landing OR (jump W/2 height) OR ((bilateral OR unilateral OR countermovement OR squat OR drop OR vertical) W/4 jump*) OR ((leg OR legs OR limb OR limbs OR knee OR knees OR functional OR strength OR muscle OR index OR indices) W/4 (asymmetr* OR symmetr*))) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "ed"))

Web of Science Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI

Date searched: June 5, 2020

Results: 1259

TS=((anterior-cruciate-ligament OR acl) NEAR/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND TS=((anterior-cruciate-ligament OR acl) NEAR/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND DOCUMENT TYPES: (Article OR Book OR Book Chapter OR Correction OR Data Paper OR Letter OR Note OR Retracted Publication OR Retraction OR Review)

Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

Dissertations and Theses Global(Proquest interface)

Date searched:June 5, 2020

Results: 118

noft(((anterior-cruciate-ligament OR acl) NEAR/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*))) AND (forceplate* or force-plate* or force-platform* or balance-platform* or balance-board* or wii-balance or unstable-platform or KAT-2000 or KAT2000 or platform-system or stability-system or balance-system)

APPENDIX 3.2: Scoping review - Data Extraction Tables

Table 1 Data Extraction Table for Studies Assessing Landing/Jumping

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), Activity level, time since surgery (mean±SD), sample size by sex and age (mean±SD)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates (n=56)						
Bell et al, 2014 [26] **Cross Sectional** **USA** **In English**	PA: Soccer (8), flag football (3), basketball (2), gymnastics (2), softball (1), long jump (1), volleyball (1), handball (1) Level: N/R Time Since ACLR: 26.3±12.6 months ACLR: (m=0), (f=19); Age: 19.6±1.3 y/o Control: N/A ACLD: (m=0), (f=1); Age: N/R y/o	To examine anterior knee laxity and 3-dimensional hip and knee kinematics and kinetics across the menstrual cycle in a population of women with previous unilateral, noncontact ACL injuries	GRF	1440 Hz	5	Participants completed 5 trials of a jump-landing task on a box that was 30 cm high and positioned at 50% of their heights from the edge of a force plate. They jumped forward and landed on both feet with the test limb on the force plate. Immediately after landing, participants jumped as high as possible
Birchmeier et al, 2019 [27] **Cross Sectional** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 37.6±23.7 months ACLR: (m=19), (f=33); Age: 22.94±5.0 y/o Control: N/A ACLD: N/A	To assess the association of isometric knee extension strength characteristics and plyometric characteristics measured during a single-leg drop	Ground contact time	1200 Hz	3	Shoes on Participants stood on a 30-cm box placed 40 cm from the middle of the embedded force plate. They were instructed to jump to a target in the middle of the force place, land on a single-leg, then immediately perform

		landing(amortization time and RSI), with single-leg hop performance in individuals with a history of ACLR				a maximal vertical jump off the same leg
****Blache et al, 2017** [79] **Cross Sectional France** **In English**	PA: Soccer, Basketball, Handball Level: 2-3 times/week (level N/R) Time Since ACLR: 7.3 (range 5-9) months ACLR: (m=12), (f=0); Age: 23.9±5.8 y/o Control: (m=12), (f=0); Age: 25.5±4.5 y/o ACLD: N/A	to evaluate the inter-joint coordination asymmetry between IL and NIL in patients after ACL-R during single-leg vertical jumping in comparison to a healthy population	Vertical jump height was obtained from vGRF	1000 Hz	3	15-min warm-up, including single-leg squat jumps Barefoot, on 1 leg, arms akimbo Three single-leg squat jumps with the right and left legs on force plate. Participants asked to jump as high as possible without any countermovement
Chang et al, 2018 [28] **Quasi Experimental South Korea** **In English**	PA: N/R Level: N/R Time Since ACLR: ACLR: 35.2±13.2 months ACLR: (m=0), (f=18); Age: ACLR: 19.9±1.2 Control: (m=0), (f=12); Age: 21.0±2.6 y/o ACLD: N/A	To compare the landing biomechanics of ACLR females who pass or fail an FTB to the matched-limb landing biomechanics of healthy females before and after completion of a sustained exercise protocol	Peak vGRF	1560 Hz	3	5-min submaximal warm-up on a stationary bike. For double-leg jump landing, participants stood atop a 30-cm high box placed 50% of their height from the front edge of the force plate. They were instructed to jump forward off the box and land on the force plates with both feet then immediately jump vertically. For single-leg jump landing, participants stood on the floor behind a line marked 50% of their height from the front edge of the force plate. Then, they were instructed to jump over a 17-cm high hurdle placed 25% of their height from the force plate, land on 1 foot (testing foot), and then cut as quickly as possible to the other

						direction of the landing foot (e.g. right foot landing then cut to the left side).
Chang et al, 2020 [29] **Cross Sectional South Korea** **In English**	PA: N/R Level: N/R Time Since ACLR: 35.2±18.4 months ACLR: (m=0), (f=18); Age: 19.9±1.2 y/o Control: (m=0), (f=12); Age: 21.0±2.6 y/o ACLD: N/A	To compare the knee joint landing and cutting biomechanics asymmetry of ACLR females that pass and fail an FTB with healthy females before and after the completion of a sustained exercise protocol. It was hypothesized that there would be no differences in landing and cutting mechanics asymmetry between ACLR females that pass an FTB (ACLR-pass) and healthy females; but that ACLR females that fail an FTB (ACLR-fail) would exhibit different landing and cutting mechanics asymmetry compared to ACLR-pass and healthy females.	Peak vGRF vGRF loading rate	1560 Hz	3	For double-leg jump landing, participants stood atop a 30-cm high box placed 50% of their height from the front edge of the force plate. They were instructed to jump forward off the box and land on the force plates with both feet then immediately jump vertically. For single-leg jump landing, participants stood on the floor behind a line marked 50% of their height from the front edge of the force plate. Then, they were instructed to jump over a 17-cm high hurdle placed 25% of their height from the force plate, land on 1 foot (testing foot), and then cut as quickly as possible to the other direction of the landing foot (e.g. right foot landing then cut to the left side).
Dashti Rostami et al, 2020 [30]	PA: N/R Level: exercise for at least 3 sessions per week for 30 minutes	To evaluate relationships between lower extremity	Peak vertical GRF Peak	2000 Hz	3	Hand on the hips Contralateral knee in flexion, and tibia is not touching the other leg.

Cross Sectional Iran **In English**	per session Time Since ACLR: 26.55±4.31 months ACLR: (m=20), (f=0); Age: 26.77±3.75 y/o Control: N/A ACLD: N/A	muscle activity (quadriceps, hamstrings, gastrocnemius, and quadriceps to hamstring [Q: H] co-activation ratio) and peak vertical and posterior ground reaction forces (vGRF and pGRF) during a single-leg drop-landing task.	posterior GRF			Following a verbal cue, participants dropped off the platform and landed upon the force plate. Participants performed 3 practice trials followed by 3 test trials. Trials were considered valid if participants successfully landed with the entire foot on the force plate and maintained balance upon the injured limb only.
****deFontenay et al, 2014** [80] **Cross Sectional France** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.3±1.1 months ACLR: (m=11), (f=0); Age: 23.3±3.8 y/o Control: N/A ACLD: N/A	To highlight the alterations observed in the IL during the performance of a dynamic movement after ACL reconstruction.	Push off phase duration	1000 Hz	3	Warm-up and jump-training sessions to become familiar with the task. Countermovements were not allowed. Hands stay on hips. Each participant performed 6 maximal single-legged squat jumps: 3 jumps on the injured limb and 3 jumps on the uninjured limb in randomized order. The initial position was the preferred position they chose, and they were instructed to jump as high as possible without downward movement.
Decker et al, 2002 [31] **Cross Sectional USA** **In English**	PA: Athlete Level: Recreational Time Since ACLR: More than 1 year (mean±SD: N/R) ACLR: (n=11), (Sex: N/R); Age: 27.3 (SD: N/R) y/o Control: (n=11), (Sex: N/R); Age:	To evaluate and compare the kinetic and kinematic landing performances of healthy and hamstring ACLR individuals.	vGRF	1200 Hz	8	Warm-up on the treadmill for 5 minutes Hands folded on chest The landing task consisted of stepping off a 60-cm box onto a landing platform. The subjects were

	26.9 (SD: N/R) y/o ACLD: N/A					instructed to step off the box, without jumping up or stepping down, and to land as naturally as possible with both feet on the landing platform. One foot landed upon a force plate, and the other landed next to the force plate on the landing platform.
Elias et al, 2015 [32] **Cross Sectional** **USA** **In English**	PA: Basketball, skiing, soccer, volleyball, football and other Level: Recreational Time Since ACLR: 23.6±14 months ACLR: (m=14), (f=20); Age: 21.9±4.5 y/o Control: N/A ACLD: N/A	To examine training-induced changes in quadriceps and hamstring muscle activity following instruction for what has been reported as a preferred strategy for impact attenuation during a single-leg landing task in persons who have undergone ACLR.	vGRF	1200 Hz	5	Warm-up on treadmill for 5 minutes Shoes on Before instructions: Subjects stood approximately 10 cm from the edge of a 20-cm box with their hands on their hips, and were instructed to gain their balance on a single-leg before hopping forward off the box with their eyes looking forward. After instructions: To land as softly and quietly as possible by hitting toes first and bending their knees during landing. Participants were instructed to keep their chest over their knees and their knees over their toes during landing.
Flanagan et al, 2008 [33] **Cross Sectional** **Ireland** **In English**	PA: Field sports such as rugby and soccer Level: N/R Time Since ACLR: 27.0±14.5 months ACLR: (m=8), (f=2); Age: 23.8±6 y/o Control: (m=8), (f=2); Age:	To determine whether rehabilitated ACL-R individuals were left with residual deficits in performance after their rehabilitation programs.	Peak ground reaction force Flight time Contact time	1000	3	Setting on a 30 degrees inclined sledge. Shoes on Movement is only in the sagittal plane Participants were asked to perform squat jumps, countermovement

	23.3±3.1 y/o ACLD: N/A					Jumps, drop Jumps and rebound Jumps
Ford et al, 2016 [34] **Cross Sectional** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 8.3±2.5 months ACLR: (m=37), (f=64); Age: 16.7±3.0 y/o Control: (m=15), (f=42); Age: 17.2±2.5 y/o ACLD: N/A	To objectively classify the preferred landing leg during a bipedal landing task in athletes previously injured and uninjured To determine if limb asymmetries during single-leg hops would be observed within ACLR and control groups based on group allocation.	The absolute time difference between the initial contacts for each leg was calculated and compared between ACLR and control groups.	1200 Hz	3	Both feet at the same time Drop down of a box on a force plate and jump vertically.
Frank et al, 2014 [35] **Quasi Experimental** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 35.0±16.9 months ACLR: (m=0), (f=14); Age: 19.6±1.5 y/o Control: N/A ACLD: N/A	To investigate the effects of fatigue on lower extremity biomechanics and postural control in active females with ACLR	vGRF	1400 Hz	5 Double-leg jump landings 3 single-leg balance	5-min of a light, self-directed stationary bike warm up followed by 5-min of stretching before testing Double-Leg Jump Landing Jump of a 30-cm box placed at a distance equal to one half the participant's height from the leading edge of the force plate. On landing, participants were instructed to jump up as high as possible. Single-Leg Balance Eyes closed while standing unshod atop the center of a force plate. Participants were instructed to place their hands on their hips for the duration of the balance task. Each participant attempted to balance on

						their ACLR limb for 20 seconds while center-of-pressure (CoP) data were recorded.
Furlanetto et al, 2016 [36] **Cross sectional Brazil** **In English**	PA: N/R Level: N/R Time Since ACLR: 6 months ACLR: (n=20), (Sex: N/R); Age: 29.2±8.1 y/o Control: (n=20), (Sex: N/R); Age: 27.8±4.0 y/o ACLD: N/A	Evaluate and compare proprioception, postural control and knee function in subjects with and without unilateral ACL reconstruction	Postural control: Amplitude of CoP (anterior-posterior and medial-lateral directions) Step up and down: first peak vGRF, load application rate (LAR)	2000 Hz	3 trials each (PC), 5 trials each (SUD)	Postural control (PC): Right and left uni-podal support lasting for 30 sec each. The individual was asked to remain still in the indicated position with his/her hands on the anterio-superior iliac crests (ASIC), silently, gaze fixed on a target, located 1m from the eye level of each participant. Step up and down (SUD): 30 cm high wooden box placed on 1st force plate. The test started off the force platform with the patient in static position, legs together and hands on anterior superior iliac spine. The individual climbed the step with 1 of his/her lower limbs and descended it by stepping on 2nd force plate in a continuous single movement.
Gokeler et al, 2010 [37] **Cross Sectional The Netherlands** **In English**	PA: Level 1-2 sports (jumping, pivoting, hard-cutting, lateral motion) Level: N/R Time Since ACLR: 6.75±0.38 months ACLR: (m=6), (f=3); Age: 28.4±9.7 y/o Control: (m=8), (f=3); Age: 26.3±5.5 y/o ACLD: N/A	To assess the bilateral lower limb joint kinematics and kinetics and onset time of EMG activity during the single-leg hop test in ACL-reconstructed patients during the single-leg hop for distance. These data will be	Horizontal and vertical GRF (normalized to body weight)	750 Hz	10	Single-leg, wearing own shoes Force plate was placed at maximum hop distance for that subject, and the subject was instructed hop with 1 limb and land onto the center of the force plate.

		compared with a control group.				
Gokeler et al, 2016 [38] **Cross Sectional** **The Netherlands** **In English**	PA: N/R Level: Hours sport per week (prior to injury) = 6.8±3.8 Time Since ACLR: 8.9±2.3 months ACLR: (m=10), (f=10); Age: 23.5±4.3 y/o Control: (m=10), (f=10); Age: 22.7±2.3 y/o ACLD: N/A	To evaluate the influence of immersion in virtual reality on movement patterns in patients after ACLR while performing a step-down task.	GRF normalized to body weight	N/R	8	Shoes on, arms across chest. Virtual reality and non-virtual reality conditions Step-down from a 20-cm-high box onto 2 force plates of 40 × 60 cm that were embedded in the floor in front of the box. Virtual reality environment condition customized with CAREN
Grooms et al, 2018 [39] **Cross Sectional** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 36.18±26.50 months ACLR: (m=7), (f=8); Age: 21.4±2.6 y/o Control: (m=7), (f=8); Age: 23.2±3.5 y/o ACLD: N/A	To investigate the effects of stroboscopic visual-feedback disruption (SVFD) on drop vertical-jump (DVJ) landing mechanics and determine the influence of ACLR history on the effect of SVFD on neuromuscular control	Peak GRF (as % body mass)	N/R	3	3 conditions: full vision, low SVFD, and high SVFD For the DVJ assessment, participants fell forward from a 30-cm box, immediately performed a vertical jump, raised both upper extremities, and hit a target set at 90% of their maximal jump height. The SPARQ Vapor Strobe goggles (Nike, Inc, Beaverton, OR) imposed the SVFD condition
Holsgaard-Larsen et al, 2014 [40] **Cross Sectional** **Denmark** **In English**	PA: N/R Level: N/R Time Since ACLR: 26.5±6.6 months ACLR: (m=23), (f=0); Age: 27.2±7.5 y/o Control: (m=25), (f=0); Age: 27.2±5.4 y/o ACLD: N/A	To conduct concurrent assessments of lower limb loading patterns during bilateral and unilateral vertical jumping, isolated mechanical muscle function and functional outcome in ACL reconstructed patients and to test the	vGRF	1000 Hz	3	A standardized warm-up consisting of two times 10 toe rises, 10 bilateral squats, 10 unilateral squats (for each leg) and two to three submaximal vertical jumps (countermovement jumps: CMJ). Double-leg stance, hands on hips, barefoot

		hypothesis that patients demonstrate greater between-limb asymmetry in these parameters compared with age-matched controls. Additionally, to more closely investigate the origin of between-limb asymmetry by means of kinematic/kinetic movement analysis.				Starting from a full erect standing position, the subjects were instructed to perform a fast downward movement (to about 90° knee flexion) immediately followed by a fast upward movement, and to jump as high as possible.
Kilic et al, 2018 [41] **Cross Sectional Turkey** **In English**	PA: Soccer Level: Amature Time Since ACLR: (Range 6-15) months ACLR: (m=11), (f=0); Age: 23.1±3.62 y/o Control: (m=9), (f=0); Age: 22.2±2.48 y/o ACLD: N/A	To determine how ground reaction forces, moments and knee flexion angles differ between Healthy Controls and reconstructed subjects during single-leg landing phases.	Phase vGRF	1000 Hz	3	5-min warm-up Shoes on Drop jump from a custom-made takeoff platform from 20cm vertical height that was placed next to the edge of a force plate. For each landing task all participants began with a standard takeoff position by standing on a takeoff platform with hands placed on the hips, legs shoulder width apart, and the toes of both feet aligned with the edge of the takeoff platform. Participants were then instructed to stand on their dominant leg, drop off, and land as naturally as possible with their dominant foot only centered on the force plate and jump vertically as soon as possible. The participants were asked to keep their hands on

						their hips when landing to reduce any variability from swinging arms.
King et al, 2018 [42] **Cross Sectional Ireland** **In English**	PA: Multidirectional field sport Level: N/R Time Since ACLR: 8.8±0.7 months ACLR: (m=156), (f=0); Age: 24.8±4.8 y/o Control: N/A ACLD: N/A	To identify biomechanical and performance variable differences between ACLR and non-ACLR limbs 9 months after surgery across a number of jump tests	GRF (vertical, posterior)	1000 Hz	3 trials of each limb and jump	A standardized warm-up: a 2-min jog, 5 bodyweight squats, 2 submaximal and 3 maximal double-leg countermovement jumps. Double-legs drop jump (DLDJ). Single-leg drop jump (SLDJ), single-leg hop for distance (SLHD) and hurdle hop (HH) tests. Wearing own footwear, hands on hips DLDJ (30cm step), SLDJ (20cm step): subject was asked to roll from the step and upon hitting the ground, to jump as high as possible while spending as little time as possible on the force plate. For the DLDJ the subject started with their feet approximately hip width apart and landed with 1 foot on each of the force plates. HH (15cm hurdle): starting by standing on the leg to be tested then jumping over the hurdle towards the contralateral side and then rebound over the hurdle again to the start position
King et al, 2019 [85] **Cross Sectional Ireland** **In English**	PA: Multidirectional field sports Level: N/R Time Since ACLR: 9.4±0.7 months ACLR: (m=156), (f=0); Age: 24.8±4.2 y/o Control: (m=62), (f=0); Age:	To identify differences in asymmetry of biomechanical and performance variables during jump and change of direction testing between	Ground reaction force (N/kg) in vertical, medial and posterior directions	1000 Hz	3	A standardized warm-up: a 2-min jog, 5 bodyweight squats, 2 submaximal and 3 maximal double-leg counter movement jumps. Wearing own athletic footwear

	24.7±3.9 y/o ACLD: N/A	athletes who were 9 months post-ACLR and a matched healthy cohort				The testing protocol included the DLDJ from 30 cm, the SLDJ from 20 cm, the SLHD, and 90° planned and unplanned change of direction
***Krafft et al, 2017** [82] **Cohort** **Germany** **In English**	PA: Athletes Level: Recreational Time Since ACLR: 6 months ACLR: (m=N/R), (f=); Age: 32.0±13.3 y/o Control: (m=N/R), (f=N/R); Age: 33.3±13.4 y/o ACLD: N/A	To examine the functional state of ACL reconstructed subjects comprehensively by the combination of self-evaluating questionnaires, functional clinical as well as static and dynamic functional performance testing (FPTs) and in comparison to matched Healthy Control subjects	Jumping height (absolute value) Acceleration impulse during take-off (LSI) Deceleration impulse during landing (LSI)	1000 Hz	3	Double-leg support Double-leg support Subjects performed 3 countermovement jumps (CMJs) akimbo
Królikowska et al, 2018 [44] **Case Control** **Poland** **In English**	PA: Different sports Level: Recreational Time Since ACLR: 25.8±10.3 months ACLR: (m=38), (f=0); Age: 29.7±8.6 y/o Control: (m=38), (f=0); Age: 26.3±4.1 y/o ACLD: N/A	To investigate whether double-leg and single-leg vertical hop landing between-limb symmetry in males, an average of 2 years after ACLR, is associated with the duration of postoperative physiotherapy supervision.	Peak vGRF vGRF normalized to the body mass (BM) The vGRF BM limb symmetry index (LSI)	N/R	10	Sport outfit and sport shoes. While single hopping, the contralateral knee was flexed 90◦ The participant placed his right foot on the middle of the right force plate and left foot on the middle of the left plate. Then, he performed 10 continuous double-leg vertical hops. Next, the vGRF values during the single-leg vertical hops were measured, starting with the uninvolved leg in ACL-reconstructed patients and with the dominant limb in the control

						group. The examined participant placed the foot of the studied leg in the middle of the force plate and performed 10 continuous single-leg vertical hops
Królikowska et al, 2018 [45] **Cross Sectional Poland** **In English/Polish**	PA: Different sports Level: Recreational Time Since ACLR: 28.1±11.0 months ACLR: (m=15), (f=0); Age: 29.8±4.5 y/o Control: (m=15), (f=0); Age: 23.1±1.7 y/o ACLD: N/A	To assess the lower limb loading asymmetry in the landing phase of hops in males, 2 years after ACLR and the assessment of the supervised postoperative physiotherapy during the period shorter than 6 months.	vGRF normalized to the body mass The vGRF BM limb symmetry index (LSI)	N/R	10-Jun	Warm-up on a cycle ergometer. Sport outfit and sport shoes. While single hopping, the contralateral knee was flexed 90◦ The participant placed his right foot on the middle of the right force plate and left foot on the middle of the left plate. Then, he performed 6-10 continuous double-leg vertical hops. Next, the vGRF values during the single-leg vertical hops were measured, starting with the uninvolved leg in ACL-reconstructed patients and with the dominant limb in the control group. The examined participant placed the foot of the studied leg in the middle of the force plate and performed continuous single-leg vertical hops
Krolikowska et al, 2018 [46] **Case Control Poland** **In English**	PA: Different sports Level: Recreational Time Since ACLR: 7.5±1.7 months ACLR: (m=35), (f=0); Age: 25.8±5.2 y/o Control: (m=20), (f=0); Age: 22.5±1.8 y/o ACLD: N/A	To investigate the vertical jump landing limb symmetry at 7 months after ACL reconstruction between a group of patients receiving a longer supervised physiotherapeutic	Body mass peak vertical ground reaction force Limb symmetry index (LSI)	N/R	10-Jun	Warm-up on cycle ergometer. Sport outfit and sport shoes. While single hopping, the contralateral knee was flexed 90◦ Each jump was performed in the upright position. The protocol did not allow for countermovement, and arm movement during the jumps was

		procedure and a group of patients who followed a shorter supervised physiotherapy.				restricted. First, VGRF values during two-legged vertical jumps landing were measured. At the beginning of the measurement the participant placed his right foot on the middle of the right force plate and left foot on the middle of the left plate. The participant then performed 6 - 10 continuous 2-legged vertical jumps. Second, VGRF values during 1 legged vertical jumps landing were measured, starting with the uninvolved leg in Groups I and II and with the right leg in Group III. The participant placed the foot of the studied leg in the middle of the force plate and performed 6 - 10 continuous 1-legged jumps. The second leg was flexed 90 degrees at the knee joint. Measurement was then performed for the second leg in the same way.
Kuster et al, 1999 [47] **Quasi Experimental Switzerland** **In English**	PA: N/R Level: N/R Time Since ACLR: 33.6±7.2 months ACLR: (m=24), (f=12); Age: 31.7±9.9 y/o Control: N/A ACLD: N/A	“The present study used the one-legged stance test to evaluate the enhancement of muscle control and coordination afforded by the use of an elastic compression sleeve after ACL reconstruction. It also included a one-legged drop jump to further	Peak impact loading for the landing phase. Force-time integrals Path length (PL), Root mean square error	100 Hz	3	Participants were required to perform a standing drop jump from a 10-cm-high platform onto a force plate landing on 1 leg and thereafter maintain a one-legged balance for 25 s. This task was repeated on the previously injured leg 3 times without and 3 times with an elastic compression sleeve.

		stress the balance control system."	of the force components CoP			
Labanca et al, 2016 [48] **Cohort** **Italy** **In English**	PA: Sports Level: Competitive level Time Since ACLR: 6 months ACLR: (m=53), (f=5); Age: 22.0±6.0 y/o Control: N/A ACLD: N/A	To investigate the relationship between asymmetrical lower extremities loading 1 mo. after ACL reconstruction measured by means of STS movement and asymmetrical lower extremity loading 6 mo. after surgery measured by means of CMJ.	GRF LSI	100 Hz	3	Subjects were asked to stand in an upright position with shoes on and hands on their hips. They were then asked to quickly squat with knees flexes to approximately 90 degrees and then jump immediately as high as possible without pausing. A total of 3 CMJ trials with 1-min rest in between were performed for each session.
Labanca et al, 2018 [49] **Experimental** **Italy** **In English**	PA: Sports Level: Competitive Time Since ACLR: 6 months ACLR: (m=63), (f=0); Age: 23.2±4.6 Control: N/A ACLD: N/A	To investigate the effectiveness of introducing an additional rehabilitation exercise based on NMES of the quadriceps muscle superimposed on voluntary sit-to-stand-to-sit exercises (STSTS) during the early phase of rehabilitation after ACL reconstruction compared with a traditional rehabilitation protocol alone or a traditional	GRF LSI	100 Hz	3	Shoes on Patients were asked to stand in an upright position and maintain their hands on their hips during performance of the whole movement. They were asked to quickly squat with knees flexed to approximately 90 degrees and then jump immediately as high as possible without pausing.

		protocol associated with STSTS exercises without NMES.				
Lam et al, 2011 [50] **Cross Sectional China** **In English**	PA: N/R Level: N/R Time Since ACLR: 10.3±3.9 months ACLR: (m=10), (f=0); Age: 27.2±4.7 y/o Control: N/A ACLD: N/A	To prospectively investigate the range of tibial rotation of ACLD and ACLR knees during a high-demand task	Vertical ground reaction force (only presented in a graph as an example, but not quantified)	1080 Hz	N/R	Pivot direction (testing left and right leg) Participants jumped off a platform, 40cm in height and 10 cm behind the force plate, and landed with both feet on the ground, with only the testing foot on the force plate. After the foot contact, they pivoted 90° to the lateral side of the testing leg, which acted as the core leg during pivoting. They were then instructed to run away with their maximum effort for 3 steps after completing the pivoting movement
Markstrom et al, 2020 [51] **Cross Sectional Sweden** **In English**	PA: Athletes Level: Moderate to high (Tegner 7.0 ±2.0) Time Since ACLR: Median (IQR): 16.0 (35.2) months ACLR: (m=8), (f=24); Age: 24.1±4.5 y/o Control: (m=8), (f=24); Age: 22.9±3.1 y/o ACLD: N/A	To investigate landing control after ACLR with regard to dynamic knee robustness and whole body movement strategies during sports-mimicking side hops, and to evaluate functional performance of hop tests and knee strength.	Peak vGRF	1200 Hz	05-Mar	Barefoot, holding a short rope (25 cm, with knots at each end) with both hands behind their back. Participants hopped on 1 leg to the side (laterally with respect to the hopping leg) over a distance of 25% of body height, followed by an immediate rebound back to the starting position for the same leg. Trials were deemed successful if the following criteria were fulfilled: a minimum 3-second single-leg stance after landing without releasing the rope, no contact of the contralateral foot with the floor, and no moving of

						the ipsilateral foot to maintain balance. They alternated between legs every trial to reduce fatigue. Participants had ~5 seconds of rest between trials and ~5 minutes of rest between tests. The biomechanical analyses focused on the landing phase after the lateral hop of the SRSH, defined from initial contact (IC; vertical force .20 N) until peak knee flexion
Markstrom et al, 2018 [52] **Test-retest design** **Sweden** **In English**	PA: Athletes and non athletes Level: Moderate (Tegner score: 6.5±5) Time Since ACLR: Median (IQR): 19.0 (122.0) months ACLR: (m=8), (f=22); Age: 24.5±4.4 y/o Control: (m=8), (f=22); Age: 22.5±3.1 y/o ACLD: N/A	To evaluate within-session reliability and agreement for trunk, hip and knee angles and moments for ACLR persons in end phase of or post-rehabilitation and healthy-knee controls during SRSH landings. Further, we aimed to evaluate test-retest reliability and agreement for controls. Finally, we assessed reliability and agreement of Time to Stabilization (TTS), another measure used to evaluate knee function in ACL-injured persons	Time to Stabilization (TTS)	1200 Hz	10	Barefoot, holding a short rope (25 cm, with knots at each end) with both hands behind their back Participants stood on 1 leg on the side of 1 tape and were instructed to laterally hop over and land on the other side of the other tape, and to as fast as possible rebound back to the starting position. They were told to control the 2nd Landing and achieve a stable posture as quickly as possible and keeping the foot of the landing leg still on the floor. Trials were deemed successful provided that: the participant accomplished 3 s of single-leg stance after landing without letting go of the rope, did not put the contralateral foot on the floor, and did not make significant adjustments with the

						ipsilateral foot in order to maintain balance. Participants alternated between legs every trial to avoid fatigue, starting on the non-affected leg for ACLR and dominant leg (defined as the self-preferred leg for kicking a ball) for CTRL. The time between each trial was approximately 5s.
Melińska et al, 2015 [53] **Cross Sectional Poland** **In English**	PA: N/R Level: N/R Time Since ACLR: 8 months ACLR: (m=6), (f=0); Age: 26.2±2.3 y/o Control: (m=22), (f=0); Age: 25.1±4.3 y/o ACLD: N/A	To evaluate balance during the landing phase in a control group and patients after anterior cruciate ligament reconstruction (ACLR)	Horizontal components ratio of ground reaction force, sum and average of fluctuations of eCoG (estimated body's mass center of gravity)	N/R	1	Warm-up involved trotting (3-4 minutes), 5-7 jumps, and (after a 20s interval) 4-5 squats. Jump-down performed from 3 step heights (0.1, 0.2, and 0.3 m). Participants jumped down and were instructed to land on toes and metatarsus on both limbs (1 limb per platform)
Miranda et al, 2013 [54] **Cross Sectional USA** **In English**	PA: N/R Level: Recreational Time Since ACLR: 60 months ACLR: (m=4), (f=6); Age: 26.96±5.3 y/o Control: (m=5), (f=5); Age: 25.20±5.2 y/o ACLD: N/A	To compare force plate kinetic data and knee kinematic measurements from male and female ACLINT and ACLREC recreational athletes during a jump-cut maneuver in hopes that the differences would point to	Peak GRF (magnitude of body weight), peak vertical GRF time, peak vertical GRF magnitude	5000 Hz	10	Subjects stood 1 m from force plate with knees bent approx. 45 degrees. Upon hearing "go" prompt, subject jumped forward to landing target on force plate, and a visual directional prompt cued subject to cut left or right after landing on the target with 1 leg. Upon landing, subjects performed a side step cut and then jogged past the respective angled targets.

		plausible risk factors for injury				
***Moya-Angeler et al, 2017** [83] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 6 and 12 months ACLR: (m=74), (f=0); Age: 34.0±9.0 y/o Control: N/A ACLD: N/A	To evaluate the functional status prior to and at different times after ACLR, and to analyze the changes in the kinetic patterns of the involved and uninvolved limb lower during gait, sprint and 3 hop tests	Drop vertical jump: fallen maximum vertical force (MVF), impulse MVF	N/R	3	All activities performed on force plates. Gait: 5-m walkway with force plates embedded, walk at self-selected comfortable pace. Sprint: patient started standing on both platforms, instructed to sprint as fast as possible for 5 s Single-leg hop: stand on 1 leg, hop as far forward as possible Drop vertical jump: dropped off 30 cm box and performed maximal jump after landing Vertical hop test: begin standing on both platforms, hop using arms as countermovement
Nagelli et al, 2019 [55] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.7±3.7 months ACLR: (m=8), (f=10); Age: 19.4±7.2 y/o Control: (m=4), (f=6); Age: 16.4±3.6 y/o ACLD: N/A	The primary purpose of the study is to determine whether a neuromuscular training (NMT) program can change single-leg landing knee biomechanics within the group of athletes with ACLR. The secondary purpose	Vertical GRF (N/kg)	1200 Hz	5	Single-leg drop (SLD) landings of both limbs off of a 30.5- cm plyometric box onto embedded force plates

		of this study was to compare the post-training single- leg landing knee mechanics between the ACLR cohort and an uninjured, control cohort.				
Nagelli et al, 2018 [56] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.7 ±3.7 months ACLR: (m=8), (f=10); Age: 19.4±7.2 y/o Control: (m=4), (f=6); Age: 16.0±3.7 y/o ACLD: N/A	To quantify the effects of a neuromuscular training (NMT) training program on hip biomechanics and neuro- muscular control in an ACLR cohort. Second, this study sought to frame post training hip biomechanics of an ACLR cohort with reference to the same measures for a group of uninjured control athletes who also participated in the NMT program.	Peak vGRF	1200 Hz	5	The athletes performed 5 successful drop vertical jumps (DVJs) - a bilateral drop-landing task from a 31-cm-tall box, followed by an immediate maximum effort vertical jump
Niederer et al, 2020 [57] **Cross Sectional** **Germany** **In English**	PA: N/R Level: N/R Time Since ACLR: 39±12 months ACLR: (m=14), (f=13); Age: 29.7±3.1 y/o Control: N/A ACLD: N/A	1) to delineate a potential deficit in the ability to perform unanticipated jump-landing maneuvers, 2) to develop a standardized and reproducible assessment of	Time to stabilization (calculated over body weight and over the normal force), peak vGRF, path	50 Hz	3	Warm-up included 30 jumping jacks. Participants performed (bilateral take- off) countermovement jumps with single-leg landings. At takeoff, the participants received visual information indicating the landing leg. A left or right footprint located on the left or right side of a vertical

		unanticipated single-leg jump-landing ability and quality, and 3) to assess the duration of such a (potential) unanticipated landing impairment after ACL reconstruction and RTS.	length of the center of pressure			line appeared on a laptop screen placed in the line of sight. Leg side was chosen randomly using a complete randomization.
Niemeyer et al, 2019 [58] **Cross Sectional** **Germany** **In English**	PA: Football (2), basketball (1), tennis (2), handball (2), kickboxing (1), skiing (1), dancing (1), triathalon (1) Level: N/R Time Since ACLR: 12.7±3.5 months ACLR: (m=5), (f=6); Age: 35.6±12 y/o Control: N/A ACLD: N/A	1) Reproduce previous findings of a side-to-side asymmetry in unanticipated jump-landing outcomes after ACL-reconstruction 2) Reveal if the values themselves and/or the LSI of such landings provide more relevant in- formation, 3) Determine if the jump-landing assessment, in comparison to well-established RTS jumping criteria, provides unique information	Time to stabilization and peak GRF at landing	50 Hz	3	A standardized warm-up, consisting of slow running 2 minutes on a treadmill (10% incline, 10 km/h) and three drop jumps (drop height: 15 cm) Left and right leg landing Unanticipated jump landing: perform a countermovement jump with a single-leg landing; at takeoff visual info depicts landing leg to be used. Drop jump: performed from 32 cm box; start with bipedal hip-width stance on box: frontal step, drop, explosive reactive jump with shortest possible ground time; instructed to jump as high as they could
Oberlander et al, 2013 [59] **Cohort** **Germany**	PA: Soccer, basketball, skiing Level: N/R Time Since ACLR: 6 and 12 months ACLR: (m=N/R), (f=); Age:	To examine knee extensor muscular capacity and landing mechanics (i.e., trunk angle characteristics,	GRF (magnitude)	1000 Hz	5	Subjects performed a modified single-leg hop test (SLHT) for distance, keeping their hands on their hips and wearing their own sports shoes. This hop was performed with

In English	28.0±7.0 y/o Control: N/A ACLD: N/A	joint kinetics, and postural dynamic stability control) in a group of unilateral ACL re- construction patients at 6 and 12 months after surgery, using an SLHT on the involved and uninvolved legs. Moreover, we aimed to combine the results from the current work with our previous findings (25) to identify potential changes in the extent of functional recovery, from the ACLD state to 6 and 12 months after ACLR using the same patients.				1 leg over a given distance of 0.75 x body height. Landing had to be on the force plate within a target area corresponding to the given distance +/- 5 cm. Subjects had to perform 5–10 valid SLHTs with each leg.
***Orishimo et al, 2010** [84] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.2±2.7 months ACLR: (m=9), (f=4); Age: 33±10 y/o Control: N/A ACLD: N/A	To compare joint ranges of motion, joint moments and joint powers in the involved and noninvolved legs of patients who have had an ACL reconstruction as they performed the single-leg hop test.	Overall peak GRF magnitude, peak anterior GRF, peak vertical GRF	960 Hz	3	Alternating the involved and non-involved legs Takeoff trials: subjects started in single-leg stance with their foot in the center of the force plate. They then performed a single-leg hop for maximal horizontal distance, landing on the same leg on the laboratory floor. There were no restrictions of upper extremity movement. Hop distance was measured from the toe in the starting position to the heel at

						landing. The average distance of the 3 takeoff trials was measured from the center of the force plate and marked as the starting point for the landing trials. Landing trials: subjects started in single-leg stance with their toe at the starting point and performed 3 single-leg hops onto the force plate.
Paterno et al, 2011 [60] **Cross Sectional** **USA** **In English**	PA: Jumping, pivoting or cutting activity (Level I/II sports) Level: Competitive Time Since ACLR: 6.9±1.7 months ACLR: (m=21), (f=35); Age: 16.4±3.0 y/o Control: (m=12), (f=29); Age: 16.8±2.3 y/o ACLD: N/A	While asymmetries in loading patterns during dynamic landing tasks were observed in female athletes 2 years after ACLR, it is unknown if there are similar patterns of asymmetry at the time of RTS after ACLR in male athletes. Therefore, the purpose of this study was to determine if a similar pattern of lower limb asymmetries might exist at the time of RTS after ACLR in both males and females.	Peak VGRF (normalized to body weight), peak VGRF Limb Symmetry Index ((involved/un-involved)*100%)	1200 Hz	3	The participant was positioned on top of a 31-cm box and instructed to drop off the box, with both feet leaving the box simultaneously and each foot landing on a separate force platform, then to immediately execute a maximal effort vertical jump towards an overhead target
Patterson et al, 2013 [61] **Cross Sectional** **Ireland**	PA: Gaelic football, soccer, hockey, basketball Level: Club or county level Time Since ACLR: 42.0±38.9 months	To examine time to stabilization (TTS) values in a group of female athletes who had returned to full	Time to stabilization for forward land and diagonal land	2000 Hz	3	Barefoot Forward landing trials: each subject standing on top of a 35-cm box with feet shoulder width apart. They were

In English	ACLR: (m=17), (f=0); Age: 20.8±1.1 y/o Control: (m=17), (f=0); Age: 22.6±3.4 y/o ACLD: N/A	sports participation following ACL reconstruction as well as in a group of controls. TTS from a diagonal landing was compared to TTS from a forward landing.	in: AP, ML, RV (resultant vector) directions			then instructed to place their hands on their hips and to look straight ahead. After an audio cue, each subject stepped forward, leading with the test leg, and dropped from the step, landing on the force plate on the test leg only. Subjects were instructed to stabilize as quickly as possible upon landing and to hold a still position for 15 s Diagonal landing task: subjects stood bare-foot in single-leg stance at the posterior lateral aspect of a force plate on the non-test leg. They were then required to perform a diagonal jump to land onto the middle of another force plate, land on the test leg and remain still for 15 s. Subjects were instructed to stabilize as quickly as possible upon landing.
Pfeiffer et al, 2018 [62] **Cross Sectional** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 49.6±40.6 months ACLR: (m=9), (f=26); Age: 22.1±3.4 y/o Control: N/A ACLD: N/A	The primary purpose of this study was to determine if individuals with a unilateral ACLR, who demonstrate greater peak kinematic and kinetic magnitudes in the ACLR and uninjured limb during walking gait also demonstrate greater peak kinematic and kinetic magnitudes in	Peak vGRF, instantaneous loading rate, linear loading rate	1200 Hz	5	Gait: Participants completed walking trials barefoot. During all walking gait trials, participants were instructed to walk at a self-selected speed over 2 force plates embedded in a staggered formation towards the middle of a 6m walkway so that the entire stance phase for both limbs could be collected during a single trial Jump landing: All participants wore their own athletic footwear for the jump-landing trials. Participants

		each limb during jump-landing. Additionally, we will determine if those who demonstrate greater kinematic and kinetic asymmetries during walking gait also demonstrate greater asymmetries during jump-landing using limb symmetry indices (LSI).				performed jump- landing from a 30cm box positioned 50% of the participant's height from the front edge of the force plates on each force plate, and immediately jump vertically as high as possible
Pua et al, 2017 [63] **Cohort Singapore** **In English**	PA: N/R Level: Competitive (65 participants) Time Since ACLR: 6 months ACLR: (m=60), (f=10); Age: 25.4±5.9 y/o Control: N/A ACLD: N/A	To evaluate the prospective associations among quadriceps strength and RTD and single-leg hop for distance, single-leg vertical jump, as well as the vGRF and loading rate during landing from a vertical jump in persons who have undergone ACLR. Also examined performance measures such as hop distance and jump height as they are common clinical measures and provide a gross measure of athletic performance	Normalized vGRF, loading rate	1000 Hz	2	Single-leg vertical countermovement jump. Patients placed hands on hips, instructed to jump as high as they could while maintaining a stable landing

****Read et al, 2020** [81] **Cross Sectional** **Qatar** **In English**	PA: Soccer Level: Professional Time Since ACLR: 7.2±0.8 and months ACLR: (m=124), (f=0); Age: 23.8±6.1 y/o Control: (m=204), (f=0); Age: 24.2±4.7 y/o ACLD: N/A	Our primary aim was to compare the performances of each group with those of matched controls. The second aim was to determine which kinetic variables measured during the CMJ best distinguished between the healthy players and those with a history of ACLR.	Concentric impulse, concentric peak force asymmetry, eccentric mean force asymmetry, eccentric deceleration impulse asymmetry, eccentric rate of force development asymmetry, peak landing force asymmetry	1000 Hz	3	Countermovement jump. Patients stood upright with hands on hips, remained motionless on force plates for 3 sec, then performed downward motion to self-selected depth, and then immediate upward motion.
Richter et al, 2019 [64] **Cross Sectional** **Ireland** **In English**	PA: Multi-directional sport Level: N/R Time Since ACLR: 9.4±0.7 months ACLR: (m=156), (f=0); Age: 24.8±4.8 y/o Control: (m=62), (f=0); Age: 24.8±4.2 y/o ACLD: N/A	To develop and test a data driven framework (feature generation based on no expert or prior knowledge) to classify movement patterns of normal and rehabilitating athletes using only biomechanical data	vGRF	1000 Hz	3	A standardized warm-up Shoes on Subjects performed 7 exercises (only 3 had force plate data): double-leg drop jump, single-leg hop, hurdle hop
Rudroff et al, 2003 [65] **Cross Sectional** **Germany**	PA: Soccer Level: N/R Time Since ACLR: 24 months ACLR: (m=30), (f=0); Age: 30.9±5.4 y/o Control: (m=10), (f=0); Age:	To compare the clinical outcome of ACL reconstruction using the four-strand ham- string tendon autografts and ACL	Vertical jump-off force, first vertical maximum	1000 Hz	Squats: 5 trials; gait, one- and two-legged	Two-legged jump: jumped down from a 26-cm step 6 consecutive times One-legged jump: initiated from standing anatomical position with

In English	31.1±4.7 y/o ACLD: N/A	reconstruction using the patellar tendon graft 2 yr. after surgery.			jumps: 6 trials	hands on hips, flexed hip/knee to 90 degrees and performed maximal jump Squats: in standing position, femurs rotated externally (feet abducted 20 degrees), lowered center of mass to 90 degrees at approx. 30 deg/sec Gait: walk barefoot over 2 force plates 6 times; data of last 5 trials used
Schilling et al, 2020 [66] **Cohort** **USA** **In English**	PA: Sports Level: Collegiate Athlete Time Since ACLR: Range (6-71) months ACLR: (m=7), (f=14); Age: 20.3±1.7 y/o Control: N/A ACLD: N/A	To assess the readiness for return to sport in a sample of division III athletes following ACLR and medical clearance.	vGRF	N/R	3	Participants performed a single maximum single-leg squat test (SLST) while standing on a 12 in.-high step (30.48 cm). The participants were then asked to perform a single-leg landing task from the step and land on a force plate that was located 12 inches away from the step.
Schneider et al, 2017 [67] **Cross Sectional** **USA** **In English**	PA: Different sports Level: N/R Time Since ACLR: Returned to sport (i.e., more than 6 months) months Dominant/Non-dominant: N/R ACLR: (m=10), (f=26); Age: 16.4±1.1 y/o Control: (m=45), (f=22); Age: 17.3±1.9 y/o ACLD: N/A	To evaluate a mass-spring-damper model may serve as an extension of biomechanical data from 3 dimensional motion analysis and epidemiological data.	The force produced by the spring is Fs = kspring*L The force produced by the damper is Fd = kdamper*V given that L is the length of the spring	50 Hz	3	Box height of 31 cm Subjects were instructed to drop off the box, to land on the ipsilateral foot directly in front of the box and to hold the landing for 3 second Subjects were instructed to line up at their individual starting positions located at 50% of their maximum double-limb broad jump distance (taken from a previous test). Subjects were instructed to initiate the

			(leg deformation) and V is the velocity of the mass. Spring and Damper ratios LSI			movement while balancing on 1 foot, to hop as far forward as possible, and to land on the ipsilateral foot with their heels beyond a tapeline located at the front edge of a portable force plate. A landing stabilized for 1-second was required for a successful trial.
Shimizu et al, 2019 [68] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: Range (6-36) months ACLR: (m=17), (f=14); Age: 31.3±7.8 y/o Control: N/A ACLD: N/A	To investigate the longitudinal changes in landing mechanics and knee kinematics for patients both before and 3 years after ACLR and to investigate the association between changes in landing mechanics and magnetic resonance (MR) knee kinematics.	vGRF	1000 Hz	3	The drop-jump task, as previously described,11 involved the participant standing on a 30-cm high platform, stepping off with 1 foot, and landing with 1 foot on each of the force plates. The participant was instructed to land with both feet contacting the ground simultaneously and then immediately jump as high as possible. A successful trial was defined as 1 in which the participant stepped off the platform as opposed to jumping off or lowering himself or herself down, landed with both feet simultaneously with 1 foot on each force plate, and immediately performed a maximal vertical jump. Three successful drop-jump trials were collected and used for analysis.
Shimizu et al, 2020 [69] **Cohort** **USA, Japan** **In English**	PA: N/R Level: N/R Time Since ACLR: Range (6-36) months ACLR: (m=20), (f=16); Age: 31.3±7.8 y/o	(1) to investigate the longitudinal changes in meniscal T1r/T2 values and biomechanics during gait and landing tasks	Peak vGRF	1000 Hz	3	Shoes on Participants were instructed to walk at a controlled speed of 1.35 m/s. Standing on a 30-cm platform,

	Control: (m=9), (f=5); Age: 31.4±4.9 y/o ACLD: N/A	after ACLR (2) to investigate the associations between changes in meniscal composition using T1r/T2 mapping and biomechanics in patients with ACLR.				stepping off with 1 foot, and landing with 1 foot on each of the force plates. The participant was instructed to land with both feet contacting the ground simultaneously and then immediately jump as high as possible. A successful trial was defined as 1 in which the participant stepped off the platform as opposed to jumping off or lowering himself or herself down, landed with both feet simultaneously with 1 foot on each force plate, and immediately performed a maximal vertical jump. Three successful drop-jump trials were collected and used for analysis.
Shimizu et al, 2019 [70] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: Range (6-36) months ACLR: (m=17), (f=14); Age: 31.3±1.4 y/o Control: (m=10), (f=6); Age: 31.7±1.3 y/o ACLD: N/A	To investigate the changes in landing biomechanics over a 3-year period and their correlation with cartilage degenerative changes in the MTFJ of the knee after ACLR using MR T1r mapping.	Peak vGRF vGRF impulse	1000 Hz	3	Standing on a 30-cm high platform, stepping off with 1 foot and landing with 1 foot on each of the force plates. The participants were instructed to land with both feet contacting the ground simultaneously and then immediately jump as high as possible
Smeets et al, 2020 [71] **Cross Sectional** **Belgium, UK** **In English**	PA: A sport that involves cutting, pivoting or jumping Level: Intermediate to high Time Since ACLR: 8.6±1.8 months ACLR: (m=15), (f=6); Age: 23.8±4.2 y/o Control: (m=15), (f=6); Age: 21.5±1.5 y/o ACLD: N/A	to combine conventional biomechanical observation (joint kinematics, kinetics, and muscle activations) to assess single-joint alterations (i.e., biomechanical	vGRF	1000 Hz	3	A standardized warm-up included 5-min cycling on a stationary bike, 10 squats and 10 squat-jumps. Single-leg hop for distance: to jump as far as possible on 1 leg. Medial and lateral hop: to jump sideways over a 0.24-mhigh hurdle

		changes in a single joint) with marker-based PCA to assess whole-body alterations (i.e., a combination of biomechanical changes in multiple joints) during landing strategies. Through this novel combined approach, we want to emphasize that RTS decision should consider both joint-specific alterations as well as whole-body compensatory movements.				(1.5 cm wide) on 1 leg, to cover a medio-lateral distance that was half the leg length (i.e., the distance between the anterior superior iliac spine and medial malleolus). Vertical hop with 90° of medial rotation and vertical hop with 90° of lateral rotation: to jump as high as possible on 1 leg while performing an inward/outward rotation of 90°. For all 3 tasks, participants were instructed to take off and land on the same leg. Trials were considered valid if the landing was central on the force plate and the participant could maintain his/her balance for 5 s after landing without shuffling on the stance leg.
Tsai et al, 2012 [72] **Cross Sectional** **USA** **In English**	PA: Athletes Level: Recreational Time Since ACLR: 36.2±18.5 months ACLR: (m=0), (f=10); Age: 25.3±2.4 y/o Control: (m=0), (f=10); Age: 24.9±1.7 y/o ACLD: N/A	To examine tibio-femoral compressive and shear forces as well as muscle co-contraction and knee flexion during a single-leg drop-land task between females who have undergone ACLR and healthy female controls.	GRF	1500 Hz	3	25cm high platform For the single-leg drop-land task, subjects started from a single-leg standing position on a platform in front of the force plate. Subjects were instructed to land with the tested foot on the force plate and then jump upward as high as possible.
Vairo et al, 2008 [73] **Experimental** **USA**	PA: Athletes Level: Recreational Time Since ACLR: 21.4±10.7 months	To investigate the effects of ISGA ACLR on neuromuscular and biomechanical	vGRF Peak vGRF	1200	3	Standing erect upon only the lower extremity being tested with the foot in neutral position, participants stepped off a 30 cm high platform

In English	ACLR: (m=5), (f=9); Age: 22.5±4.1 y/o Control: (m=5), (f=9); Age: 22.8±3.5 y/o ACLD: N/A	performance during a single-leg vertical drop landing (VDL).				placed 11 cm from the edge of the force-plate. Participants were instructed to land in the center of the force-plate on the lower extremity being tested only. To control for countermovement, participants were restricted to perform VDLs with hands upon hips and the contra-lateral knee joint flexed to 90. It was also stressed that the non-tested shank segment did not come into contact with the tested lower extremity. This aimed at limiting horizontal displacement and enabled the participant to land with a more vertical approach. Following a verbal cue, participants dropped off the platform and landed upon the force-plate
Ward et al, 2018 [74] **Cross Sectional Australia** **In English**	PA: Athletes Level: Moderate Time Since ACLR: 52.0±42.0 months ACLR: (m=7), (f=21); Age: 22.4±3.7 y/o Control: N/A ACLD: N/A	To evaluate the associations between indices of quadriceps neuromuscular function (strength, voluntary activation, and spinal-reflex and cortico-motor excitability) and sagittal-plane knee kinetics (peak KEM), kinematics (knee-flexion angle at initial contact [IC], peak knee-flexion angle, and knee flexion	Peak vGRF	1200	3	Shoes on Participants performed a jump-landing task from a 30-cm box positioned at 50% of the participant's height from the front edge of the force plates.31 We instructed them to jump forward off the box to a double-legged landing with 1 foot on each force plate and then immediately jump vertically as high as possible. A trial was considered successful if the participant left the box with both feet at the same time, landed on the force plates, and jumped straight up in the air. If the

		excursion), and peak vGRF during jump landings after ACLR.				trial was unsuccessful, a subsequent trial was collected for analysis.
Webster et al, 2004 [75] **Cross Sectional Australia** **In English**	PA: Sport Level: High Time Since ACLR: 11.6±2.6 months ACLR: (m=18), (f=2); Age: 25.5±6.4 y/o Control: N/A ACLD: N/A	To examine and compare sagittal plane joint angles, moments and ground reaction forces in patients with hamstring tendon (HS) and PT graft ACL reconstructions during 2 functional landing tasks.	Peak vGRF	400 Hz	6	15 cm high box Subjects were instructed to stand on the test leg, place their hands on their hips and, at the experimenter's count of three, hop forward and land on the same leg, in the center of the force plate. They were further instructed that on landing they were to look straight ahead and stabilize as quickly as possible. Once the experimenter had judged that the subject was stable a cue was given to notify the subject of completion of the activity
Webster et al, 2004 [76] **Cross Sectional Australia** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.5 (range 6–9) months ACLR: (m=5), (f=3); Age: 25 (range 18-32) y/o Control: N/A ACLD: N/A	To determine whether, compared to the barefoot state, wearing sports shoes influenced knee kinetics and kinematics during single limb landing in subjects following ACL reconstruction.	Peak vGRF	400 Hz	6	Subjects were required to perform one-legged vertical hops from a 15 cm high box on to the force plate, both barefoot and whilst wearing sports shoes. The subject was directed to stand on the test leg, with hands on hips, and at the count of three, hop forward and land on the center of the force plate. They were required to keep the foot fixed at the landing position until stable at which time they were instructed by the experimenter to ''walk forward'' to clear the force plate.
Webster et al, 2010 [77] **Cross**	PA: Collegiate athletics Level: Division 1 Time Since ACLR: 30±14.2	to use TTS to measure differences in dynamic postural control during	Time to stabilization (TTS)	180 Hz	3	Athletic clothing and athletic shoes

Sectional **Australia** **In English**	months ACLR: (m=0), (f=12); Age: 20.5±1.2 y/o Control: (m=0), (f=12); Age: 19.3±1.1 y/o ACLD: N/A	jump landings in ACLR knees compared with healthy knees among Division I female athletes.				Participants were instructed to stand behind a mark on the floor that was 70 cm away from the center of the force platform. They were instructed to jump off anteriorly from 2 feet, hit the target on the Vertec with their fingers, and land on the force platform on the designated foot. All participants were right-hand dominant and used the right hand to hit the Vertec. They were instructed to ''stick the landing,'' place their hands on their hips as soon as possible, and hold the position as motionless as possible for 10 seconds.36 These were the only restrictions placed on the technique of the jump and landing.
Wren et al, 2018 [78] **Retrospective Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 7.2±1.3 months ACLR: (m=19), (f=27); Age: 15.6±1.7 y/o Control: (m=12), (f=24); Age: 14.7±1.5 y/o ACLD: N/A	To assess biomechanics and symmetry of adolescent athletes following ACLR during a single-leg hop for distance.	Peak GRF	2400 Hz	3	5-min warm-up For the single-leg hop, participants were instructed to stand on 1 leg and jump as far as possible, landing on the same leg on a target force plate. For a trial to be successful, participants were required to stick the landing for a minimum of 2 seconds.
Studies used Contact Mats Connected to a Jump system to assess "Jumping" (n=3)						
Borin et al, 2017 [87] **Experimental** **Brasil** **In English**	PA: Athletes Level: N/R Time Since ACLR: 22.9±16.1 months ACLR: (m=18), (f=8); Age: Range (18-30) y/o	To evaluate the effects of a specific training program for the hip musculature on the functional alterations of athletes of both genders	Jump height Total Power Relative Power	N/R	3	In order to evaluate the explosive strength of the lower limbs, the technique of Counter Movement Jump (CMJ) was used with the aid of the arms. Athletes stood with the trunk erect and knees in 180°

	Control: N/A ACLD: N/A	submitted to ACL reconstruction surgery.				extension. Then, the knees were flexed to ~120° followed by knee 81 extension push the body vertically. The knees remained in extension during the flight phase. The interval between attempts was 10 sec. Three attempts were made from which the best jump was recorded.
Papandrea et al, 1990 [90] **Cross Sectional** **Italy** **In Italian**	PA: Volleyball Level: N/R Time Since ACLR: 24.0 months (SD:N/R) ACLR: (m=2), (f=10); Age: 23.0 (SD:N/R) y/o Control: N/A ACLD: N/A	To analyze jumping ability of volleyball players after ACLR.	LSI	N/R	3 squat jumps 10 CMJs	N/R
Petschnig et al, 1997 [91] **Cross Sectional** **Austria** **In English**	PA: N/R Level: N/R Time Since ACLR: 13.7±1.1 months ACLR: (m=27), (f=0); Age: 28.1±0.9 y/o Control: (m=50), (f=0); Age: 29.3±1.1 y/o ACLD: N/A	The first was to further evaluate dynamometric measurements, single and trip hop tests, and one-legged and two-legged vertical jump tests. These tests were chosen to compare untrained subjects with no prior history of knee injury and patients after ACL reconstruction with respect to the uninvolved leg. In addition, we attempted to determine differences between the patient's involved and uninvolved legs, and the	Jump heights calculated from flight time	N/R	3	One-legged and two-legged jump vertical jump: subjects performed three 10-s jumping trials at maximum frequency and jumping as high as possible. Subjects were instructed to keep both their hands on the hips to avoid using them for generating momentum. Best trial used for analysis.

		dominant and non-dominant leg in a control group. The second objective was to determine the relationship between knee extensor strength of the quadriceps, one-legged hop test for distance, and the vertical jump test. We were also looking for a relationship between the one-legged and two-legged vertical jump tests. The final goal was to determine if there existed any differences in 2 different phases of the follow-up period.				
Studies used Single-sensor Insoles to assess "landing" (n=2)						
Peebles et al, 2019 [92] **Cohort** **USA** **In English**	PA: N/R Level: N/R Time Since ACLR: 6.9±1.2 ACLR: (m=9), (f=21); Age: 19.4±4.2 y/o Control: N/A ACLD: N/A	The purpose of the present study was to determine the effect of wearing a custom fit extension constraint functional knee brace on hop distance and plantar loading symmetry during a single, triple, and crossover hop test throughout the RTS transition in patients with ACLR	Limb symmetry index (%) for each hop type for: impact peak, loading rate, impulse	100 Hz	2	With vs. without brace; single hop vs. triple hop vs. crossover hop Each of these hop tests were completed both while wearing a custom fit functional knee brace on the surgical limb and without at each testing visit. Single hop: participants were instructed to hop as far as possible while taking off and landing on the same foot. Triple hop: participants hopped 3 consecutive times without pausing in between hops and the cumulative

						distance was recorded. Crossover hop: participants again hopped 3 consecutive times without pausing, but had to laterally cross over a 6- inch-wide strip with each hop while progressing forwards.
Peebles et al, 2019 [93] **Cross Sectional** **USA** **In English**	PA: N/R Level: Recreational Time Since ACLR: 6.95±1.27 months ACLR: (m=6), (f=19); Age: 18.7±3.0 y/o Control: (m=12), (f=18); Age: 22.2±3.8 y/o ACLD: N/A	The first purpose of this study was to compare hop distance symmetry and loading symmetry between ACLR athletes at the time of return to sport and healthy uninjured recreational athletes. The second purpose of this study was to determine the association between hop distance symmetry and loading symmetry	Limb symmetry index (%) for each hop type for: impact peak, loading rate, impulse	100 Hz	2	During the single hop test, participants were instructed to hop as far as possible while taking off and landing on the same foot. For the triple hop test, participants hopped 3 consecutive times without pausing be- tween hops. Similarly, for the crossover hop test, participants hopped 3 consecutive times without pausing; however, they had to laterally crossover a 6-inch wide strip while still hopping forward. Participants crossed the strip toward the non-hopping leg on the first and third hop and toward the hopping leg on the second hop (38,39). For all 3 tests, participants were required to stick the final landing, defined as maintaining balance for 2 s without touching the ground with the contralateral leg or either hand.
Studies used Balance Platforms to assess "jumping" (n=1)						
Czamara et al, 2011 [88] **Cohort** **Poland** **In**	PA: Team games, athletics, skiing and dancing Level: 17 athletes competitive 46 athletes amateur Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=38), (f=25); Age:	An objective evaluation of physical fitness level in the athletes after ACLR, allowing them to return to training, using the measurement devices in the form of a	Number of jumps Peak and minimum values of GRF	N/R	N/R	One leg jumps with the measurement of ground reaction force values (N) for the vertical component on the MTD balance platform and counting the number of jumps performed.

English/Polish	27.0±8.0 y/o Control: N/A ACLD: N/A	tailored sport-related determinant of functional assessment				
Studies used Pressure Mats to assess "jumping" (n=1)						
Dan et al, 2019 [89] **Cross Sectional** **Australia** **In English**	PA: N/R Level: N/R Time Since ACLR: Range (8-15) months ACLR: (m=47), (f=18); Age: 33.8±10.1 y/o Control: (m=17), (f=20); Age: 25.1±8.5 y/o ACLD: N/A	to explore the utility of this accelerometer and gyroscope system as well as a pressure sensing mat (MatScan, TekScan, South Boston, Massachusetts, USA) in detecting kinetic differences in patients prior to return to sport following ACL reconstruction.	Peak Load flight time	N/R	N/R	Barefoot Single and double-leg

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *IQR* Interquartile range, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *GRF* Ground reaction force, *vGRF* vertical ground reaction force, *pGRF* Posterior grand reaction force, *CoP* center of pressure, *LSI* limb symmetry index, *N/Kg* Newton per kilogram, *AP* anterior posterior, *ML* medial lateral, *RV* resultant vector.
* Studies used force plate for "Landing and Jumping" (n=3)
**Studies used force plate for "Jumping" (n=3)

Table 2 Data Extraction Table for Studies Assessing Standing Balance

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), level, time since surgery, side of surgery, sample size by sex, age)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates to assess "Standing Balance" (n=23)						
Ahmadi et al, 2020 [15] Quasi Experimental Iran In English	PA: Soccer players Level: N/R Time Since ACLR: 14.10±3.99 months ACLR: (m=20), (f=0); Age: 26.55±3.54 y/o Control: (m=20), (f=0); Age: 25.95±4.88 y/o ACLD: N/A	Compare external focus (EF) and continuous cognitive task (CCT) on postural stability after ACL reconstruction	Postural sway area, displacement (AP) and (ML) in CoP, velocity of CoP, and the mean power frequency of the CoP	100 Hz	3	External focus, continuous cognitive task, control condition Maintaining balance while standing on a wobble board on a force plate and then calculating balance related outcomes based on measured CoP trajectories
Birmingham et al, 2001 [94] Cross Sectional Canada In English	PA: N/R Level: N/R Time Since ACLR: 19.4±14.5 months ACLR: (m=15), (f=15); Age: 27.2±11.3 y/o Control: N/A ACLD: N/A	To evaluate the effects an ACL brace has on measures of knee proprioception and postural control assessed using testing situations that involved differing sensory inputs and that challenged postural control to varying degrees	CoP length of path CoP medio-lateral displacement CoP anterior-posterior displacement	60 Hz	3	Brace/no-brace conditions Single-leg standing on a stable platform/7 cm medium density poly-foam Eyes open/closed The balance tests included: 1) standing on the stable platform with eyes open, 2) standing on a foam mat placed over the platform with eyes open, 3) standing on the platform with eyes closed, and 4) standing on the platform after landing from a maximal single-limb forward hop
Bodkin et al, 2018 [95]	PA: N/R Level: N/R	To assess single-leg postural control in	CoP velocity	50 Hz	3	Starting with the non-involved side

Cross Sectional USA In English	Time Since ACLR: 6.5±1.4 months ACLR: (m=59), (f=49); Age: 21.7±8.3 y/o Control: (m=51), (f=49); Age: 21.9±4.0 y/o ACLD: N/A	healthy individuals and ACLR patients around the time point of return to sport progression.				Alternating single-leg balance for 10 seconds on each leg, and repeated 3 times.
Bonfim et al, 2005 [96] Cross Sectional Brazil In Portuguese	PA: N/R Level: N/R Time Since ACLR: 19.6±6.5 months ACLR: (m=N/R), (f=); Age: 24.4±4.5 y/o Control: (m=N/R), (f=N/R); Age: 24.4±3.0 y/o ACLD: N/A	To examine if the performance of postural control of individuals post ACL reconstruction is dependent on the task performed. Specifically, to examine the breadth, the speed and the average frequency oscillation and the displacement area of the center of mass and the pressure center, in the bipedal position and mono-podal, in individuals ACL reconstruction.	Center of pressure displacement in anterior-posterior, and medio-lateral. Center of pressure velocity	100 Hz	3	Standing on 2 legs, arms crossed on chest, eyes closed Standing on right leg, arms crossed on chest, eyes closed, hip neural, knee in 90 flexion Standing on left leg, arms crossed on chest, eyes closed, hip neural, knee in 90 flexion Three trials for each testing condition. Each trial lasted for 30 seconds, with one-minute break in between trials.
Bonfim et al, 2003 [97] Cross Sectional Brazil In English	PA: N/R Level: N/R Time Since ACLR: 18 (range 12-30) months ACLR: (m=7), (f=3); Age: 24.4±4.5 y/o Control: (m=7), (f=3); Age: 24.4±3.0 y/o ACLD: N/A	To examine position perception and threshold for detection of passive knee motion, latency onset of hamstring muscles, and upright stance control in individuals who had	Center of pressure displacement in anterior-posterior, and medio-lateral.	100 Hz	3	Standing barefoot on 2 legs, arms crossed on chest, eyes closed Standing on right leg, arms crossed on chest, eyes closed, hip and knee in 90 flexion Standing on left leg, arms crossed on chest, eyes closed, hip neural, knee in 90 flexion

		undergone ACL reconstruction				Assuming the testing positions (conditions) during 3 trials for each testing condition. Each trial lasted for 30 seconds, with 1 minute break in between trials.
Brunetti et al, 2006 [98] Experimental Italy In English	PA: N/R Level: N/R Time Since ACLR: 9.0 months (SD:N/R) ACLR: (m=30), (f=0); Age: 25.0±3.0 y/o Control: N/A ACLD: N/A	To find a new method of applying vibratory stimulation in order to permanently restore balance and motor function in patients having undergone ACL reconstruction	CoP velocity Elliptic area (CoP displacement)	100 Hz	N/R	Standing on 1 leg with the knee flexed at 15 , the hip joint fully extended, and with their arms crossed over the chest. Eyes open/closed Standing on the force plate on 1 leg with the knee flexed at 15 , the hip joint fully extended, and with their arms crossed over the chest, eyes open/closed for 20 seconds. Short break was given between trials.
DiFabio et al, 2018 [99] Cross Sectional USA In English	PA: Exercise regularly Level: Recreational Time Since ACLR: 6.86±3.07 months ACLR: (m=35), (f=41); Age: 21.8±8.4 y/o Control: (m=35), (f=19); Age: 23.4±13.1 y/o ACLD: N/A	To determine if the different components of the a Lower Extremity Assessment Protocol (LEAP) provide unique information regarding performance and symmetry in both ACLR and healthy participants using an	Average center of pressure velocity and area of displacement of the center of pressure	50 Hz	3	Participants warmed up with 5-min of treadmill walking at a self-selected speed. Single-leg, hands on hips and eyes closed Participants were tested on the uninvolved or dominant limb first, in a single-leg stance with the foot in the middle of the force plate. Participants were instructed to stand on a single limb to hold the position for 10 seconds with their eyes closed

		exploratory factor analysis				and hands on hips. The test was then repeated on the involved limb. If the participant fell out of position, opened their eyes, or put the opposite foot down, the test was repeated.
Dingenen et al, 2015 [100] Cross Sectional Belgium In English	PA: N/R Level: N/R Time Since ACLR: 23.0±14.0 months ACLR: (m=5), (f=15); Age: 22.3±2.3 y/o Control: (m=5), (f=15); Age: 23.4±2.6 y/o ACLD: N/A	To evaluate postural stability during the transition from DLS to SLS in ACLR subjects and non-injured control subjects.	Contralateral push-off CoP excursion Contralateral push-off CoP displacement Peak CoP velocity Time to new stability point Mean absolute CoP velocity during intermediate phase CoP displacement during 3 seconds after time to new stability point	500 Hz	3	Barefoot. Arms hanging at the side. Double/single-leg Eyes open/closed Participants were asked to stand barefoot on a force plate with the feet separated by the width of the hips and the arms hanging loosely at the side. They performed a transition task from DLS (13 s) to SLS (13 s). Both legs of both groups were tested. The leg that was tested first was assigned randomly. The position of the feet during DLS was indicated on a paper lying on the force plate to ensure that subjects returned to the same starting position after each trial. Subjects were instructed to lift 1 leg on the command of the examiner toward approximately 60 —————— of hip flexion within 1 s, using a metronome as a reference. As most postural stability outcomes during this experimental task can be influenced by the speed, it was suggested to standardize the speed of the transitional movement among the 2 groups

						Barefoot. Arms hanging at the side. Double/single-leg. Eyes open/closed Participants were asked to stand barefoot on a force plate with the feet separated by the width of the hips and the arms hanging loosely at the side. They performed a transition task from DLS (13 s) to SLS (13 s) (Fig. 1). Both legs of both groups were tested. The leg that was tested first was assigned randomly. The position of the feet during DLS was indicated on a paper lying on the force plate to ensure that subjects returned to the same starting position after each trial. Subjects were instructed to lift 1 leg on the command of the examiner toward approximately 60 of hip flexion within 1 s, using a metronome as a reference. As most postural stability outcomes during this experimental task can be influenced by the speed, it was suggested to standardize the speed of the transitional movement when comparing non-injured and pathological subjects
Dingenen et al, 2016 [101] Cross Sectional Belgium In English	PA: N/R Level: N/R Time Since ACLR: 23.0±14.0 months ACLR: (m=5), (f=15); Age: 22.3±2.3 y/o Control: (m=5), (f=15); Age: 23.4±2.6 y/o ACLD: N/A	To investigate muscle activation onset times of knee, hip and ankle muscles of both legs in ACLR and non-injured control subjects	Peak CoP velocity	500 Hz	3	
Ferdowsi et al, 2018 [14] Cross Sectional	PA: Soccer Level: Recreational Time Since ACLR: 16.0 months (SD:N/R)	To assess the intra- and inter-session test retest reliability of balance due to the	CoP displacement for range sideways	500 Hz	3	Barefoot Eyes open at a fixed point localized on a facing wall. Each testing

Iran In English	ACLR: (m=20), (f=0); Age: 27.2±3.7 y/o Control: (m=20), (f=0); Age: 26.2±3.2 y/o ACLD: N/A	transitional task from DLS to SLS in athletes with and without ACLR	(Rsw) and range fore-aft (Rfa), area, and the mean velocity (Mv) of CoP			procedure started with a 25 second DLS where the athletes were asked to stand barefoot on the center of a single force platform and kept the arms along the body. Next, the athletes were instructed to do transition to SLS on their legs while they maintained 60° hip flexion for 30 seconds on their tested leg. Finally, the athletes' transition to DLS for 5 seconds on a line lying on the center of the force plate ensure that they were localized at the correct position. It is necessary to mention that the first 5 seconds of SLS phase was considered as the loading phase, while the last 5 seconds of the total testing procedure was regarded as the unloading phase
Frank et al, 2014 [35] Quasi Experimental USA In English	PA: N/R Level: N/R Time Since ACLR: 35.0±16.9 months ACLR: (m=0), (f=14); Age: 19.6±1.5 y/o Control: N/A ACLD: N/A	To investigate the effects of fatigue on lower extremity biomechanics and postural control in active females with ACLR	vGRF CoP sway speed	1400 Hz	5 Double-leg jump landings 3 single-leg balance	Participants performed 5-min of light; self-directed stationary bike warm-up followed by 5-min of self-directed stretching prior to testing. Double-Leg Jump Landing Jump of a 30-cm box placed at a distance equal to 1 half the participant's height from the leading edge of the force plate. On landing, participants were instructed to jump up as high as possible. Single-Leg Balance Barefoot. Hands on hips Eyes closed while standing unshod

						atop the center of a force plate. Participants were instructed to place their hands on their hips for the duration of the balance task. Each participant attempted to balance on their ACLR limb for 20 seconds while center-of-pressure (COP) data were recorded.
Furlanetto et al, 2016 [36] Cross sectional Brazil In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=N/R), (f=); Age: 29.2±8.1 y/o Control: (m=N/R), (f=N/R); Age: 27.8±4.0 y/o ACLD: N/A	Evaluate and compare proprioception, postural control and knee function in subjects with and without unilateral ACL reconstruction	Postural control (PC): Amplitude of CoP (anterior-posterior and medial-lateral directions) Step up and down (SUD): first peak vGRF, load application rate (LAR)	2000 Hz	3 trials each (PC), 5 trials each (SUD)	Postural control (PC): right and left uni-podal support lasting for 30 sec each. The individual was asked to remain still in the indicated position with his/her hands on the anterosuperior iliac crests (ASIC), silently, gaze fixed on a target, located 1m from the eye level of each participant. Step up and down (SUD): Start with L and R lower limb. 30 cm high wooden box placed on 1st force plate. The test started off the force platform with the patient in static position, legs together and hands on ASIC. The individual climbed the step with 1 of his/her LLs and descended it by stepping on 2nd force plate in a continuous single movement.
Goetschius et al, 2013 [102] Cross Sectional USA	PA: N/R Level: Recreationally active Time Since ACLR: 60±51.6 months ACLR: (m=10), (f=10); Age:	This study aimed to compare the effects of 36 min of continuous exercise on postural control and joint	CoP excursions (medial-lateral and anterior-		3	Uni-pedal, eyes closed Participants standing on the test limb, foot centered on the force plate, contralateral hip and knee flexed to

In English	25.5±5.5 y/o Control: (m=10), (f=10); Age: 24.6±5.0 y/o ACLD: N/A	reposition acuity in patients with anterior cruciate ligament reconstruction (ACL-R) and Healthy Controls.	posterior directions), CoP velocity, CoP area			30 degrees and 45 degrees, and arms held across the chest
Head et al, 2019 [19] Cross Sectional USA, Canada In English	PA: N/R Level: N/R Time Since ACLR: 7.6 (range 5.3-10.3) months ACLR: (m=4), (f=11); Age: 18.1±2.9 y/o Control: (m=4), (f=11); Age: 18.1±2.9 y/o ACLD: N/A	To examine dynamic postural stability using the Dynamic Postural Stability Index (DPSI) in athletes following ACLR at the time of release for RTS, and to compare these findings with Healthy Controls. A secondary purpose was to examine differences in dynamic postural stability between the involved and uninvolved lower extremities in the ACLR group.	Dynamic Postural Stability Index (DPSI)	1200 Hz	3	A f-min warm-up on a stationary bike. Single limb jump-landing tasks: forward jump (FJ), lateral jump (LJ), and diagonal jump (DJ) Subjects completed a series of single-limb jump-landing tasks. Subjects were instructed to land on the pre-determined test leg in the center of the force plate, stabilize as quickly as possible, and balance for 10 s with hands on hips, facing straight ahead
Heinert et al, 2018 [103] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 13.9±4.7 months ACLR: (m=7), (f=7); Age: 18.5±3.8 y/o Control: N/A ACLD: N/A	The purpose of this study was to examine the DPSI in a surgically reconstructed ACL limb compared to the uninjured leg in athletes that had been cleared for sport.	Stability indices (medial-lateral, anterior-posterior, vertical and total (DPSI))	1200 Hz	5	A 5-min warm-up on a stationary bike at self-selected speed. Standardized footwear, single-leg hop Subjects performed single landings over a 12-inch hurdle in the anterior direction onto a force platform. The participants began from a distance

						corresponding with 40% of their height to the force platform. They were allowed to use their arms to propel themselves over the barrier and assist with obtaining postural control. Participants were given instructions to place their hands on their hips immediately following stabilization and hold that position for 10 seconds.
Hoch et al, 2018 [104] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 50.4±34.8 months ACLR: (m=1), (f=19); Age: 23.2±4.3 y/o Control: (m=4), (f=36); Age: 22.9±3.1 y/o ACLD: N/A	1- To examine the differences in PROMs and CBOs between post-ACLR and Healthy Control participants 2- To determine the diagnostic accuracy and cut-off scores of these outcomes in order to discriminate between post-ACLR and Healthy Control participants	(TTB-mean minima) was measured in seconds and provided an estimate of the average amount of time it took the subject to make postural corrections and was assessed in both the anterior-posterior (TTB-mean-minima-AP) and medio-lateral (TTB-mean-minimal-ML) directions	N/R	3	Single limb (ACLR). Hands on hips. Eyes closed/open Subjects were instructed to balance on the test limb, keep their hands on their hips at all times, and remain as still as possible. Each subject performed 1 practice and 3 test trials for 10-seconds each on the test limb, first with their eyes open (EO), then eyes closed (EC).

Hoffman et al, 1999 [105] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 9.5 months (SD:N/R) ACLR: (m=8), (f=12); Age: 23.4±5.8 y/o Control: (m=13), (f=7); Age: 24.0±4.1 y/o ACLD: N/A	To investigate quadriceps strength and static and dynamic balance in the ACL reconstructed patient and to compare these findings with an age-matched, injury-free control group.	Sway path linear mean Dynamic phase duration (perturbation phase)	50 Hz	4	A warm-up session (no details) Single-leg stance on a force plate, place hands on hips, and focus on a visual target placed 1m away at the eyes level Each participant of the experimental group performed 4 20-second trials on both the legs. Dynamic balance was done in the same way in static, but with electric perturbation through stimulating the tibial nerve of the supporting leg.
Kuster et al, 1999 [47] Quasi Experimental Switzerland In English	PA: N/R Level: N/R Time Since ACLR: 33.6±7.2 months ACLR: (m=24), (f=12); Age: 31.7±9.9 y/o Control: N/A ACLD: N/A	"The present study used the one-legged stance test to evaluate the enhancement of muscle control and coordination afforded by the use of an elastic compression sleeve after ACL reconstruction. It also included a one-legged drop jump to further stress the balance control system."	Peak impact loading for the landing phase, force-time integrals, path length (PL), root mean square error, CoP	100 Hz	3	With/without compression sleeves Participants were required to perform a standing drop jump from a 10-cm-high platform onto a force plate landing on 1 leg and thereafter maintain a one-legged balance for 25 s. This task was repeated on the previously injured leg 3 times without and 3 times with an elastic compression sleeve.
Pahnabi et al, 2014 [106] Cross Sectional Iran In English	PA: Football Level: Competitive Time Since ACLR: 7±0.5 months ACLR: (m=N/R), (f=N/R); Age: 23.1±1.0 y/o Control(m=N/R), (f=N/R); Age:	To determine the sway of the center for gravity in football players with and without ACL reconstruction 7	Medio-lateral axis (distance X) & anterior–posterior axis (distance Y) movement	100 Hz	3	Left and right side; open and closed eyes; barefoot All tests were done in unilateral standing on the bare foot on each side. Three trials were carried out with open and closed eyes. When the

	23.0±1.1 y/o ACLD: N/A	months after the surgery	distance of CoP; velocity of CoP sway			eyes were open, the subjects' glance aimed at a fixed point at a 1-m distance on the front wall. The test duration was 30 seconds while keeping the arms along the body. On unilateral standing, the stance foot was at the center of the zero reference of the platform and the testing leg had contact with the opposite leg. Static unilateral standing tests began with the non-ACLR side or ACLR side randomly. The knee was positioned in the 20 degree angle of flexion, valgus and internal rotation (posture of injury).
Peultier-Celli et al, 2017 [107] Cohort France In English	PA: N/R Level: Amateur or professional Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=47), (f=20); Age: 29.1±7.5 y/o Control: N/A ACLD: N/A	To compare an innovative rehabilitation protocol with an "aquatic part" (balneotherapy) and a "dry part" and a conventional rehabilitation protocol (1) in terms of dynamics of recovery and development of the proprioceptive skills in athletes with ACL reconstruction. A secondary objective was to compare both groups in terms of functional improvement, i.e., pain, joint amplitude,	Sway area, sway path, somatosensory contribution to postural control (R_{SOM}), the visual contribution to postural control (R_{VIS}), the vestibular contribution to postural control (R_{VEST})	40 Hz	N/R	Eyes open on firm support, eyes closed on firm support, vision altered on firm support, eyes open on foam support, eyes closed on foam support, vision altered on foam support Each subject was asked to stand upright on the platform, barefoot, feet abducted at 30°, heels separated by 3 cm, arms along the body, remaining as stable as possible and breathing normally in 6 conditions to test somatosensory cues

		muscular strength, and walking performance.				
Stensdotter et al, 2013 [108] Cross Sectional Sweden In English	PA: N/R Level: Moderate Time Since ACLR: 19.6±0.9 months ACLR: (m=18), (f=10); Age: 44.7±4.4 y/o Control: (m=18), (f=10); Age: 47.0±5.0 y/o ACLD: (m=12), (f=6); Age: 46.2±4.8 y/o	To compare the ability for single-limb stance more than 20 years after unilateral ACL injury across 2 groups who had either rehabilitation including ACL reconstruction or a tailored physiotherapy program, and compared with knee-Healthy Controls.	CoP Path CoP SD in ML direction CoP SD in AP direction	1200	N/R	Eyes open. Barefoot. Arms folded across chest. Controlled room temperature. Silence was maintained The uplifted foot was held apart from the stance leg, thighs and knees not touching. No further restrictions for leg positions were issued. The person was asked to stand as still as possible, i.e. not to talk or move head and arms, and abstain from all movements not involved in keeping the balance. ACL-injured subjects stood on the uninjured leg first and thereafter on the injured leg. Knee-healthy subjects always started on their dominant leg.
Stensdotter et al, 2016 [109] Cross Sectional Norway In English	PA: N/R Level: Moderate Time Since ACLR: 20.2±2.4 months ACLR: (m=21), (f=10); Age: 46.0±4.1 y/o Control: (m=13), (f=7); Age: 46.7±4.9 y/o ACLD: (m=22), (f=9); Age: 48.2±5.5 y/o	To compare postural sway and control strategies in 2 groups of ACL-injured subjects (with or without reconstructive surgery) to uninjured control subjects.	CoP Path CoP SD in ML direction CoP SD in AP direction	1200 Hz	N/R	Barefoot Quiet standing was performed on a force plate; 3 min for each of 2 conditions; standing with eyes closed on a (1) firm surface and on a (2) compliant surface (Airex balance pad, 495 ——— 406 ——— 63 mm), barefoot with feet a foot-width apart, and arms folded across the chest. The subject was asked to stand still and abstain from all

						movements not involved in maintaining quiet standing.
ZouitaBenMoussa et al, 2009 [110] Cross Sectional Tunisia In English/French	PA: Soccer Players Level: N/R Time Since ACLR: 8.0±0.5 months ACLR: (m=N/R), (f=); Age: 22.0±3.1 y/o Control: (m=N/R), (f=N/R); Age: 24.0±2.0 y/o ACLD: N/A	To analyse postural stability and single-leg hop'' measurements in post-ACLR subjects and compare them with an age- and activity-matched control group.	Postural sway velocity (deg/s)	N/R	3	The testing session started with a 5-minute warm-up. Subjects were then instructed to perform several lower body flexibility exercises. Hands free, barefoot, eyes open/closed The assessment quantifies postural sway velocity while the athlete stands calmly on 1 foot on the force plate. The relative absence of sway in the ''hold still'' position indicates better stability. The single-leg stance assessment consisted of 4 sets of 3 trials, normally conducted in the following order: knee fully extended (left, right) (EXT) knee flexed at 20 (left, right) (FLEX This assessment quantifies the postural sway velocity of each leg. The sway velocity (in degrees per second) is given for all 3 trials. Subjects were allowed a 1-minute rest between tests.
Studies used Balance Platforms to assess "Standing Balance" (n=28)						
Akhbari et al, 2015 [112] Cross Sectional Iran, Belgium	PA: Soccer Level: N/R Time Since ACLR: 11.5±2.5 months ACLR: (m=25), (f=0); Age:	To assess the intra and inter-session test-retest reliability of balance and cognitive tasks under single and	Reaction time (RT), latency and amplitude from the baseline of	500 Hz	3	Dynamic balance and cognitive tests under single- and dual-task conditions, barefoot with eyes open and close

In English	28.2±4.8 y/o Control: (m=19), (f=0); Age: 27.6±4.0 y/o ACLD: (m=23), (f=0); Age: 26.6±5.1 y/o	dual-task conditions in ACLD, ACLR and matched athletes.	this maximum excursion.			Standing with 1 leg on a balance platform and responding to perturbation and auditory cognitive tasks under different testing conditions.
Alonso et al, 2009 [113] Cross Sectional Brazil In English	PA: Soccer Level: Recreational Time Since ACLR: 36.0±10.0 months ACLR: (m=24), (f=0); Age: 29±6 y/o Control: (m=20), (f=0); Age: 26±6 y/o ACLD: N/A	To compare the dislocation of the center of gravity (CG) and postural balance in sedentary and recreational soccer players with and without reconstruction of the ACL using the Biodex Balance System.	Stability index (anterio-posterior, medio-lateral and general (sum of the first two))	N/R	3	Balance on the platform on 1 leg barefoot, arms on chest. Standing on 1 leg barefoot on the platform and trying to keep balance at different stability levels while having a feedback on the screen about the center of gravity displacement.
An et al, 2015 [114] Cohort South Korea In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=10), (f=8); Age: 27.2±6.6 y/o Control: N/A ACLD: N/A	To investigate whether the proprioceptive and dynamic balancing effects of rehabilitation exercises performed after anterior cruciate ligament reconstruction are different between males and females	Change in dynamic balance functions	N/R	N/R	Balance on platform (Condition was not reported) Standing on the balance platform and stabilizing in response to different stability levels.
Baczkowicz et al, 2013 [115] Cross Sectional Poland	PA: N/R Level: N/R Time Since ACLR: Range (11-13) months ACLR: (m=19), (f=7); Age: 28.4±6.3 y/o	To assess neuromuscular control in patients after ACL reconstruction, and in particular to	The overall stability index (OSI) The anterio-posterior stability index	N/R	2	Hands down, standing barefoot on 1 leg and 2 legs with eyes open The maintenance of the single-leg and two-leg standing position on an unstable surface was assessed

In English	Control: (m=26), (f=11); Age: 27.3±5.2 y/o ACLD: N/A	determine, by evaluating dynamic balance control, to what degree deficits of afferent input affect the function of the sensorimotor system	(APSI) The medio-lateral stability index (MLSI)			
Bartels et al, 2019 [116] Cohort Germany, USA In English	PA: N/R Level: N/R Time Since ACLR: 6 months ACLR: (m=14), (f=16); Age: 31.9±12.4 y/o Control: N/A ACLD: N/A	To assess if postural stability is retained for extended periods of time following surgery. The current study is a follow-up to this previous work with the purpose of extending the postoperative testing periods: six-weeks, twelve-weeks, six-months, one-year, and two-years postoperative	Stability indicator (ST), weight distribution index (WDI), synchronization (foot coordination) and sway intensities (postural subsystems).	32 Hz	1	With and without foam pads, eyes open and closed, head is rotated 45 degrees to the right/left or neutral, neck in flexion and extension Postural regulation was tested at six-months, one-year and two-years post-ACLR under 8 different conditions.
Denti et al, 2000 [117] Cross Sectional Italy In English	PA: Sports Level: Professional: 18 Amature: 32 Time Since ACLR: 73.2, (range 60-96) months ACLR: (m=43), (f=7); Age: 30.8 (SD:N/R) y/o Control: (m=29), (f=21); Age: 30.3 (SD:N/R) y/o ACLD: N/A	To investigate the long-term effect of anterior cruciate ligament (ACL) reconstruction on motor control function in the lower extremity.	Balance Index Score	25 Hz	3	With/without visual cues Static tests are performed either in double- or single-limb support and characterize the ability of the subject to maintain stable equilibrium without visual cues from the system. Dynamic tests, which are performed only on double-limb support, characterize motor control function as the subject displaces the platform

						in response to visual cues from the system.
Gandolfi et al, 2018 [118] Cohort Italy In English	PA: N/R Level: Non-competitive sports Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=29), (f=10); Age: 29.6±10.8 y/o Control: N/A ACLD: N/A	Evaluate the time course of sensorimotor integration processes involved in balance recovery during 1-year follow-up after arthroscopy and to understand whether an association exists between balance performance and semitendinosus muscle morphometric features	Percentage difference of sway (PDS) between eyes open (EO) and eyes closed (EC)	N/R	1	Barefoot, arms by side Subject maintains standing position in different sensory conditions. The patient stands barefoot with arms alongside the body and feet in a standardized heel-to-toe position Mean magnitude of sway area (A) (mm2) with eyes open (EO) and eyes closed (EC). Each assessment was performed on a firm (floor) and a compliant surface (foam mats). Each session lasted 30 s. Body sway and sensorimotor integration processes were evaluated by computing sway area with and without vision in the 2 sensory conditions and by calculating the percentage difference of sway (PDS) between EC and EO conditions
Harrison et al, 1994 [119] Cross Sectional Canada In English	PA: N/R Level: N/R Time Since ACLR: Range (10-18) months ACLR: (m=7), (f=10); Age: 27.0±7.6 y/o Control: (m=40), (f=38); Age: 24.6±5.5 y/o ACLD: N/A	To determine whether there is a difference in single-leg standing balance between the ACL-reconstructed leg and the healthy leg. To establish the inter-rater reliability of an observational method of evaluating balance, as this is a critical concern in clinical research.	Postural sway (dispersion index)	100 Hz	1	Single-leg, arms crossed over chest For the eyes-open tests, subjects were instructed to cross their arms over the chest with the hands-on opposite shoulders, flex the non-weight-bearing knee to 90 degrees, and fix their eyes on a stationary marking on the wall in front of them. Eyes-closed test was the same, but test started when eyes were closed

Karasel et al, 2010 [120] Cross Sectional Turkey In English	PA: Athelets 8 Non-athletes 30 Level: N/R Time Since ACLR: 16.0±9.8 months ACLR: (m=33), (f=5); Age: 27.6±6.4 y/o Control: N/A ACLD: N/A	To evaluate muscle strength, proprioception, balance, functional capacity, and activity levels of patients who received a modified accelerated rehabilitation program following ACL reconstruction with a PT graft.	Static balance index	N/A	3	A standardized warm-up for 15 minutes. Single-leg support Arms crossed over shoulders Contralateral knee is at 20 flexion Participants were asked to keep the cursor in the middle of the screen for 30 seconds
Kocak et al, 2010 [121] Cohort Turkey In English	PA: Football (9), basketball (5), volleyball (2), handball (3), other (8) Level: 18 professionals and 9 amateurs Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=22), (f=5); Age: 26.51±8.24 y/o Control: (m=14), (f=4); Age: 20.88±3.59 y/o ACLD: N/A	To determine the functional level of activity and postural control after rehabilitation of anterior cruciate ligament reconstructed knees and compare them with non- operated limbs and healthy limbs in control subjects	Static and dynamic balance scores	N/R	3	Left/right leg standing, static/dynamic conditions Performing one-leg standing (eyes open and closed), static (eyes open and closed) and dynamic postural control on The Kinaesthetic Ability Trainer-KAT 2000 at the 3, 6 and 12 month post- operation.
Lee et al, 2019 [122] Cohort Korea In English	PA: Soccer (48), baseball (14), basketball (25), other (9) Level: N/R Time Since ACLR: Range (6-12) months ACLR: (m=59), (f=37); Age: 29.6±9.2 y/o Control: N/A ACLD: N/A	To evaluate serial change in neuromuscular control in both operated and non-operated knees after ACLR up to 1 year postoperatively by using AT and dynamic postural	Overall stability index (OSI)	N/R	2	Barefoot, 1 leg at a time Dynamic single-leg test; each subject stood barefoot, stood with 90° flexion of the opposite knee on the platform, arms held at the pelvis. Condition changed from most stable level to most unstable

		stability in nonathletic patients who underwent ACLR using hamstring tendon autografts				
Lim et al, 2019 [123] Cohort Korea In English	PA: N/R Level: Not professional athletes Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=19), (f=11); Age: 35.5±10.4 y/o Control: N/A ACLD: N/A	To investigate differences in improvements in isokinetic knee strength, endurance, and proprioception between patients participating in a home-based rehabilitation (HBR) or in a supervised rehabilitation (SR) exercise program.	Overall stability index (OSI)	N/R	2	The patients were positioned without shoes and socks on the BSS platform and stood on 1 foot, with the weight bearing knee in a semi-flexed position at 20◦–30◦ and the contralateral knee maintained in 90◦ flexion. The patients put their hands on their waists and maintained an upright posture with the supporting leg while focusing at the screen in front of them.
Mattacola et al, 2002 [124] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 18.0±10.0 months Dominant/Non-dominant: N/R ACLR: (m=11), (f=9); Age: 25.8±8.1 y/o Control: (m=11), (f=9); Age: 24.5±6.9 y/o ACLD: N/A	To compare postural stability, single-leg hop, and isokinetic strength measurements in subjects after ACL reconstruction with an age- and activity-matched control group	Postural stability index (anterior-posterior plane and medial-lateral plane) for single-limb and bilateral limb	N/R	1	A 5-min warm-up on stationary bicycle followed by several lower body flexibility exercises. Single limb (right vs. left) and bilateral stance BSS progressed from most stable to least stable level. Subjects stood with knees flexed 10-15 degrees and looked straight ahead.
Mohammadi-Rad et al, 2016 [125] Cross Sectional Iran	PA: N/R Level: N/R Time Since ACLR: Range (6-12) months ACLR: (m=16), (f=1); Age: 26.8±6.5 y/o Control: (m=16), (f=1); Age:	To further examine dual-tasking effect on dynamic postural stability in individuals who have undergone ACL-R and a	Anterior-posterior stability index (APSI), medial-lateral stability index (MLSI),	20 Hz	4	Four conditions: stability level of 8 with eyes open/closed; stability level of 6 eyes open/closed. Performed with and without auditory Stroop test Participants were asked to stand on the involved limb in the ACL-R

In English	26.2±7.3 y/o ACLD: N/A	matched control group using BBS	overall stability index (OSI)			group or the limb matched to the involved limb in the control group over a period of 30 seconds with eyes open and eyes closed. Participants stood barefoot with their hands placed upon the iliac crests and their unsupported foot behind the weight-bearing ankle during testing
Mohammadi-Rad et al, 2012 [126] Cross Sectional Iran In English	PA: N/R Level: N/R Time Since ACLR: 12.0±6.0 months ACLR: (m=14), (f=1); Age: 26.0±7.31 y/o Control: (m=14), (f=1); Age: 23.3±6.5 y/o ACLD: N/A	To determine the intra- and inter-session reliability of dynamic balance measures obtained using the Biodex Balance System® (BBS) for a group of athletes who had undergone ACLR and a matched control group without ACLR, while using a dual-task paradigm	Overall stability index (OSI), anterior-posterior stability index (APSI), and medial-lateral stability index (MLSI)	20 Hz	4	Stability levels: levels 8 and 6; eyes open and closed Participants were asked to stand on the involved limb (or in the case of the controls, the limb matched to the ACLR limb of their paired subject) on the BBS® platform with their eyes open and then closed for 30 seconds during each trial. Participants stood barefoot with both hands placed upon the iliac crests.
Novaretti et al, 2018 [127] Cohort Brazil In English	PA: N/R Level: N/R Time Since ACLR: 25.2 (range 12-52.8) months ACLR: (m=47), (f=11); Age: 34.5±11.3 y/o Control: N/A ACLD: N/A	(1) evaluate rates of return to sport after ACLR, (2) correlate 3 objective tests (isokinetic evaluation, postural stability analysis, and drop vertical jump test) completed 6 months postoperatively to return to pre-injury activity level, (3) correlate patient	Postural stability analysis	N/R	3	Left and right limb Patients were positioned at the center of the platform on a single limb. The tested limb was maintained in 10° of knee flexion, with the non-tested limb flexed and arms crossed with hands resting on the contralateral shoulder. Patients were instructed to maintain posture at the center of the platform for 20 seconds at level 4 stability testing.

		satisfaction and return to play after ACLR, and (4) compare quadriceps strength deficit cut-off values of 80% and 90% to return to pre-injury sport level				
Ogrodzka-Ciechanowicz et al, 2018 [128] Cohort Poland In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) Dominant/Non-dominant: N/R ACLR: (m=31), (f=0); Age: 28.4±9.5 y/o Control: N/A ACLD: N/A	To evaluate effectiveness of rehabilitation in patients before and after ACLR, on the basis of stabilographic indicators.	CoP sway path an x and y axis. CoP anterio-posterior sway path length in the y axis. CoP medio-lateral sway path length in the x axis.	N/R	2	Standing on the right leg with eyes open (the left leg bent in the knee). Standing on the left leg with eyes open (the right leg bent in the knee). Stood barefoot with arms along body and legs straight; focused attention on a point and asked to stand on 1 leg and bend the other leg so it wouldn't touch the ground. Patients were not allowed to connect lower limbs or support elevated leg on examined leg.
Palm et al, 2015 [129] Cross Sectional Germany In German	PA: N/R Level: N/R Time Since ACLR: 20.0 (range 11.7-27.0) months ACLR: (m=22), (f=3); Age: 29.8±10.1 y/o Control: N/A ACLD: N/A	The aim of this work was to investigate whether through the reconstruction of the ACL if the postural control can be restored.	Overall stability index, medio-lateral stability index, anterio-posterior stability index	N/R	3	Healthy vs. injured leg; barefoot Subjects centered foot on platform (single-leg), measured in BSS Level 8
Pasquini et al, 2017 [130] Cross Sectional Italy	PA: N/R Level: Amateur athletes Time Since ACLR: 12.0 months (SD:N/R) ACLR: (m=30), (f=0); Age:	To evaluate neuromuscular recovery in athletes who underwent ACL reconstruction with	Path of Center Of Mass (Y) Open Eyes Oscillation Medio-Lateral	N/R	N/R	Barefoot; open vs. closed eyes; single-leg The recording was performed for a time of 30 seconds bare-foot on the

In English	28.17±7.9 y/o Control: N/A ACLD: N/A	BPTB and HS autografts	Open Eyes Oscillation Anterior-Posterior Open Eyes Path of Center Of Mass (Y) Closed Eyes (Oscillation Medio-Lateral Closed Eyes Oscillation Anterior-Posterior Closed Eyes			stabilometric platform with arms at their sides and at the beginning with opened eyes staring a point and then with closed eyes
Paterno et al, 2013 [131] Cross Sectional USA In English	PA: Jumping, pivoting or cutting activity (Level I/II sports) Level: Competitive Time Since ACLR: 7.9±1.7 months ACLR: (m=21), (f=35); Age: 16.4±3.0 y/o Control: (m=13), (f=29); Age: 16.8±2.3 y/o ACLD: N/A	To determine if postural sway deficits during single limb stance on a dynamic, movable platform persist in subjects following ACLR and completion of rehabilitation prior to their return to sport (RTS).	Postural sway	N/R	3	Left and right limb; eyes open, shoes on The subject was positioned and balanced centrally on a single limb in the center of the dynamic, unstable platform. The subject stood with the test limb in slight flexion (less than 10 degrees) with the contralateral limb flexed and both arms crossed
Pinheiro et al, 2010 [132] Cross Sectional Portugal In French	PA: N/R Level: N/R Time Since ACLR: 6.19±3.43 months ACLR: (m=18), (f=13); Age: 28.9±5.63 y/o Control: (m=15), (f=16); Age: 25.6±5.8 y/o ACLD: N/A	To compare postural stability in healthy subjects and patients operated on for ACL reconstruction 2 to 5 years ago.	Total instability index, anterio-posterior stability index, medio-lateral stability index	N/R	3	Left vs. right limb Positioned center of foot on platform; supporting limb is slightly flexed, arms crossed, maintain balance for 20 sec

Plocki et al, 2018 [133] Cross Sectional Poland In English	PA: N/R Level: N/R Time Since ACLR: Range (36-48) months ACLR: (m=39), (f=13); Age: 34.6±7.3 y/o Control: N/A ACLD: N/A	To compare the postural stability in patients after ACL reconstruction with LARS and autogenous graft	CoP path length, mean CoP deviation in anterio-posterior and lateral direction, Mean CoP velocity in AP and L direction, CoP path length area plotted, distribution of load for healthy lower limb and lower limb after reconstruction	N/R	2	With double-leg stance: the Romberg test with open eyes and the Romberg test with eyes closed to assess postural stability and the test to assess the distribution of loads with eyes open. Three tests were performed in the double- leg stance position: the Romberg test with open eyes and the Romberg test with eyes closed to assess postural stability and the test to assess the distribution of loads with eyes open. The tests lasted 30 seconds.
Risberg et al, 2007 [134] RCT Norway In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=47), (f=27); Age: 28.4 (range 16.7-40.3) y/o Control: N/A ACLD: N/A	To determine the effect of an NT program versus a traditional ST program on knee function (Cincinnati Knee Score) following ACL reconstruction. A secondary aim was to evaluate the effect on muscle strength, other patient-related out-come measures (visual analog scale	Balance index (static - uninvolved leg, static - involved leg, dynamic)	N/R	3	Static and dynamic balance; involved vs. uninvolved limb Each subject completed a 1-leg static balance test on each leg (3 trials on each leg) and a 2-leg dynamic test (3 trials). The position of the feet was recorded, and the same position was identified at the follow-up tests.

		[VAS] and 36-Item Short-Form Health Survey [SF-36]),17 pain, functional performance (hop tests), proprioception, and balance.				
Shiraishi et al, 1996 [135] Cross Sectional Japan In English	PA: N/R Level: N/R Time Since ACLR: 2.1±1.8 months ACLR: (m=22), (f=31); Age: 21.5±6.4 y/o Control: (m=15), (f=15); Age: 22.7±2.9 y/o ACLD: (m=15), (f=15); Age: 23.7±5.3 y/o	To examine the hypotheses that anterior cruciate ligament (ACL) reconstruction improves the proprioception of the knee beyond the level of ACLD knees, and that proprioception of the knee correlates well with knee function after ACL reconstruction.	Length of the movement of CoP	N/R	3	Single-leg Knee flexed to 20 degrees Contralateral knee flexed to 90 Standing on 1 leg and looking at a fixed mark for 20 seconds
Unver et al, 2005 [136] Cohort Turkey In Turkish	PA: Sports Level: Recreational Time Since ACLR: Range (6-12) months ACLR: (m=10), (f=0); Age: 29.4±6.6 y/o Control: (m=10), (f=0); Age: 29.4±6.6 y/o ACLD: N/A	To determine the functional level of activity and postural control of anterior cruciate ligaments reconstructed patients following rehabilitation and to compare the results with healthy individuals.	Balance Score Index	N/R	3	Balance was assessed at difficulty level 6 Arms crossed around chest Focus point is at 180 cm high, and 130 cm away Static: Maintain the position on each leg for 30 seconds while focusing on the focus point Dynamic: Standing on both legs, and move a

						ball using the platform 360 degrees within 30 seconds.
Vathrakokilis et al, 2008 [137] Exerimental Greece In English	PA: Athletes Level: Compititive Time Since ACLR: 22 (range 8-30) months ACLR: (m=17), (f=7); Age: 28.6±6.1 y/o Control: N/A ACLD: N/A	To assess the influence of a balance-training program on knee joint proprioception, between ACLR patients who had a lack of proprioceptive ability on the reconstructed limb in relation to the healthy one and they had undergone ACLR at a mean of 22 months (range 8–30) before the initiation of the study.	Stability (time) in sagittal plane. Dynamic stability (time) in sagittal plane. Stability (time) in frontal plane. Dynamic stability (time) in frontal plane. Stability (time) in all directions. Over all Stability index AP Stability index ML Stability index	N/R	3	Balance evaluations in the current study made at stability level 2 on the electronic stability system, for both legs (injured and healthy). Balance ability was assessed in all subjects at baseline and after the completion of the 8-week balance program. All the participants were instructed to focus on the visual feedback screen directly in front of them and to maintain the cursor at the center of the bull's-eye on the screen. They performed three 20 sec trials out of which only the best score was recorded
Wrzesien et al, 2019 [138] Cross Sectional Poland In English	PA: basketball players Level: Professional Time Since ACLR: 38.4±14.8 months ACLR: (m=0), (f=10); Age: 23.3±3.9 y/o Control: (m=0), (f=10); Age: 22.0±4.1 y/o ACLD: N/A	To assess muscle strength, postural stability and quality of movement patterns according to the FMS method in female basketball players after surgical reconstruction of the	Overall Stability Index ML Stability Index AP Stability Index	N/R	3	10-min warm-up consisted of the following exercise; a) two series of eight repetitions in the pattern of both feet squat with the load equal to the body mass of the subject, b) two series of eight repetitions in the pattern of one foot squat with the load equal to 1/2 of the body mass of

		ACL who returned to professional sports.				the subject, c) two series of eight repetitions in the pattern of one foot squat with the load equal to 3/4 of the body mass of the subject. The subjects did 1 leg stance on dynamo-graphic platform. The protocol consisted of 3 trials lasting 30 seconds each, with 10-second break, without changing body position. There were 3 trials on stable surface and 3 trials on unstable surface, whose degree of stability was 4. We restricted the view of the cursor on the screen of the platform so that the subjects could not correct the setting of the base of the platform.
Zallinger et al, 2004 [139] Cohort Austria In German	PA: N/R Level: N/R Time Since ACLR: Range (6-12) months ACLR: Sex: N/R; Age: N/R Control: N/A ACLD: N/A	To assess knee stability after rehabilitation post ACLR	Stability Index	N/R	N/R	N/R
Studies used Wii Balance Boards to assess "Standing Balance" (n=4)						
Clark et al, 2017 [140] Cross Sectional Australia In English	PA: N/R Level: N/R Time Since ACLR: 12.8 (range 10.1-18.0) months ACLR: (m=234), (f=180); Age: 27.8±10.3 y/o Control: N/A ACLD: N/A	To examine inter-limb and sex differences during single-leg-standing balance in a large cohort of patients 1 year post-ACLR.	Range of AP & ML displacement of the CoP Path length in the AP & ML of the CoP Fast sway and	N/A	N /R	Eyes open Participants stood with a barefoot on a Nintendo Wii Balance Board (WBB) (Nintendo, Japan), with the longitudinal axis of the foot positioned on the long axis of the board, and aligned with the centre of

		To examine whether static single-leg balance was associated with demographic or physical function variables, as this has not been well elucidated in a large cohort of patients and has implications for the importance of implementing this testing protocol.	slow sway in AP & ML directions of the CoP			the board. They were instructed to remain as still as possible throughout the test and the limbs were tested sequentially and independently. This technique has been validated against typical laboratory force platforms in numerous studies
Clark et al, 2014 [141] Retrospective Cohort Australia In English	PA: The majority play sport Level: Recreational Time Since ACLR: 10.7±4.3 months ACLR: (m=30), (f=15); Age: 26.0±9.8 y/o Control: (m=30), (f=15); Age: 26.4±9.8 y/o ACLD: N/A	To assess balance using traditional, wavelet and signal irregularity based measures in a group of ACLR and matched control subjects.	CoP path velocity CoP amplitude (AP) CoP standard deviation (SD), Moderate frequency (cm/s) Low frequency (cm/s) Very low frequency (cm/s) Ultra low frequency (cm/s)	N/A	3	Participants stood barefooted on the WBB on 1 leg, with the middle of the longitudinal axis of their foot aligned with a line showing the centre of the WBB in the AP plane. They were instructed to stand as still as possible for 30 s on their ACLR limb or matched limb for the control group. Specific positioning regarding the weight bearing knee (slightly flexed to aproximately 20), non-weight bearing knee (flexed to 90), non-weight bearing hip (neutral flexion/extension) and hands (on hips) was adjusted on the basis of visual observation by the investigator. Participants fixed their gaze on a white dot displayed on a computer monitor positioned at eye-level 1.4 m from the WBB.

			Sample entropy			
Culvenor et al, 2016 [142] Cross Sectional Australia In English	PA: N/R Level: N/R Time Since ACLR: 13.0±1.0 months ACLR: (m=66), (f=31); Age: Median (IQR): 28 (23-35) y/o Control: (m=20), (f=28); Age: Median (IQR): 30 (25-34) y/o ACLD: N/A	To determine whether dynamic postural control during a single-leg squat is impaired following ACLR compared with the uninjured contralateral limb and with Healthy Controls. To evaluate the relationship between dynamic postural control and self-reported and objective function in the ACLR group.	CoP path velocity, cm/s ML range, cm ML SD, cm AP range, cm AP SD, cm	N/A	5	Eyes open. Arms crossed on chest. Barefoot From the starting position of full knee extension in single-leg stance, participants were instructed to squat until their buttocks just touched the plinth (placed at 60 cm high behind the participant), then return to the starting position. This was repeated 5 times, and no specific instructions were provided regarding trunk position or movement. A metronome was used to control the speed of the 5 repetitions (2 seconds lowering, 2 seconds rising). The non– weight-bearing leg was held in hip flexion and knee extension, so that the foot was positioned in front of the body and just off the ground.
Howells et al, 2013 [143] Cross Sectional Australia In English	PA: Sports Level: (4–7 days/week) 9 (1–3 days/week) 25 (1–3 times/month) 2 (no sports) 9 Time Since ACLR: 10.7±4.3 months ACLR: (m=30), (f=15); Age: 26.0±9.8 y/o Control: (m=30), (f=15); Age: 26.4±9.8 y/o ACLD: N/A	To compare postural control, with and without a secondary task that required controlled movement of the upper limb, in patients following ACL reconstruction with a control group.	CoP path AP CoP path ML CoP path total	N/R	3	Barefoot. Knee of supporting knee at 20, other knee 90 flexion, hands on hips or (1 arm performing abd/adduction), gazing on a white dot placed 1.4 me at eye level Standing on 1 leg for 30 seconds while holding an accelerometer in the hand on the contralateral side to the supporting leg. Participants were asked to abduct the shoulder through the full ROM while the elbow is extended. The accelerometer

						movement resulted in the movement of a red marker on the computer screen. Participants were instructed to match this red 'angle' marker to the movement of a larger yellow 'target' marker that moved vertically up and down on a sliding scale. This target marker was controlled by a sine wave oscillating at 0.33 Hz, resulting in 10 full adduction/abduction cycles per 30s trial. Participants were reminded that the aim of the test was to 'stand as still as possible.
Studies used Pressure Mats to assess "Standing Balance" (n=2)						
Chaves et al, 2012 [144] Cross Sectional Brazil In English	PA: Soccer Level: Professional Time Since ACLR: Range (4-12) months ACLR: (m=22), (f=0); Age: 21.8±4.4 y/o Control: N/A ACLD: N/A	To evaluate the neuromuscular efficiency of the vastus medialis oblique (VMO) and postural balance in high-performance soccer athletes after anterior cruciate ligament (ACL) reconstruction, between 4 and 12 month post-operation, comparing to the unaffected limb.	Ellipse surface	N/R	2	For the bi-podalic evaluation, the athlete was instructed to remain in a standing position with feet put into a triangular shape, which accompanies the appliance, at an external rotation of 15º, along with arms at their sides, gaze directed to the horizon, and keep their temporomadibular joint relaxed (open mouth) for 51 seconds. For the mono-podalic test, the individuals were supported by their left foot, keeping the right foot elevated with the knee flexed and then reversed, holding each position for 5 seconds. All tests were performed twice, first with open eyes and the second with closed eyes.
Kouvelioti et al, 2015 [145] Cross	PA: Basketball, handball, soccer, volleyball Level: N/R	To examine the test–retest reliability of balance variables	Sway ellipse, SD of CoP in x and y	25 Hz	3	Double-leg balance test, right and left leg balance test; barefoot

Sectional Greece In English	Time Since ACLR: Median 24 months (IQR:N/R) ACLR: Sex: N/R; Age: 24.4±3.5 y/o Control: Sex: N/R; Age: 26.7±2.4 y/o ACLD: N/A	measured in double-leg and single-limb stance in subjects who underwent ACL reconstruction and controls	directions, total center of pressure path, center of pressure velocity, sway area		Subjects stood erect, as motionless as possible, eyes looking straight ahead, feet shoulder width apart at arms at sides. Instructed to keep quiet stance posture for 30s

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *IQR* Interquartile range, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *CoP* center of pressure, *AP* anterior posterior, *ML* medial lateral, *DPSI* Dynamic postural sway index, *TTB* Time to balance.

Table 3 Data Extraction Table for Studying Assessing Gait

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), level, time since surgery, side of surgery, sample size by sex, age)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates to assess "Gait" (n=26)						
Azus et al, 2018[166] Cohort USA In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=25), (f=20); Age: 29.6±8.5 y/o Control: N/A ACLD: N/A	To evaluate the correlations between gait patterns and Knee injury and Osteoarthritis Outcome Score (KOOS) survey data at 3 time points (pre-surgery, six- and twelve-month post-surgery) in subjects with ACL injury and reconstruction.	GRF	1000 Hz	4	Walking a successful trial the foot of the tested limb was within borders of either of the force plates from initial contact to toe-off
Blackburn et al, 2016 [164] Cross Sectional USA In English	PA: N/R Level: Exercise at least 30 minutes 3 times per week (Level N/R) Time Since ACLR: 49.0±39.0 months ACLR: (m=11), (f=28); Age: 22.0±3.0 y/o Control: N/A ACLD: N/A	To examine relationships between several indices of quadriceps function and gait biomechanics linked to knee OA development in individuals with ACLR.	Peak vGRF vGRF Linear Loading Rate vGRF Instantaneous Loading Rate Heel-strike Transient Heel-strike Transient Linear Loading Rate Heel-strike	1200 Hz	5	Barefoot Patients were asked to walk 5 times on a 7m walkway that has force plates embedded in it.

			Transient Instantaneous Loading Rate			
Blackburn et al, 2016 [146] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 46.2±39.7 months ACLR: (m=0), (f=29); Age: 21.7±3.1 y/o Control: N/A ACLD: N/A	To compare loading characteristics between ACLR and contralateral limbs To compare loading characteristics between individuals who consistently displayed heel-strike transient (HST) during gait and those who did not using the classification schema developed by Radin et al. (1986) to determine the validity of the HST as an indicator of impulsive loading.	Peak vGRF (xBW) Linear Loading Rate (xBW/s) Instantaneous Loading Rate (xBW/s)	1200 Hz	5	Subjects translated at least 3m barefoot via 3-5 steps (at self-selected speed) prior to contact with the first force plate, and completed at least 2 steps following contact with the second force plate
Blackburn et al, 2020 [147] Cross Sectional USA In English	PA: N/R Level: Exercise regularly for 20 minutes 3/week. (Level N/R) Time Since ACLR: 27±16 months ACLR: (m=20), (f=52); Age: 21. 0 ±3.0 y/o Control: N/A ACLD: N/A	to compare somatosensory function (proprioception and vibratory perception) in the ACLR limb to the contralateral limb, and to evaluate associations between somatosensory function and gait biomechanics	Peak vGRF vGRF Loading Rate	1200 Hz	5	At least 5 practice trials were performed to determine the average preferred gait speed and ensure subjects could consistently strike the force plates without noticeably altering their gait

		previously linked to PTOA development				
Blackburn et al, 2019 [148] Retrospective Cohort USA In English	PA: N/R Level: Exercise regularly for 20 minutes 3/week. (Level N/R) Time Since ACLR: 27±15 months ACLR: (m=15), (f=35); Age: 20.0±3.0 y/o Control: (m=19), (f=6); Age: 20±1.0 y/o ACLD: N/A	To compare co-activation during walking between the ACLR and contralateral limbs, as well as Healthy Control subjects. to evaluate relationships between co-activation and gait biomechanics in individuals with ACLR	Peak vGRF vGRF Linear Loading Rate vGRF Instantaneous Loading Rate # of trials Heel-strike Transient	1200 Hz	5	At least 5 practice trials were performed to determine the average preferred gait speed and ensure subjects could consistently strike the force plates without noticeably altering their gait
Bulgheroni et al, 1997 [149] Cross sectional Italy In English	PA: N/R Level: N/R Time Since ACLR: 17.0±5.0 months ACLR: (m=15), (f=0); Age: 27.0±6.0 y/o Control: (m=5), (f=0); Age: 28.0±3.0 y/o ACLD: (m=10), (f=0); Age: 25.0±3.0 y/o	To analyze the changes in select gait parameters following anterior cruciate ligament (ACL) reconstruction	GRF	500 Hz	5	Each subject was asked to perform at least 5 trials of walking at his natural cadence. A 20-m distance was used to allow the subject to reach a steady state of walking.
Colne et al, 2006 [167] Cross Sectional France In English	PA: The majority play sport Level: Recreational Time Since ACLR: 11.0±12.0 months ACLR: (m=N/R), (f=); Age: 27.0±8.0 y/o Control: (m=N/R), (f=N/R); Age: 29±11.0 y/o	To study the dynamics of balance recovery and the muscular activities after a forward fall in patients presenting an ACL lesion, and in control subjects.	Balance recovery duration. Toe-off latency. Heel-off latency. Swing phase duration.	500 Hz	10	The subject stands on a force plate in a forward inclined posture at 15 degree. The body is straight, the arms hang alongside the body and the eyes look straight ahead. The subject is held by a restraining device composed of an abdominal belt and a horizontal steel cable connected to an electromagnet mounted on a

	ACLD: (m=N/R), (f=N/R); Age: 38±10.0 y/o		Braking time. Velocity of the step. Negative peak of the vertical acceleration of the (CoG) before toe-off of the swing limb. Positive peak of the vertical acceleration of the reaction phase (before toe-off). Vertical velocity of the CoG at heel contact. Variation of the height of the CoG at heel contact. Step Length.			dynamometer. The device is released, without the subject's knowledge, causing the subject to fall forward. The subject is instructed to take a few steps to recover balance. Participants were instructed to move forward with either the injured side or the healthy side.
Johnston et al, 2019 [150] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 27.1±27.9 months ACLR: (m=34), (f=64); Age: 21.8±3.2 y/o Control: N/A ACLD: N/A	To compare walking gait biomechanics previously implicated in the mechanical pathogenesis of knee osteoarthritis between individuals with HT and PT grafts.	Peak vGRF vGRF loading rate	1200 Hz	5	Participants were asked to walk barefoot at their self-selected speed on a walkway with embedded force plates.
Lim et al, 2015 [168]	PA: N/R Level: N/R	To compare the early functional recovery	GRF	1200 Hz	3	5-min warm up (no details)

Cohort South Korea In English	Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=N/R), (f=); Age: 31.6±7.0 y/o Control: (m=N/R), (f=); Age: 33.4±6.0 y/o ACLD: N/A	using biomechanical properties between ACL- and PCL-reconstructed patients and to determine the biomechanical deficit of PCL-reconstructed patients compared to ACL-reconstructed patients				Participants were required to perform a cutting 45°, 90°, 135°, and 180° turn walking, and 180° turn running task along the laboratory gateway.
Luc-Harkey et al, 2016 [151] Cross Sectional USA In English	PA: Sports Level: Recreational Time Since ACLR: 43.5±37.7 months ACLR: (m=12), (f=29); Age: 21.8±3.2 y/o Control: N/A ACLD: N/A	To determine if involved limb sagittal plane knee kinematics (knee flexion angle at heelstrike, peak knee flexion angle, knee flexion excursion) predict kinetics (peak vGRF, vGRF loading rate) in the involved limb of individuals with ACLr during walking gait. Additionally, in order to determine if inter-limb differences in the selected kinematics predict inter-limb differences in kinetics, we sought to determine if kinematic limb symmetry index LSI) is predictive of kinetic LSI in	Peak vGRF normalized to body weight Instantaneous vGRF loading rate Linear vGRF loading rate vGRF LSI	1200 Hz	5	Barefoot wearing tight fitting spandex shorts Five walking gait trials were then collected and were considered acceptable for data analysis if 1) both feet individually struck a single force plate, 2) participants maintained a forward eye gaze and did not aim for the force plates, 3) gait speed was within ±5% of the average speed determined during practice trials, and 4) gait kinematics were not visibly altered during the trial (e.g. trip or stutter step).

		individuals with ACLr during walking gait.				
Mantashloo et al, 2020 [152] Cross Sectional Iran In English	PA: N/R Level: N/R Time Since ACLR: More than 6 months ACLR: (m=28), (f=0); Age: 23.7±2.0 y/o Control: (m=28), (f=0); Age: 24.6±2.4 y/o ACLD: N/A	To examine the symmetry of vGRF (frst and second peak) and selected knee muscle (Gastrocnemius (GC), rectus femoris(RF), and biceps femoris(BF)) activity in male subjects with and without unilateral ACL reconstruction gait cycles	First and second peaks of vGRF Phase related SI of vGRF	500 Hz	3	Warm-up was given (no details) The subjects were asked to cross an 8 m path through the force plate. Subjects needed to place both feet on the force plate and cross it. They were asked to walk normally; if any of the legs were not completely on the force plate, the test was repeated. The tests were repeated long enough to obtain 3hree correct tests
Milandri et al, 2017 [153] Cross Sectional South Africa In English	PA: N/R Level: N/R Time Since ACLR: Approx. 60 months ACLR: (m=15), (f=0); Age: 37.4±10.7 y/o Control: (m=15), (f=0); Age: 28.6±6.8 y/o ACLD: N/A	To investigate biomechanics in males long after ACL-reconstruction during both common conditions of walking and running. To address gap in the literature for males with primary ACL injury and links to biomechanical deviations, and for tests after ACL-reconstruction. To better understand chronic joint loading in males long after	vGRF	N/R	5	Participants were requested to perform straight-line barefoot walking and jogging at self-selected speeds, to allow recording of natural level-ground gait

		ACL-reconstruction surgery				
Moya-Angeler et al, 2017 [83] Cohort USA In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=74), (f=0); Age: 34.0±9.0 y/o Control: N/A ACLD: N/A	To evaluate the functional status prior to and at different times after ACLR, and to analyze the changes in the kinetic patterns of the involved and uninvolved limb lower during gait, sprint and 3 hop tests	Gait: anterior-posterior shifting point (APSP), heel maximum vertical force (MVF), single-limb MVF, impulse MVF, maximum anterior force (MAF) and maximum posterior force (MPF) Sprint: MVF	N/R	3	All activities performed on force plates. Gait: 5-m walkway with force plates embedded, walk at self-selected comfrotable pace. Sprint: patient started standing on both platforms, instructed to sprint as fast as possible for 5s Single-leg hop: stand on 1 leg, hop as far forward as possible Drop vertical jump: dropped off 30 cm box and performed maximal jump after landing Vertical hop test: begin standing on both platforms, hop using arms as countermovement
Perraton et al, 2018 [154] Cross Sectional Australia In English	PA: Level I/II sports Level: N/R Time Since ACLR: 16.5±3 months ACLR: (m=38), (f=23); Age: 28.5±6.5 y/o Control: N/A ACLD: N/A	To compare knee joint moments measured during overland running of individuals with satisfactory and poor knee function—i.e. self-reported knee function and/or hop tests. The secondary aim was to compare sagittal plane knee	Peak vGRF (per kg body mass)	1080 Hz	3	Shoes on. Participants were instructed to look forward (to avoid targeting force plates) and run at a comfortable speed. To increase external generalisability, running speed was not constrained. Participants wore Nike Straprunner IV running sandals (Nike, Beaverton, US). Three trials involving a complete foot strike on a single force plate were acquired for

		kinematics, quadriceps strength and vertical ground reaction force (vGRF) of both groups to help explain any differences in knee joint moments observed between groups.				each participant. At the end of the running trials, partici- pants were asked whether they experienced knee pain during running (yes/no).
Pfeiffer et al, 2018 [155] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 49.6±40.6 months ACLR: (m=9), (f=26); Age: 22.1±3.4 y/o Control: N/A ACLD: N/A	The primary purpose of this study was to determine if individuals with a unilateral ACLR, who demonstrate greater peak kinematic and kinetic magnitudes in the ACLR and uninjured limb during walking gait also demonstrate greater peak kinematic and kinetic magnitudes in each limb during jump-landing. Additionally, we will determine if those who demonstrate greater kinematic and kinetic asymmetries during walking gait also demonstrate greater asymmetries during jump-landing	Instantaneous loading rate, linear loading rate	1200 Hz	5	Gait: all participants in this cohort completed all walking trials barefoot. During all walking gait trials, participants were instructed to walk at a self-selected speed over 2 force plates embedded in a staggered formation towards the middle of a 6m walkway so that the entire stance phase for both limbs could be collected during a single trial Jump landing: All participants wore their own athletic footwear for the jump-landing trials. Participants performed jump- landing from a 30cm box positioned 50% of the participant's height from the front edge of the force plates on each force plate, and immediately jump vertically as high as possible

		using limb symmetry indices (LSI).				
Pietrosimone et al, 2016 [156] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 43.2±36.4 months ACLR: (m=9), (f=11); Age: 22.0±3.6 y/o Control: N/A ACLD: N/A	The primary purpose of the current study was to determine if habitual walking speed, recorded in a motion analysis laboratory, associates with serum biomarkers of collagen and proteoglycan breakdown in individuals with an ACLR. Identifying relationships between walking speed and biomarkers of collagen and proteoglycan breakdown would be an initial step in determining whether walking speed may be a useful clinical indicator of post-traumatic OA development in individuals with an ACLR	Peak vGRF and peak vGRF loading rate	1200 Hz	5	Participants were instructed to walk barefoot at a self-selected speed described as “comfortably walking over a sidewalk.” Participants were instructed to focus on an X marked on the wall in the laboratory and walk across the entire 6-meter capture volume.
Pietrosimone et al, 2016 [157] Cross	PA: N/R Level: N/R Time Since ACLR: 37.9±29.3 months	To explore the associations between peak vGRF and vGRF loading rate	peak vGRF, peak vGRF, loading rate	1000 Hz	5	Participants were instructed to walk barefoot at a self-selected speed over 2 force plates embedded in a 6-m walkway. The 2 force plates were

Sectional USA In English	ACLR: (m=8), (f=11); Age: 21.6±3.4 y/o Control: N/A ACLD: N/A	and serum biomarkers of collagen breakdown (collagen type II cleavage product [C2C]), collagen synthesis (collagen type II C-propeptide [CPII]), collagen degradation: synthesis ratios (collagen breakdown: collagen synthesis [C2C:CPII]), and proteogly- can breakdown (aggrecan) in the injured and uninjured limb of individuals with ACLR.				staggered such that the entire stance phase for both the right and left limbs could be collected from a single trial. Participants were instructed to look straight ahead and maintain a constant speed
Rudroff et al, 2003 [65] Cross Sectional Germany In English	PA: Soccer Level: N/R Time Since ACLR: 24.0 months (SD:N/R) ACLR: (m=30), (f=0); Age: 30.9±5.4 y/o Control: (m=10), (f=0); Age: 31.1±4.7 y/o ACLD: N/A	To compare the clinical outcome of ACL reconstruction using the four-strand hamstring tendon autografts and ACL reconstruction using the patellar tendon graft 2 yr. after surgery.	Vertical jump-off force, first vertical maximum	1000 Hz	Squats: 5 trials; gait, one- and two-legged jumps: 6 trials	Gait: walk barefoot over 2 force plates 6 times; data of last 5 trials used
Schliemann et al, 2018 [158] Cohort Germany In English	PA: N/R Level: N/R Time Since ACLR: Range (6-12) months ACLR: (m=22), (f=8); Age: 29.1±12.0 y/o	To compare the early functional results after DIS with those after ACL reconstruction in a	vGRF	600 Hz	N/R	Patients walked at self-selected speed across the force plates and repeated trials were stored for further analyses

	Control: N/A ACLD: N/A	prospective randomized study.				
Schmalz et al, 1998 [159] Cohort Germany In German	PA: Athletes Level: Recreational Time Since ACLR: Range (6-12) months ACLR: Sex: N/R; Age: 29.0±6.0 y/o Control: Sex: N/R; Age: 28.0±5.0 y/o ACLD: N/A	To evaluate the rehabiliation of a group of patients with patellar tendon autograft reconstructed knees by means of gait parameters in the first postoperative year	GRF	400 Hz	12-Oct	Participants walked at a fast speed 10-12 times, and the GRF was measured.
Shimizu et al, 2020 [69] Cohort USA, Japan In English	PA: N/R Level: N/R Time Since ACLR: Range (6-36) months ACLR: (m=20), (f=16); Age: 31.5±7.6 y/o Control: (m=9), (f=5); Age: 31.4±4.9 y/o ACLD: N/A	(1) To investigate the longitudinal changes in meniscal T1r/T2 values and biomechanics during gait and landing tasks after ACLR (2) To investigate the associations between changes in meniscal composition using T1r/T2 mapping and biomechanics in patients with ACLR.	Peak vGRF	1000 Hz	3	Participants were instructed to walk at a controlled speed of 1.35 m/s. with shoes on
Sritharan et al, 2020 [165] Cross Sectional Australia In English	PA: N/R Level: Moderate Time Since ACLR: 17.0±3.0 months ACLR: (m=33), (f=22); Age: 28.0±7.0 y/o Control: N/A ACLD: N/A	To determine whether impairments in lower limb biomechanics during running are evident in the ACLR limb, compared with the uninjured limb, at 12 to 24 months after ACLR.	vGRF AP GRF	1080 Hz	3	Running trials were repeated until 3 trials involving a complete foot-strike on a single force plate were acquired for each leg for every with shoes on

Teng et al, 2017 [160] Cohort USA In English	PA: N/R Level: N/R Time Since ACLR: Range (6-12) months ACLR: (m=20), (f=13); Age: 30.6±8.6 y/o Control: (m=8), (f=4); Age: 31.7±5.5 y/o ACLD: N/A	The primary purpose of this study was to examine whether gait characteristics (ie, peak KFM, KFA, and vGRF) observed before and 6 months and 1 year after ACLR are associated with prospective changes in MTFJ cartilage T1r and T2 at 6 months, 1 year, and 2 years after ACLR. The secondary purpose was to compare gait characteristics (ie, peak KFM, KFA, and vGRF) observed before and 6 months and 1 year after ACLR to those of Healthy Controls.	Peak vGRF	1000	3	Participants were instructed to walk at a controlled speed of 1.3 m/s. A trial was considered successful when the foot of the tested limb fell within the borders of the force platform from initial contact to toe-off and the speed was within 65% of the target speed.
Webster et al, 2012 [161] Cross Sectional Australia In English	PA: N/R Level: N/R Time Since ACLR: 10.3±2.7 months ACLR: (m=32), (f=0); Age: 25.7±6.2 y/o Control: (m=32), (f=0); Age:	To compare the knee adduction moment recorded during level gait between a group of patients with patellar tendon ACL reconstruction, a group with hamstring	vGRF	N/R	3	Subjects were asked to walk barefooted up and down the walkway several times at their own pace until they were relaxed and accustomed to the markers. This also enabled a starting point to be identified so that the subject would contact the force plate in normal stride. Subjects were

	25.0±5.0 y/o ACLD: N/A	tendon ACL reconstruction and a control comparison group.				then asked to complete a number of walks at their self-selected comfortable speed whilst data were collected. They were not aware of the presence of the force plates until data collected was completed. Data collection continued until a minimum of 3 trials with good force plate contact was recorded for both left and right limbs.
Webster et al, 2012 [162] Cohort Australia In English	PA: N/R Level: N/R Time Since ACLR: Range (10.0±2.0 to 39.6±4.8) months ACLR: (m=13), (f=3); Age: 26.0±6.0 y/o Control: N/A ACLD: N/A	To conduct a longitudinal gait study in a group of patients who had undergone ACL reconstruction surgery in order to examine the extent to which gait patterns at an early initial assessment (within 12 months of surgery) are maintained or changed at follow-up of greater than 3 years after surgery.	vGRF	N/R	3	Subjects were asked to walk barefooted up and down the walkway several times at their own pace until they were relaxed and accustomed to the markers. This also enabled a starting point to be identified so that the subject would contact the force plate in normal stride. Subjects were then asked to complete a number of walks at their self-selected comfortable speed whilst data were collected. They were not aware of the presence of the force plates until data collected was completed. Data collection continued until a minimum of 3 trials with good force plate contact was recorded for both left and right limbs.
Wellsandt et al, 2017 [163] Cross Sectional USA In English	PA: Soccer, basketball, skiing and tennis Level: 17 level 1 13 level 2 Time Since ACLR: 6.7±0.7 months ACLR: (m=19), (f=11); Age:	To determine if ground reaction forces, knee joint moments, and muscle co-contraction predict knee joint contact	vGRF	1080	3	Patients walked at a self-selected speed which was maintained (5%) throughout the testing session.

	30.5±11.1 y/o Control: N/A ACLD: N/A	forces 6 months after ACL reconstruction.				
Studies used Force Measuring Treadmills to assess "Gait" (n=6)						
Evans-Pickett et al, 2020 [169] Cross-Over USA In English	PA: N/R Level: N/R Time Since ACLR: 9.0±1.4 months ACLR: (m=8), (f=4); Age: 20.5±3.8 y/o Control: N/A ACLD: N/A	to evaluate the effects of modifying the vGRF impact peak of stance on the stance waveforms of 4 lower extremity biomechanical variables associated with post-traumatic OA development: (i.e. vGRF, knee flexion angle, internal knee extension moment, and knee abduction moment).	vGRF	1200 Hz	N/A (GRF was measured in the last 5 minutes of walking)	Walking on the treadmil on a predetermined walking speed.
Goetschius et al, 2018 [170] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 52.7±14.9 months ACLR: (m=17), (f=39); Age: 22.9±3.5 y/o Control: (m=7), (f=13); Age: 22.4±3.2 y/o ACLD: N/A	To evaluate and compare the presence of abnormal knee and hip joint biomechanics during walking and jogging in groups of individuals at early, mid, and late time frames after unilateral ACLR surgery and a group of Healthy Controls.	vGRF	1000 Hz	10	5-min warm-up periods before each task (no details) Preferred jogging shoes, standardized speeds of 1.34 m/s and 2.68 m/s Walking and jogging motion capture analysis of knee and hip kinetics and kinematics were measured in the sagittal and frontal planes on a split-belt instrumented treadmill
Luc-Harkey et al, 2018 [172] Experimental	PA: Sports Level: Recreational Time Since ACLR: 47.8±27.0	To determine if peak vGRF, vGRF loading rate (vGRF-LR), the	Peak Vertical Ground Reaction	1000	5	Pre-determined self selected walking speed. Real-Time Biofeedback

USA In English	months ACLR: (m=9), (f=21); Age: 20.4±2.9 y/o Control: N/A ACLD: N/A	root mean square error (RMSE) between actual vGRF and target vGRF displayed via RTBF, and perceived difficulty of altering peak vGRF during walking differ when Real-Time Biofeedback Condition (RTBF) is provided to promote high-loading (increased vGRF), low-loading (decreased vGRF) and symmetrical loading in individuals with ACLR.	Force Instantaneous Vertical Ground Reaction Force Loading Rate Root Mean Square Error			Conditions/Without Once participants began walking on the treadmill, kinetic and kinematic outcomes were collected during five 60-second trials during each testing session, including Baseline,Acquisition1 (first intervention minute), Acquisition19 (final intervention minute), Recall1 (first post-intervention minute) and Recall45 (45-minutes post-intervention) All participants were provided with a strategy that focused on manipulating the vertical displacement of their center of mass (CoM) to maximize the likelihood that participants would consistently reach the target. Specifically, participants were told that increasing or decreasing their vertical displacement of their CoM may result in a subsequent increase or decrease in peak vGRF. RTBF was not provided during the assessment of recall (Recall1, Recall45) and participants were instructed to “walk in the same manner as when attempting to match each vertical bar to the target line.
Luc-Harkey et al, 2018 [173] Cross Sectional	PA: Sports Level: Recreational Time Since ACLR: 47.8±27.0 months	To determine if peak vGRF and instantaneous vGRF loading rate on the	ACLR limb peak vGRF (xBW) Contralateral	1000	N/A	Pre-determined self-selected over-ground walking speed was used to set the speed of the instrumented treadmill for each participant.

USA In English	ACLR: (m=9), (f=21); Age: 20.4 (2.9) y/o Control: N/A ACLD: N/A	ACLR limb and inter-limb asymmetry (limb symmetry index [LSI] = injured limb/uninjured limb) of these loading characteristics associate with the change in serum COMP concentration following a 20-minute bout of walking in individuals with ACLR.	limb vGRF (xBW) Peak vGRF limb symmetry index (%) ACL limb instantaneous vGRF loading rate (xBW/s) Contralateral limb instantaneous vGRF loading rate (xBW/s) Instantaneous vGRF loading rate limb symmetry index (%)			Participants then walked on the instrumented treadmill for 5 min to allow for acclimation and then rested quietly for 30 min prior to collection of the first blood sample (COMPpre). Following collection of the first blood sample, participants walked on the the instrumented treadmill for 1 min to allow for collection of the peak vGRF and instantaneous vGRF loading rate, and continued walking at their self-selected speed for 20 min. A second blood sample was collected immediately following completion of the 20 min of walking (COMPpost).
Luc-Harkey et al, 2018 [171] Cross Sectional USA In English	PA: Sports Level: Recreational Time Since ACLR: 47.8±27.0 months ACLR: (m=9), (f=21); Age: 20.4±2.9 y/o Control: N/A ACLD: N/A	To determine the associations between kinesiophobia and walking gait characteristics in physically active individuals with ACLR. Specifically, we separately determined the associations between kinesiophobia and 1) self-selected walking speed, 2) ACLR limb biomechanical	vGRF Instantaneous vGRF Loading Rate vGRF LSI	1000	N/A	Participants walked on the treadmill at a pre-determined self selected walking speed for 5 min prior to collection of lower extremity biomechanical outcomes to allow for acclimation to treadmill walking. We collected kinematics and kinetics during a 60-s trial

		outcomes (peak vGRF, instantaneous vGRF loading rate, peak KEM and knee flexion excursion, and 3) limb symmetry indices (LSI) of these biomechanical outcomes (peak vGRF LSI, instantaneous vGRF loading rate LSI, peak KEM LSI and knee flexion excursion LSI).				
Morgan et al, 2019 [174] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=7), (f=8); Age: 21.2±8.4 y/o Control: (m=8), (f=7); Age: 21.0±4.4 y/o ACLD: N/A	To use Autoregressive (AR) modeling to delineate differences in dynamic stability between control and post-ACLR individuals as a result of peak vGRF data during running. vGRF data were analyzed during running because running is a more demanding task than walking, thus differences in motor control and dynamic stability would become more apparent	Peak vGRF (in relation to body weight)	1200 Hz	1	Shoes on. Participants ran at a self-selected speed to get acclimated to the instrumented split-belt treadmill. Once acclimated, participants were instructed to jog at a comfortable pace.

Studies used Pressure Mats to assess "Gait" (n=1)						
Armitano-Lago et al, 2020 [175] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 8.9±6.0 months ACLR: (m=8), (f=8); Age: 29.2±6.9 y/o Control: (m=8), (f=8); Age: 28.9±6.2 y/o ACLD: N/A	1- To assess whether individuals with a history of ACLR exhibit altered neuro-motor function when compared to Healthy Controls. 2- To examine spatiotemporal, balance, ankle dorsiflexion ROM, proprioception, joint laxity, patellar tendon reflex latency, and quadriceps strength measures to provide a robust picture of the participants overall neuro-motor function and to help identify the locus of differences between the ACLR and control individuals	Spatiotemporal gait measures (i.e., velocity, cadence, step length and width)	150 Hz	3	Preferred walking speed, and fast walking speed Participants walked a total of 28 ft. with a 20 ft. walking surface positioned in the center of the path.

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *IQR* Interquartile range, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *GRF* Ground reaction force, *vGRF* vertical ground reaction force, *xBW* Normalized to body weight, *CoG* center of gravity, *LSI* limb symmetry index, *SI* Symmetry index.

Table 4 Data Extraction Table for Studies Assessing Cutting Movements/Change of Directions

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), level, time since surgery, side of surgery, sample size by sex, age)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates to assess "Cutting Movement/Change in Direction" (n=8)						
Bjornaraa et al, 2011 [177] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 55.2±32.4 months ACLR: (m=0), (f=17); Age: 26.5±6.3 y/o Control: (m=0), (f=17); Age: 25.3±6.0 y/o ACLD: N/A	1) Determine if subjects with ACL reconstruction display different knee displacements, velocities, and time to peak GRF during cutting activities than healthy subjects 2) Observe if subjects with visual disruption display differences in these variables than with vision available 3) Determine if visual deprivation alters these same variables in subjects with ACL reconstruction more significantly than in healthy subjects. Additionally, limb to limb comparisons will be completed within the ACLR group and	Time to peak GRF during cutting activities	1000 Hz	10	Shoes on, full vision/disturbed vision Cutting movement during which knee position was measured via a 3D electromagnetic system. Visual conditions were randomized to disrupt vision for 1 second as the subject began the cutting movement, or allow full vision for movement duration. Independent variables were lead/push off leg (ACLR limb or healthy non-dominant limb) and vision (disrupted or full)

		healthy group to determine whether asymmetries exist between surgical and non-surgical or dominant and non-dominant extremities, respectively				
Chang et al, 2018 [28] Quasi Experimental South Korea In English	PA: N/R Level: N/R Time Since ACLR: ACLR: 35.2±13.2 months ACLR: (m=0), (f=18); Age: ACLR: 19.9±1.2 Control: (m=0), (f=12); Age: 21.0±2.6 y/o ACLD: N/A	To compare the landing biomechanics of ACLR females who pass or fail an FTB to the matched-limb landing biomechanics of healthy females before and after completion of a sustained exercise protocol	Peak vGRF	1560 Hz	3	5-min submaximal warm-up on a stationary bike For double-leg jump landing, participants stood atop a 30-cm high box placed 50% of their height from the front edge of the force plate. They were instructed to jump forward off the box and land on the force plates with both feet then immediately jump vertically. For single-leg jump landing, participants stood on the floor behind a line marked 50% of their height from the front edge of the force plate. Then, they were instructed to jump over a 17-cm high hurdle placed 25% of their height from the force plate, land on 1 foot (testing foot), and then cut as quickly as possible to the other direction of the landing foot (e.g. right foot landing then cut to the left side).
Chang et al, 2020 [29] Cross Sectional	PA: N/R Level: N/R Time Since ACLR: 35.2±18.4 months	To compare the knee joint landing and cutting biomechanics asymmetry of ACLR	Peak vGRF vGRF loading rate	1560 Hz	3	Participants warmed-up for 5-min on a stationary bike at self-selected speed

South Korea In English	ACLR: (m=0), (f=18); Age: 19.9±1.2 y/o Control: (m=0), (f=12); Age: 21.0±2.6 y/o ACLD: N/A	females that pass and fail an FTB with healthy females before and after the completion of a sustained exercise protocol. It was hypothesized that there would be no differences in landing and cutting mechanics asymmetry between ACLR females that pass an FTB (ACLR-pass) and healthy females; but that ACLR females that fail an FTB (ACLR-fail) would exhibit different landing and cutting mechanics asymmetry compared to ACLR-pass and healthy females.				For double-leg jump landing, participants stood atop a 30-cm high box placed 50% of their height from the front edge of the force plate. They were instructed to jump forward off the box and land on the force plates with both feet then immediately jump vertically. For single-leg jump landing, participants stood on the floor behind a line marked 50% of their height from the front edge of the force plate. Then, they were instructed to jump over a 17-cm high hurdle placed 25% of their height from the force plate, land on 1 foot (testing foot), and then cut as quickly as possible to the other direction of the landing foot (e.g. right foot landing then cut to the left side).
King et al, 2018 [176] Cross Sectional Ireland In English	PA: Multidirectional field sports (i.e. Gaelic Football, Soccer, Hurling, Rugby). Level: N/R Time Since ACLR: 8.8±0.7 months ACLR: (m=156), (f=0); Age: 24.8±4.8 y/o Control: N/A ACLD: N/A	The first aim of this study was to identify differences in timed performance and biomechanical variables through the kinetic chain between the ACLR and non-ACLR limbs during stance phase of a 90°	GRF	1000Hz	2 submaximal trials and 3 maximal trials	A standardized warm-up including 2-min jog, 5 bodyweight squats, 2 submaximal, and 3 maximal countermovement jumps Shoes on. Participants carried out 90 degrees maximal effort, planned and unplanned CoD tests in a 3D motion capture laboratory 9 months after

		planned and unplanned CoD. The second aim was to identify differences in kinematic and kinetic variables, between planned and unplanned CoD for each leg				ACLR. Statistical parametric mapping (2 x 2 ANOVA; limb x test) was used to identify differences in CoD time and biomechanical measures between limbs and between tests
King et al, 2019 [85] Cross Sectional Ireland In English	PA: Multidirectional field sports Level: N/R Time Since ACLR: 9.4±0.7 months ACLR: (m=156), (f=0); Age: 24.8±4.2 y/o Control: (m=62), (f=0); Age: 24.7±3.9 y/o ACLD: N/A	To identify differences in asymmetry of biomechanical and performance variables during jump and CoD testing between athletes who were 9 months post-ACLR and a matched healthy cohort	Ground reaction force in vertical, medial and posterior directions	1000 Hz	3	A standardized warm-up including 2-min jog, 5 bodyweight squats, 2 submaximal, and 3 maximal countermovement jumps Shoes on The testing protocol included the double-legged drop jump from 30 cm, the single-legged drop jump from 20 cm, the single-legged hop for distance, and 90° planned and unplanned change of direction
Lanier et al, 2020 [178] Cross Sectional USA In English	PA: Level I and II sports Level: N/R Time Since ACLR: 8.0±1.8 months ACLR: (m=3), (f=8); Age: 21.0±7.8 y/o Control: (m=11), (f=16); Age: 21.0±1.1 y/o ACLD: (m=7), (f=3); Age: 24±8.2 y/o	To determine how ACL injury, ACL reconstruction, and participation in high-performance athletics affects control strategies produced during a novel task that simulates forces produced during cutting movements	Lyapunov exponent (LyE) (high LyE suggests greater variability and poorer motor control)	N/R	3	Participants generate force in a back and forth manner, continuously, and to the beat of a metronome set at 60 beats per minute. Participants received real-time visual feedback of their AP or ML force production
Lim et al, 2015 [168] Cohort	PA: N/R Level: N/R Time Since ACLR: 6.0 months	To compare the early functional recovery using biomechanical	Ground reaction force	1200 Hz	3	5-min warm-up prior to testing

South Korea In English	(SD:N/R) ACLR: (m=N/R), (f=); Age: 31.6±7.0 y/o Control: (m=N/R), (f=); Age: 33.4±6.0 y/o ACLD: N/A	properties between ACL- and PCL-reconstructed patients and to determine the biomechanical deficit of PCL-reconstructed patients compared to ACL-reconstructed patients				Participants were required to perform a cutting 45°, 90°, 135°, and 180° turn walking, and 180° turn running task along the laboratory gateway.
Miranda et al, 2013 [54] Cross Sectional USA In English	PA: N/R Level: Recreational Time Since ACLR: 60.0 months (SD:N/R) ACLR: (m=4), (f=6); Age: 26.96±5.3 y/o Control: (m=5), (f=5); Age: 25.20±5.2 y/o ACLD: N/A	To compare force plate kinetic data and knee kinematic measurements from male and female ACLINT and ACLREC recreational athletes during a jump-cut maneuver in hopes that the differences would point to plausible risk factors for injury	Peak GRF (magnitude of body weight), peak vertical GRF time, peak vertical GRF magnitude	5000 Hz	10	Subjects stood 1 m from force plate with knees bent approx. 45 degrees. Upon hearing "go" prompt, subject jumped forward to landing target on force plate, and a visual directional prompt cued subject to cut left or right after landing on the target with 1 leg. Upon landing, subjects performed a side step cut and then jogged past the respective angled targets.

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *GRF* Ground reaction force, *vGRF* vertical ground reaction force.

Table 5 Data Extraction Table for Studies Assessing Squatting

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), level, time since surgery, side of surgery, sample size by sex, age)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates to assess "Squatting" (n=5)						
Rudroff et al, 2003 [65] Cross Sectional Germany In English	PA: Soccer Level: N/R Time Since ACLR: 24.0 months (SD:N/R) ACLR: (m=30), (f=0); Age: 30.9±5.4 y/o Control: (m=10), (f=0); Age: 31.1±4.7 y/o ACLD: N/A	To compare the clinical outcome of ACL reconstruction using the four-strand ham- string tendon autografts and ACL reconstruction using the patellar tendon graft 2 yr. after surgery.	Vertical jump-off force, first vertical maximum	1000 Hz	Squats: 5 trials; gait, one- and two-legged jumps: 6 trials	Squats: in standing position, femurs rotated externally (feet abducted 20 degrees), lowered center of mass to 90 degrees at approx. 30 deg/sec
Salem et al, 2003 [179] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 7.5±3.0 months ACLR: (m=7), (f=1); Age: 27.9±6.8 y/o Control: N/A ACLD: N/A	To characterize the bilateral lower-extremity kinematics and kinetics associated with squatting exercise after anterior cruciate ligament (ACL) reconstruction.	Peak vertical ground reaction force	600 Hz	3	5-min warm-up on a stationary bike Standing with 1 foot on each of 2 force platforms, were instructed to assume a stance width consistent with that used during their previous rehabilitation training. They were then instructed to "descend (at self-selected movement pace) to a level to where your posterior thighs are parallel to the floor and then ascend." Participants performed 3 sets of 10 repetitions of the back squat exercise using a resistance weight of 35% body weight.

Sanford et al, 2016 [180] Cross Sectional USA In English	PA: Sport Level: N/R Time Since ACLR: 86.4±75.6 months ACLR: (m=3), (f=5); Age: 28.0±7.0 y/o Control: (m=3), (f=5); Age: 25.0±4.0 y/o ACLD: N/A	To test whether ACL reconstructed subjects have symmetric three-dimensional ground reaction forces as assessed using PCA and symmetric AP translation rates of the femur with respect to the tibia when compared with Healthy Control subjects.	AP GRF ML GRF vGRF	1000 Hz	2	Barefoot. Feet shoulder width apart. Keep the torso as upright as possible and to perform continuous bilateral squats to a comfortable level of knee flexion with arms held straight out in front of the chest. Participants were asked to squat at a self-selected pace for an interval of 25 s for 2 trials of data collection.
Schilling et al, 2020 [66] Cohort USA In English	PA: Sports Level: Collegiate Athlete Time Since ACLR: Range (6-71) months ACLR: (m=7), (f=14); Age: 20.3±1.7 y/o Control: N/A ACLD: N/A	To assess the readiness for return to sport in a sample of division III athletes following ACLR and medical clearance.	vGRF	N/R	3	Participants performed a single maximum single-leg squat test (SLST) while standing on a 12 in.-high step (30.48 cm). The participants were then asked to perform a single-leg landing task from the step and land on a force plate that was located 12 inches away from the step.
Webster et al, 2015 [181] Cross Sectional Australia In English	PA: Sports Level: N/R Time Since ACLR: 17.3±2.3 months ACLR: (m=10), (f=0); Age: 23.0±3.0 y/o Control: (m=10), (f=0); Age: 32.0±2.0 y/o ACLD: N/A	To analyze weight-bearing symmetry along with hip and knee joint symmetry during a double-leg squat in a group who had undergone ACLR surgery, both at baseline and following fatigue, and compare symmetry to	vGRF Weight bearing symmetry	N/R	3	During testing, participants were asked to stand with 1 foot on each force plate with a comfortable stance width. Ten consecutive double limb squats were then performed at a steady pace (4 s/squat; 2 s descent, 2 s ascent). Participants were instructed to descend to a level where the thighs were parallel to the floor, whilst keeping the arms parallel to the

		an uninjured control group.				ground and then ascend to a full upright position.
Studies used Pressure Mats to assess "Squatting" (n=1)						
Dan et al, 2019 [89] Cross Sectional Australia In English	PA: N/R Level: N/R Time Since ACLR: Range (8-15) months ACLR: (m=47), (f=18); Age: 33.8±10.1 y/o Control: (m=17), (f=20); Age: 25.1±8.6	To explore the utility of this accelerometer and gyroscope system as well as a pressure sensing mat in detecting kinetic differences in patients prior to return to sport following ACL reconstruction.	Peak Load	N/R	N/R	Barefoot Single and double-leg

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *GRF* Ground reaction force, *vGRF* vertical ground reaction force, *AP* Anterior Posterior, *ML* Medial Lateral.

Table 6 Data Extraction Table for Studies Assessing Stop Jump, Step-Over & Lunges

Study Characteristic (author, year, design, country, language)	Sample Characteristic (Physical Activity (PA), level, time since surgery, side of surgery, sample size by sex, age)	Study Objectives	Parameters	Sampling Frequency	Number of Repetitions	• Testing Condition or Challenges • Protocol Summery
Studies used Force Plates to assess "Stop Jump" (n=2)						
Queen et al, 2020 [182] Cross Sectional USA In English	PA: N/R Level: N/R Time Since ACLR: 6.6±1.6 months ACLR: (m=13), (f=9); Age: 17.3±2.2 y/o Control: (m=13), (f=9); Age: 22.3±2.7 y/o ACLD: N/A	To test the performance of these indices on previously unpublished data on ACL-R patients and to propose a new index to resolve some of these limitations.	Indices for peak vGRF (ratio index, gait asymmetry index, symmetry index, symmetry angle, normalized symmetry index)	2400 Hz	5	Bilateral Participants were told to approach as quickly as possible and to jump as high as they felt was safely possible, and no instructions about landing position or technique were provided.
Renner et al, 2018 [183] Cohort USA In English	PA: N/R Level: Recreational or high school sport Time Since ACLR: 6.0 months (SD:N/R) ACLR: (m=9), (f=14); Age: 16.0±1.3 y/o Control: N/A ACLD: N/A	To examine differences in movement and loading patterns across time and between limbs in ACLR patients over 4 visits in the first year post-ACLR.	Peak vertical GRF, Peak posterior GRF, loading rate, impulse	2400 Hz	5	Jump task includes several running steps, a jump off 1 foot, a two-footed landing, and a subsequent two-footed jump. Participants were told to approach the force plate as quickly as possible and to jump as high as was safely possible. No instruction on landing was given
Studies used Force Plates to assess "Step-Over & Lunges" (n=1)						
Mattacola et al, 2004 [184] Cross	PA: N/R Level: N/R Time Since ACLR: 14.5±4.8	To evaluate the performance of an ACL reconstruction	The lift-up index Movement	N/R	3	5-min warm-up on the treadmill.

Sectional USA In English	months Dominant/Non-dominant: N/R ACLR: (m=13), (f=5); Age: 22.8±5.8 y/o Control: (m=10), (f=8); Age: 22.5±4.1 y/o ACLD: N/A	group and a control group during 2 functional tests.	time The impact index Lunge distance, Contact time, Impact index, and Force impulse.		To perform the step-up-and-over test, each individual started by standing with both feet stationary on the force plate. They then stepped with 1 leg (lead leg) up onto a box 12-in tall, which was also on the force plate. The lagging leg was carried up and over the box, landing on the surface opposite from the original starting position. The individual started in a standing position, lunged forward with 1 leg, and then returned to the original standing position

N/R Not reported, *N/A* Not applicable, *PA* Physical activity, *Level* Activity level, *SD* standard deviation, *ACLR* Anterior cruciate ligament reconstruction, *ACLD* anterior cruciate ligament deficient, *GRF* Ground reaction force, *vGRF* vertical ground reaction force.

APPENDIX 4.1: Systematic review - Search Strategies

Ovid MEDLINE(R) ALL

Date searched: March 13, 2022

Results: 171

1. exp anterior cruciate ligament reconstruction/
2. ((Anterior cruciate ligament or ACL) adj8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*)).mp.
3. 1 or 2
4. (((Bilateral or unilateral or countermovement or counter or squat or drop or vertical or one-leg* or two-leg* or single-leg* or double-leg*) adj4 jump*) or drop land* or jump landing or jump down).mp.
5. (forceplate* or force plate* or force platform* or Kistler or GRF or GRFs or VGRF or VGRFs or pGRF? or ground reaction force* or kinetic* or center of pressure or centre of pressure or centre of mass or center of mass or Reactive strength index or RSImod or impulse or force-development or force-production or force time curve or (jump adj2 (height or duration or phase length)) or flight time or peak force* or limb-impulse* or phase specific or time curve or velocity or between limb difference* or between limb deficit* or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices or measur*) adj4 (asymmetr* or symmetr*))).mp.
6. 3 and 4 and 5

Embase 1974 to 2022 March 11 (OVID interface)

Date searched:March 13, 2022

Results: 183

1. anterior cruciate ligament reconstruction/
2. ((Anterior cruciate ligament or ACL) adj8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*)).mp.
3. (forceplate* or force plate* or force platform* or Kistler or GRF or GRFs or VGRF or VGRFs or pGRF? or ground reaction force* or kinetic* or center of pressure or centre of pressure or centre of mass or center of mass or Reactive strength index or RSImod or impulse or force-development or force-production or force time curve or (jump adj2 (height or duration or phase length)) or flight time or peak force* or limb-impulse* or phase specific or time curve or velocity or between limb difference* or between limb deficit* or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices or measur*) adj4 (asymmetr* or symmetr*))).mp.
4. (((Bilateral or unilateral or countermovement or counter or squat or drop or vertical or one-leg* or two-leg* or single-leg* or double-leg*) adj4 jump*) or drop land* or jump landing or jump down).mp.
5. (1 or 2) and 3 and 4
6. limit 5 to conference abstracts
7. 5 not 6

CINAHL Plus with Full Text (EBSCOhose interface)

Date searched: Mar 13, 2022

Results: 153

Deselect: Apply equivalent subjects

((MH "Anterior Cruciate Ligament Reconstruction") OR ((Anterior cruciate ligament or ACL) N8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*))) AND (((Bilateral or unilateral or countermovement or counter or squat or drop or vertical or one-leg* or two-leg* or single-leg* or double-leg*) N4 jump*) or drop-land* or jump-landing or jump-down) AND TX (forceplate* or force-plate* or force-platform* or Kistler or GRF or GRFs or VGRF or VGRFs or pGRF* or ground-reaction-force* or kinetic* or center-of-pressure or centre-of-pressure or centre-of-mass or center-of-mass or Reactive-strength-index or RSImod or impulse or force-development or force-production or force-time-curve or (jump adj2 (height or duration or phase length)) or flight-time or peak-force* or limb-impulse* or phase-specific or time-curve or velocity or between-limb-difference* or between-limb-deficit* or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices or measur*) N4 (asymmetr* or symmetr*)))

SPORTDiscus with Full Text (EBSCOhose interface)

Date searched: March 13, 2022

Results: 164

(((Anterior cruciate ligament or ACL) N8 (repair or reconstruct* or surgery or post-operativ* or postoperativ*))) AND (((Bilateral or unilateral or countermovement or counter or squat or drop or vertical or one-leg* or two-leg* or single-leg* or double-leg*) N4 jump*) or drop-land* or jump-landing or jump-down) AND TX (forceplate* or force-plate* or force-platform* or Kistler or GRF or GRFs or VGRF or VGRFs or pGRF* or ground-reaction-force* or kinetic* or center-of-pressure or centre-of-pressure or centre-of-mass or center-of-mass or Reactive-strength-index or RSImod or impulse or force-development or force-production or force-time-curve or (jump N2 (height or duration or phase length)) or flight-time or peak-force* or limb-impulse* or phase-specific or time-curve or velocity or between-limb-difference* or between-limb-deficit* or ((Leg or legs or limb or limbs or knee or knees or functional or strength or muscle or index or indices or measur*) N4 (asymmetr* or symmetr*)))

SCOPUS

Date searched:March 13, 2022

Results: 198

TITLE-ABS-KEY ((anterior-cruciate-ligament OR acl) W/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND TITLE-ABS-KEY (((bilateral OR unilateral OR countermovement OR counter OR squat OR drop OR vertical OR one-leg* OR two-leg* OR single-leg* OR double-leg*) W/4 jump*) OR drop-land* OR jump-landing OR jump-down) AND TITLE-ABS-KEY (forceplate* OR force-plate* OR force-platform* OR kistler OR grf OR grfs OR vgrf OR vgrfs OR pgrf* OR ground-reaction-force* OR kinetic* OR center-of-pressure OR centre-of-pressure OR centre-of-mass OR center-of-mass OR reactive-strength-index OR rsimod OR impulse OR force-development OR force-production OR force-time-curve OR (jump W/2 (height OR duration OR phase-length)) OR flight-time OR peak-force* OR limb-impulse* OR phase-specific OR time-curve OR velocity OR between-limb-difference* OR between-limb-deficit* OR ((leg OR legs OR limb OR limbs OR knee OR knees OR functional OR strength OR muscle OR index OR indices OR measur*) W/4 (asymmetr* OR symmetr*)))

Web of Science Core Collection

(Indexes=Science Citation Index (CI) Expanded, Social Sciences CI, Arts & Humanities CI, Emerging Sources CI)

Date searched: March13, 2022

Results: 189

TS= ((anterior-cruciate-ligament OR acl) NEAR/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND TS= (((bilateral OR unilateral OR countermovement OR counter OR squat OR drop OR vertical OR one-leg* OR two-leg* OR single-leg* OR double-leg*) NEAR/4 jump*) OR drop-land* OR jump-landing OR jump-down) AND TS=(forceplate* OR force-plate* OR force-platform* OR kistler OR grf OR grfs OR vgrf OR vgrfs OR pgrf* OR ground-reaction-force* OR kinetic* OR center-of-pressure OR centre-of-pressure OR centre-of-mass OR center-of-mass OR reactive-strength-index OR rsimod OR impulse OR force-development OR force-production OR force-time-curve OR (jump NEAR/2 (height OR duration OR phase-length)) OR flight-time OR peak-force* OR limb-impulse* OR phase-specific OR time-curve OR velocity OR between-limb-difference* OR between-limb-deficit* OR ((leg OR legs OR limb OR limbs OR knee OR knees OR functional OR strength OR muscle OR index OR indices OR measur*) NEAR/4 (asymmetr* OR symmetr*)))

Dissertations and Theses Global (Proquest interface)

Date searched:March 13, 2022

Results: 28

noft((anterior-cruciate-ligament OR acl) NEAR/8 (repair OR reconstruct* OR surgery OR post-operativ* OR postoperativ*)) AND noft(((bilateral OR unilateral OR countermovement OR counter OR squat OR drop OR vertical OR one-leg* OR two-leg* OR single-leg* OR double-leg*) NEAR/4 jump*) OR drop-land* OR jump-landing OR jump-down) AND (forceplate* OR force-plate* OR force-platform* OR kistler OR grf OR grfs OR vgrf OR vgrfs OR pgrf* OR ground-reaction-force* OR kinetic* OR center-of-pressure OR centre-of-pressure OR centre-of-mass OR center-of-mass OR reactive-strength-index OR rsimod OR impulse OR force-development OR force-production OR force-time-curve OR (jump NEAR/2 (height OR duration OR phase-length)) OR flight-time OR peak-force* OR limb-impulse* OR phase-specific OR time-curve OR velocity OR between-limb-difference* OR between-limb-deficit* OR ((leg OR legs OR limb OR limbs OR knee OR knees OR functional OR strength OR muscle OR index OR indices OR measur*) NEAR/4 (asymmetr* OR symmetr*)))

University of Alberta's Science Direct Journals (Advanced Search)

Date searched: March 13, 2022

Results: 38

Do not include conference abstracts

Find articles with these terms: "ground reaction force" OR kinetic OR "asymmetry index" OR "symmetry index" OR "limb symmetry" OR "limb asymmetry" OR "leg symmetry" OR "Force plate" OR "jump height"

Title, abstract or author-specified keywords: "Anterior Cruciate Ligament" AND (repair OR reconstruct OR reconstruction) AND ("drop jump" OR "vertical jump" OR "drop land" OR "landing task" OR "countermovement jump")

Pubmed Central

Date searched: March 13, 2022

Results: 74

(("anterior cruciate ligament"[Abstract] or ACL[abstract]) AND (reconstruct[Abstract] OR reconstructed[Abstract] OR reconstruction[Abstract] OR repair[Abstract] OR repaired[Abstract] OR surgery[Abstract] OR post-operative[Abstract] OR postoperative[Abstract]) AND (vertical-jump[Abstract] OR drop-jump[Abstract] OR drop-land[Abstract] OR land-task[Abstract] OR single-leg-jump[Abstract] OR one-leg-jump[Abstract] OR double-leg-jump[Abstract] OR two-leg-jump[Abstract] OR countermovement-jump[Abstract] OR counter-jump[Abstract] OR vertical-jumps[Abstract] OR drop-jumps[Abstract] OR drop-landing[Abstract] OR landing-task[Abstract] OR landing-tasks[Abstract] OR single-leg-jumps[Abstract] OR one-leg-jumps[Abstract] OR double-leg-jumps[Abstract] OR two-leg-jumps[Abstract] OR countermovement-jumps[Abstract] OR counter-jumps[Abstract])) AND ("ground reaction force" OR "ground reaction forces" OR "force plate" OR "force plates" OR forceplate* OR kinetic OR kinetics OR "asymmetry index" OR "symmetry index" OR "asymmetry indices" OR "symmetry indices" OR "limb symmetr*" OR "limb asymmetr*" OR "leg symmetr*" OR between-limb-difference* OR between-limb-deficit* OR "jump height" OR "Peak force" OR "force development" OR force-production OR force-time-curve OR kistler OR grf OR grfs OR vgrf OR vgrfs OR pgrf* OR reactive-strength-index OR rsimod OR center-of-pressure OR centre-of-pressure OR centre-of-mass OR center-of-mass OR reactive-strength-index OR rsimod OR "concentric impulse" or "eccentric impulse" or "unweighting impulse" or "breaking impulse" or "deceleration impulse" OR limb-impulse* OR "flight time")

APPENDIX 4.2: Systematic review – Data Extraction Table

Study Characteristics (author, year, design, country, language)	Sample Characteristics (size, sex, age, graft, time since surgery [in months], physical activity, activity level)	Parameters	Protocol	DB Score
Single-leg Countermovement Jump				
Giesche 2021 **Cross sectional** **Germany** **In English**	Control: [n=17, (f=0), (m=17)], age: 28±4 ACLR: [n=10, (f=0), (m=10)], age: 28±4 Graft type: N/R Time since surgery: 63±35 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Landing peak $vGRF_{(normalized)}$ -CoP length of path -TTS -Flight time	Sampling frequency: N/R Shoes on/off: N/R Hand position: On hips Warm up: N/R Number of trials: 40	11
Holsgaard-Larsen 2014 **Cross sectional** **Denmark** **In English**	Control: [n=25, (f=0), (m=25)], age: 27.2±5.4 ACLR: [n=23, (f=0), (m=23)], age: 27.2±7.2 Graft type: Hamstring Time since surgery: 26.5±6.6 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Jump Height	Sampling frequency: 1000 Shoes on/off: Off Hand position: On hips Warm up: Reported Number of trials: 3	8
Kotsifaki 2022 **Cross Sectional** **Qatar** **In English**	Control: [n=22, (f=0), (m=22)], age: 28.7±3.8 ACLR: [n=26, (f=0), (m=26)], age: 23.2±3.4 Graft type: HT 10, PT 16 Time since surgery: 9.5±2.7 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: Recreational	-*Jump Height	Sampling frequency: 1000 Shoes on/off: On Hand position: On hips Warm up: Reported Number of trials: 4	9
O'Malley 2018 **Cross Sectional** **Irland** **In English**	Control: [n=44, (f=0), (m=44)], age: 24.1±3.6 ACLR: [n=118, (f=0), (m=118)], age: 23.6±5.8 Graft type: N/R Time since surgery: 6.6±1.0 PA (Control): Multidirectional sports, Level: N/R PA (ACLR): Multidirectional sports, Level: N/R	-*Jump Height -*Peak $power_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	10
Double-leg Countermovement Jump				
Castanharo 2011 **Cross Sectional** **Brazil**	Control: [n=17, (f=0), (m=17)], age: 26±4 ACLR: [n=12, (f=0), (m=12)], age: 28±8	-Concentric peak $vGRF_{(normalized)}$ -Landing Peak $vGRF_{(normalized)}$	Sampling frequency: 1080 Hz Shoes on/off: On Hand position: On chest	8

In English	Graft type: unilateral semitendinous-gracilis tendon autograft, with no more than 25% of the meniscus removed Time since surgery: 37±9 PA (Control): N/R, Level: Recreational sports activity PA (ACLR): N/R, Level: Recreational sports activity		Warm up: N/R Number of trials: 6	
Collings 2021 **Cross Sectional** **Australia** **In English**	Control: [n=198, (f=198), (m=0)], age: 20.3±8.6 ACLR: [n=24, (f=198), (m=0)], age: 23.1±5.1 Graft type: 21 hamstring, 1 patellar, and 2 quadriceps Time since surgery: N/R PA (Control): Football, Soccer and Rugby, Level: elite PA (ACLR): Football, Soccer and Rugby, Level: elite	-Peak $GRF_{(normalized)}$ (Take-off) -Peak $GRF_{(normalized)}$ (Landing) -Take-off $Impulse_{(normalized)}$	Sampling frequency: 1000 Hz Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	11
Jordan 2018 **Cross Sectional** **Canada** **In English**	Control: [n=24, (f=12), (m=12)], age: 20.9±3.7 ACLR: [n=12, (f=12), (m=6)], age: 26.7±3.8 Graft type: N/R Time since surgery: 48, range (2y-8y) PA (Control): Skiing, Level: Mixed PA (ACLR): Skiing, Level: Mixed	-Contraction time -*Jump height -*Relative peak $power_{(normalized)}$ -Relative mean power -*Velocity max -*Relative force at max velocity -Relative force at peak $power_{(normalized)}$ -Velocity at peak $power_{(normalized)}$ -Impulse eccentric asymmetry -*Impulse concentric asymmetry	Sampling frequency: 1500 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 5	8
Jordan 2015 **Cross Sectional** **Canada** **In English**	Control: [n=9, (f=4), (m=5)], age: 22.3±2.3 ACLR: [n=9, (f=4), (m=4)], age: 26.8±4.4 Graft type: N/R Time since surgery: 26.2±11.8 PA (Control): Skiing, Level: Elite PA (ACLR): Skiing, Level: Elite	-Impulse eccentric -Impulse concentric -Impulse eccentric asymmetry -*Impulse concentric asymmetry	Sampling frequency: 500 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 10	12

Krafft 2017 **Cross sectional data of a longitudinal study** **Germany** **In English**	Control: [n=20, (f=N/R), (m=N/R)], age: 33.3±13.4 ACLR: [n=20, (f=N/R), (m=N/R)], age: 32±13.3 Graft type: combined semitendinosus and gracilis autograft, via the single-bundle technique Time since surgery: 6.31±0.64 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: Recreational	-*Jump height -*Impulse eccentric LSI -*Impulse concentric LSI	Sampling frequency: 1000 Shoes on/off: N/R Hand position: On hips Warm up: N/R Number of trials: 3	8
Miles 2019 **Cross Sectional** **Ireland** **In English**	Control: [n=22, (f=0), (m=22)], age: 23.1±3.4 ACLR: [n=44, (f=0), (m=44)], age: 24.8±4.6 Graft type: HT 22, PT 22 Time since surgery: N/R±N/R PA (Control): (Gaelic football and hurling; 66%), soccer (24%), and rugby, Level: N/R PA (ACLR): (Gaelic football and hurling; 66%), soccer (24%), and 10rugby, Level: N/R	-*Impulse$_{(normalized)}$ eccentric -*Impulse$_{(normalized)}$ concentric -*Impulse$_{(normalized)}$ landing -*Jump Height	Sampling frequency: 1000 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	11
Read 2020 **Cross Sectional** **Qatar** **In English**	Co11ntrol: [n=204, (f=0), (m=204)], age: 24.4±4.7 ACLR: [n=124, (f=0), (m=124)], age: 23.83±6.13 Graft type: N/R Time since surgery: <6 (6-9) >9± PA (Control): Soccer, Level: Elite PA (ACLR): Soccer, Level: Elite	-*Jump height -*Peak power -*Impulse concentric -*Impulse concentric asymmetry -Impulse eccentric deceleration -*Impulse eccentric deceleration asymmetry -*Concentric peak vGRF -*Concentric peak vGRF asymmetry -*Eccentric deceleration RFD -*Eccentric deceleration RFD asymmetry -*Eccentric mean GRF -*Eccentric mean GRF asymmetry -*Peak vGRF	Sampling frequency: 1000 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	10

		(Landing) -*Peak vGRF (Landing) asymmetry		
Costley 2021 **Longitudinal** **Ireland** **In English**	Control: [n=44, (f=44), (m=0)], age: 4.6±N/A ACLR: [n=N/A, (f=44), (m=0)], age: N/A±24.8 Graft type: N/A Time since surgery: N/R±5-7 months PA (Control): multidirectional field sports, Level: Recreational PA (ACLR): multidirectional field sports, Level: Recreational	-*Eccentric deceleration impulse$_{(normalized)}$ -Concentric impulse$_{(normalized)}$ -Landing impulse$_{(normalized)}$ -Jump height	Sampling frequency: 1000 hz Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	11
Single-leg Drop Jump				
Huang 2021 **Cross Sectional** **USA** **In English**	Control: [n=19, (f=19), (m=0)], age: 21.1±3.3 ACLR: [n=19, (f=19), (m=0)], age: 19.9±1.2 Graft type: N/R Time since surgery: 35.1±13.7 PA (Control): soccer, basketball, and handball, Level: Recreational PA (ACLR): soccer, basketball, and handball, Level: Recreational	-Eccentric Peak vGRF$_{(normalized)}$ symmetry -Eccentric loading rate$_{(normalized)}$ symmetry	Sampling frequency: 1500 Shoes on/off: On Hand position: Free Warm up: N/R Number of trials: 3	10
Kilic 2018 **Cross Sectional** **Turkey** **In English**	Control: [n=9, (f=N/R), (m=N/R)], age: 22.2±2.5 ACLR: [n=11, (f=N/R), (m=N/R)], age: 23.1±3.6 Graft type: patellar tendon Time since surgery: ±range (6-15) PA (Control): Soccer, Level: Recreational PA (ACLR): Soccer, Level: Recreational	-*vGRF at initial contact -*Peak vGRF -vGRF at last contact	Sampling frequency: 1000 Shoes on/off: On Hand position: On hips Warm up: Reported Number of trials: 3	10

Kotsifaki 2022 **Cross Sectional** **Qatar** **In English**	Control: [n=22, (f=0), (m=22)], age: 28.7±3.8 ACLR: [n=26, (f=0), (m=26)], age: 23.2±3.4 Graft type: HT 10, PT 16 Time since surgery: 9.5±2.7 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: Recreational	-*Jump height -*RSI -*RSR -Contact time	Sampling frequency: 1000 Shoes on/off: On Hand position: On hips Warm up: Reported Number of trials: 4	9
Ortiz 2008 **Cross Sectional** **Puerto Rico** **In English**	Control: [n=15, (f=15), (m=0)], age: 24.6±2.6 ACLR: [n=14, (f=15), (m=0)], age: 25.4±3.1 Graft type: N/R Time since surgery: 86.4±50.4 PA (Control): Jogging, running, and weight lifting, Level: Recreational PA (ACLR): Jogging, running, and weight lifting, Level: Recreational	-Peak vGRF	Sampling frequency: 1000 Shoes on/off: On Hand position: Free Warm up: Reported Number of trials: 6	9
Read 2020 **Cross Sectional** **Qatar** **In English**	Control: [n=195, (f=0), (m=195)], age: 24.7±4.3 ACLR: [n=72, (f=0), (m=72)], age: 24.2±5.1 Graft type: N/R Time since surgery: 9±N/R PA (Control): Soccer, Level: N/R PA (ACLR): Soccer, Level: N/R	-*Jump height asymmetry -*RSI asymmetry	Sampling frequency: 1000 Shoes on/off: N/R Hand position: On hips Warm up: Reported Number of trials: 3	11
Ithurburn 2019 **Longitudinal** **USA** **In English**	Control: [n=64, (f=20), (m=N/A)], age: 3.3±N/A ACLR: [n=N/A, (f=20), (m=44)], age: N/A±17 Graft type: N/A Time since surgery: N/R±7.8 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: N/R	-*Peak $vGRF_{(normalized)}$	Sampling frequency: 1200 Shoes on/off: On Hand position: Free Warm up: Reported Number of trials: 3	8
Double-leg Drop Jump				
Chang 2018 **Cross Sectional** **South Korea** **In English**	Control: [n=12, (f=12), (m=0)], age: 21±2.6 ACLR: [n=18, (f=12), (m=0)], age: 19.9±1.2 Graft type: N/R Time since surgery: 35.2±13.2 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Eccentric peak $vGRF_{(normalized)}$	Sampling frequency: 1560 Shoes on/off: On Hand position: N/R Warm up: Reported Number of trials: 3	10

Chang 2020 **Cross Sectional** **South Korea** **In English**	Control: [n=12, (f=12), (m=0)], age: 21±2.6 ACLR: [n=18, (f=12), (m=0)], age: 19.9±1.2 Graft type: N/R Time since surgery: 35.2±13.2 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Eccentric peak $vGRF_{(normalized)}$ symmetry -Eccentric loading $rate_{(normalized)}$ symmetry	Sampling frequency: 1560 Shoes on/off: On Hand position: N/R Warm up: Reported Number of trials: 3	10
Ford 2016 **Cross Sectional** **USA** **In English**	Control: [n=57, (f=42), (m=15)], age: 17.2±2.5 ACLR: [n=101, (f=42), (m=37)], age: 16.7±3 Graft type: N/R Time since surgery: 8.3±2.5 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Absolute initial contact timing differences between landing sides in (ms)	Sampling frequency: 1200 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 2	9
Funk 2016 **Cross Sectional** **USA** **In English**	Control: [n=11, (f=N/R), (m=N/R)], age: 21.1±2 ACLR: [n=12, (f=N/R), (m=N/R)], age: 20.7±1.3 Graft type: N/R Time since surgery: Less than 5 years±N/R PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Eccentric loading $rate_{(normalized)}$ -Eccentric $vGRF_{(normalized)}$ -Eccentric $hGRF_{(normalized)}$	Sampling frequency: 1400 Shoes on/off: N/R Hand position: N/R Warm up: Reported Number of trials: 3	8
Grooms 2018 **Cross Secational** **USA** **In English**	Control: [n=15, (f=8), (m=7)], age: 23.2±3.5 ACLR: [n=15, (f=8), (m=7)], age: 21.4±2.6 Graft type: 13 Hamstring, 2 patellar Time since surgery: 36.2±26.5 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: Recreational	-*Eccentric peak $vGRF_{(normalized)}$	Sampling frequency: N/R Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	11
Huang 2020 **Cross Sectional** **USA** **In English**	Control: [n=16, (f=16), (m=0)], age: 21±2.6 ACLR: [n=19, (f=16), (m=0)], age: 19.9±1.2 Graft type: N/R Time since surgery: 35.1±13.7 PA (Control): soccer, basketball, and handball, Level: Recreational PA (ACLR): soccer, basketball, and handball, Level: Recreational	-Eccentric peak $vGRF_{(normalized)}$ -Eccentric peak $pGRF_{(normalized)}$ -Time to peak vGRF -Time to peak pGRF	Sampling frequency: 1560 Shoes on/off: On Hand position: Free Warm up: N/R Number of trials: 3	10

Huang 2021 **Cross Sectional** **USA** **In English**	Control: [n=19, (f=19), (m=0)], age: 21.1±3.3 ACLR: [n=19, (f=19), (m=0)], age: 19.9±1.2 Graft type: N/R Time since surgery: 35.1±13.7 PA (Control): soccer, basketball, and handball, Level: Recreational PA (ACLR): soccer, basketball, and handball, Level: Recreational	-Eccentric peak $vGRF_{(normalized)}$ asymmetry - Eccentric loading $rate_{(normalized)}$ asymmetry	Sampling frequency: 1560 Shoes on/off: On Hand position: Free Warm up: N/R Number of trials: 3	10
Krysak 2019 **Cross Sectional** **USA** **In English**	Control: [n=3, (f=N/R), (m=N/R)], age: 20±2 ACLR: [n=7, (f=N/R), (m=N/R)], age: 20.86±1.86 Graft type: N/R Time since surgery: N/R±N/R PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Peak $vGRF_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: On Hand position: Frees Warm up: N/R Number of trials: 5	9
Kuntze 2021 **Cross Sectional** **USA** **In English**	Control: [n=48, (f=32), (m=16)], age: Median 22±Range (18-26) ACLR: [n=48, (f=32), (m=16)], age: Median 23±Range (18-26) Graft type: N/R Time since surgery: N/R±N/R PA (Control): Several, Level: N/R PA (ACLR): Several, Level: N/R	-Eccentric peak $vGRF_{(normalized)}$ -*Eccentric peak $mlGRF_{(normalized)}$ -Concentric peak $vGRF_{(normalized)}$ -Concentric peak $mlGRF_{(normalized)}$	Sampling frequency: 2400 Shoes on/off: Off Hand position: N/R Warm up: N/R Number of trials: 10	12
Meyer 2018 **Cross Sectional** **Luxembourg** **In English**	Control: [n=28, (f=14), (m=14)], age: 24.5±6.8 ACLR: [n=17, (f=14), (m=12)], age: 25.4±4.1 Graft type: HT 11, PT 6 Time since surgery: 8.9±1.3 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Eccentric peak $vGRF_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: On Hand position: On hips Warm up: Reported Number of trials: 3	9
Mohammadi 2012 **Cross Sectional** **Iran** **In English**	Control: [n=30, (f=6), (m=24)], age: 24.8±2.4 ACLR: [n=30, (f=6), (m=22)], age: 25±2.7 Graft type: HT 17, PT 13 Time since surgery: 8.4±1.8 PA (Control): soccer/basketball, Level: Recreational PA (ACLR): soccer/basketball, Level: Recreational	-*CoP AP displacement -*CoP AP velocity -*CoP ML displacement -*CoP ML velocity -*CoP mean velocity -Eccentric peak $vGRF_{(normalized)}$ -*Concentric peak $vGRF_{(normalized)}$ -Eccentric loading $rate_{(normalized)}$	Sampling frequency: 1200 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: N/R	8

Paterno 2007 **Cross Sectional** **USA** **In English**	Control: [n=18, (f=18), (m=0)], age: 20±1.2 ACLR: [n=14, (f=18), (m=0)], age: 20.7±2.5 Graft type: PT Time since surgery: 27.4±13.8 PA (Control): N/R, Level: Recreational PA (ACLR): N/R, Level: Recreational	-Eccentric Peak vGRF$_{(normalized)}$ -*Concentric peak vGRF$_{(normalized)}$ -Eccentric loading rate$_{(normalized)}$	Sampling frequency: N/R Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	8
Schmitt 2015 **Cross Sectional** **USA** **In English**	Control: [n=47, (f=32), (m=15)], age: 17±2.3 ACLR: [n=68, (f=32), (m=22)], age: 17.5±2.8 Graft type: PT 31, HS 31, Allo 6 Time since surgery: 8.2±2.1 PA (Control): Several sports, Level: Mix PA (ACLR): Several sports, Level: Mix	-*Eccentric peak vGRF$_{(normalized)}$ -Eccentric loading rate$_{(normalized)}$	Sampling frequency: 1200 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10
Shimizu 2020 **Cross Sectional data of longtudinal study** **USA** **In English**	Control: [n=14, (f=5), (m=9)], age: 31.4±4.9 ACLR: [n=36, (f=5), (m=20)], age: 31.5±7.6 Graft type: HS 24, allograft 12 Time since surgery: 6, 12, 24, 36±N/A PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-Eccentric peak vGRF$_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10
Shimizu 2019 **Cross Sectional data of longtudinal study** **USA** **In English**	Control: [n=16, (f=6), (m=10)], age: 31.7±1.3 ACLR: [n=31, (f=6), (m=17)], age: 31.3±1.4 Graft type: HS 22, allograft 9 Time since surgery: 6, 36±N/R PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Eccentric peak vGRF$_{(normalized)}$ -vGRF Impulse	Sampling frequency: 1000 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10
Ithurburn 2019 **Longitudinal** **USA** **In English**	Control: [n=N/A, (f=N/A), (m=N/A)], age: N/A±N/A ACLR: [n=64, (f=N/A), (m=20)], age: 17±3.3 Graft type: HS 39, PT 20, Allo 5 Time since surgery: 7.8±2.1 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: Recreational	-*Peak vGRF$_{(normalized)}$ asymmetry -*Peak vGRF$_{(normalized)}$	Sampling frequency: 1200 Shoes on/off: On Hand position: Free Warm up: N/R Number of trials: 3	8

Moya-Angeler 2017 Longitudinal USA **In English**	Control: [n=N/A, (f=N/A), (m=N/A)], age: N/A±N/A ACLR: [n=74, (f=N/A), (m=34)], age: 34±9 Graft type: N/R Time since surgery: 6±0 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Eccentric peak $vGRF_{(normalized)}$ -*Concentric peak $vGRF_{(normalized)}$ -*Contact time	Sampling frequency: N/R Shoes on/off: N/R Hand position: N/R Warm up: N/R Number of trials: N/R	7
Shimizu 2019 Longitudinal USA **In English**	Control: [n=N/A, (f=N/A), (m=N/A)], age: N/A±N/A ACLR: [n=31, (f=N/A), (m=17)], age: 31.3±7.8 Graft type: HS 23, allograft 8 Time since surgery: 6, 36±N/R PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Peak $vGRF_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10
Shimizu 2020 Longitudinal USA **In English**	Control: [n=14, (f=5), (m=9)], age: 31.4±4.9 ACLR: [n=36, (f=5), (m=20)], age: 31.5±7.6 Graft type: HS 24, allograft 12 Time since surgery: 6, 12, 24, 36 PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Peak $vGRF_{(normalized)}$	Sampling frequency: 1000 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10
Shimizu 2019 Longitudinal USA **In English**	Control: [n=16, (f=6), (m=10)], age: 31.7±1.3 ACLR: [n=31, (f=6), (m=17)], age: 31.3±1.4 Graft type: HS 22, allograft 9 Time since surgery: 6, 36±N/R PA (Control): N/R, Level: N/R PA (ACLR): N/R, Level: N/R	-*Peak $vGRF_{(normalized)}$ - vGRF Impulse	Sampling frequency: 1000 Shoes on/off: N/R Hand position: Free Warm up: N/R Number of trials: 3	10

* significant at p<0.05; N/R: Not Reported
ACLR: Anterior Cruciate Ligament Reconstruction; vGRF: vertical ground reaction force; CoP: center of pressure; TTS: time to stabilization; LSI: limb symmetry index; RSI: reactive strength index, RSR: reactive strength ratio.

APPENDIX 4.3: Systematic review – Parameters operationalization across the studies

Author	Parameters	Operationalization
Castanharo 2011	Concentric peak $vGRF_{(normalized)}$	Specified in the paper as the peak vGRF during the impulsion phase of the jump. Ground reaction forces were normalized to body weight.
	Landing Peak $vGRF_{(normalized)}$	Ground reaction forces were normalized to body weight.
Chang 2018	Eccentric peak $vGRF_{(normalized)}$	vGRF at either IC (vGRF >10 N) or the peak value between IC and the time of peak knee flexion. Ground reaction forces were normalized to body weight.
Chang 2020	Eccentric peak $vGRF_{(normalized)}$ symmetry	All dependent variables were identified at initial contact (vGRF>10 N) and/or the peak value during the landing phase (time from initial ground contact to peak knee flexion). Ground reaction forces were normalized to body weight.
	Eccentric loading $rate_{(normalized)}$ symmetry	Loading rate calculation not operationalized. Symmetry: (ACLR: reconstructed limb — non-reconstructed limb, healthy: non-dominant limb — dominant limb).
Collings 2021	Peak $GRF_{(normalized)}$ (Take-off)	Take-off included the eccentric countermovement and concentric propulsion phase. GRFs were normalized to body weight.
	Peak $GRF_{(normalized)}$ (Landing)	Landing was defined from initial ground contact until returning to a standing position. GRFs were normalized to body weight.
	Take-off $Impulse_{(normalized)}$	Calculated as the area under the force-time curve above standing bodyweight force. GRFs were normalized to body weight.
Costley 2021	Eccentric deceleration $impulse_{(normalized)}$	Eccentric deceleration phase: from maximal downwards velocity to zero velocity. Impulses were derived by integration of force–time curves. GRFs were normalized to body mass.
	Concentric $impulse_{(normalized)}$	Concentric phase: from zero velocity to take-off. Impulses were derived by integration of force–time curves. GRFs were normalized to body mass.
	Landing $impulse_{(normalized)}$	Landing phase: from landing to zero velocity. Impulses were derived by integration of force–time curves. GRFs were normalized to body mass.
	Jump height	The impulse–momentum relationship was used to calculate vertical velocity of the centre of mass at the instant of CMJ take-off (Linthorne, 2001), enabling the determination of peak CMJ height
Ford 2016	Absolute initial contact timing differences between landing sides	Initial contact was as the time that the unfiltered vertical ground reaction force first exceeded 10 N. The absolute time difference between the initial contacts for each leg was calculated and compared between ACLR and control groups.

Funk 2016	Eccentric loading rate$_{(normalized)}$	Rate of loading was calculated from the time of initial vertical ground reaction force to the time to peak force. Ground reaction forces were normalized to body weight.
	Eccentric vGRF$_{(normalized)}$	GRFs were normalized to body weight.
	Eccentric hGRF$_{(normalized)}$	GRFs were normalized to body weight.
Giesche 2021	Landing peak vGRF$_{(normalized)}$	GRFs were normalized to body weight.
	CoP length of path	During the first 2.5 sec upon landing
	TTS	Estimated relative to the whole standing period of 10 sec after landing. A stable stance is assumed as soon as the sequential average no longer exceeds the threshold of 0.25 SD of the overall mean ground vertical force.
	Flight time	Not operationalized
Grooms 2018	Eccentric peak vGRF$_{(normalized)}$	Initial contact of each limb was defined as the point when the vertical ground reaction force first exceeded 20 N. The landing phase was defined as the period from initial contact to peak knee flexion. Ground reaction forces were normalized to body weight.
Holsgaard-Larsen 2014	Jump Height	Calculated from the vertical velocity of the body center of mass at take-off, the latter derived by calculation of the kinetic impulse during the entire take-off phase. Specifically, vertical BCM velocity was obtained by time integration of the instantaneous acceleration signal ([Fz / m] − g, where m = body mass and g = 9.81 m/s.
Huang 2020	Eccentric peak vGRF$_{(normalized)}$	The time when the vGRF >10 Newton was identified as initial contact. Peak vGRF were calculated during the initial 100 ms after inintial contact
	Eccentric peak pGRF$_{(normalized)}$	Peak posterior ground reaction forces were calculated during the initial 100 ms after inintial contact
	Time to peak vGRF	Time from initial contact to peak vGRF
	Time to peak pGRF	Time from initial contact to peak posterior ground reaction forces
Huang 2021	Eccentric peak vGRF$_{(normalized)}$ asymmetry	During the initial 100 milliseconds after IC, which was defined as the time when the vGRF exceeded 10 N. Asymmetry was calculated as the ACLR limb minus the uninvolved limb for the ACLR group and the nondominant limb minus the dominant limb for the control group. GRFs were normalized to body mass
	Eccentric loading rate$_{(normalized)}$ asymmetry	Loading rate was calculated as the peak vGRF divided by the time from IC to peak vGRF. Asymmetry was calculated as the ACLR limb minus the uninvolved limb for the ACLR group and the nondominant limb minus the dominant limb for the control group.
Ithurburn 2019	Peak vGRF$_{(normalized)}$ asymmetry	Forces were normalized to body weight. (Involved limb value /uninvolved limb value) x 100%. GRFs were normalized to body weight
	Peak vGRF$_{(normalized)}$	Forces were normalized to body weight.

Jordan 2018	Contraction time	Determined from the onset of the vertical takeoff (start of the jump) to the instant of ground toe-off
	Jump height	Jump Height = Take-off Velocity^2/(2g)
	Relative peak power$_{(normalized)}$	Not operationalized
	Relative mean power$_{(normalized)}$	Not operationalized
	Velocity max	Not operationalized
	Relative force$_{(normalized)}$ at max velocity	Normalized to body mass
	Relative force$_{(normalized)}$ at peak power	Normalized to body mass
	Velocity at peak power$_{(normalized)}$	Not operationalized
	Impulse eccentric asymmetry	Integration of the force–time curve over the eccentric deceleration phase duration. Asymmetry was calculated as (Uninjured limb eccentric impulse - ACLR limb eccentric impulse)/(Maximum of left and right eccentric impulse) x 100
	Impulse concentric asymmetry	Integration of the force–time curve over the concentric phase duration. Asymmetry was calculated as (Uninjured limb eccentric impulse - ACLR limb eccentric impulse)/(Maximum of left and right eccentric impulse) x 100
Jordan 2015	Impulse eccentric	Integration of the force–time curve over the eccentric deceleration phase duration.
	Impulse concentric	Integration of the force–time curve over the concentric phase duration.
	Impulse eccentric asymmetry	(Uninjured limb eccentric impulse - ACLR limb eccentric impulse)/(Maximum of left and right eccentric impulse) x 100
	Impulse concentric asymmetry	(Uninjured limb concentric impulse - ACLR limb concentric impulse)/(Maximum of left and right concentric impulse) x 100
Kilic 2018	vGRF at initial contact	Initial contact phase was defined as the instant where the force plate reported values greater than 20 N. Forces were normalized to body weight.
	Peak vGRF	Forces were normalized to body weight.
	vGRF at last contact	the greatest force value after moment of jump. Forces were normalized to body weight.
Kotsifaki 2022	Jump Height	Measured as the vertical displacement of the centre of mass from toe off to the maximum height of the centre of mass
	RSI	The jump height in a drop jump, divided by the contact time
	RSR	The flight time of the jump divided by the contact time
	Contact time (s)	Not operationalized

Krafft 2017	Jump height	Not operationalized
	Impulse eccentric LSI	The deceleration impulses were measured during landing. LSIs were calculated for all parameters by the related discrete values of the injured leg divided by the uninjured leg in the ACL subjects and by the non-dominant leg divided by the dominant leg in the control subjects, respectively
	Impulse concentric LSI	The acceleration impulses were measured during take-off. LSIs were calculated for all parameters by the related discrete values of the injured leg divided by the uninjured leg in the ACL subjects and by the non-dominant leg divided by the dominant leg in the control subjects, respectively
Krysak 2019	Peak $vGRF_{(normalized)}$	Forces were normalized to body weight. The stance phase (initial contact to toe-off), with initial contact and toe-off representing the instants when the vertical ground reaction force (vGRF) first exceeded or fell below 10N
Kuntze 2021	Eccentric peak $vGRF_{(normalized)}$	Initial contact was identified using vGRF data for each force plate with a cutoff of 5% of the peak vGRF. The duration of the support phase of the DJ was determined from the time either leg first contacted the ground (ie, initial contact) until the first time either leg first left the ground (ie, toe-off). Forces were normalized to body weight.
	Eccentric peak $mlGRF_{(normalized)}$	Forces were normalized to body weight.
	Concentric peak $vGRF_{(normalized)}$	Forces were normalized to body weight.
	Concentric peak $mlGRF_{(normalized)}$	Forces were normalized to body weight.
Meyer 2018	Eccentric peak $vGRF_{(normalized)}$	Initial contact and take-off events were determined based on a 10 N threshold from the vertical ground reaction force vector. The eccentric landing phase defined as initial contact to maximal knee flexion angle. Forces were normalized to body weight.
Miles 2019	$Impulse_{(normalized)}$ eccentric	Take-off was defined as the first instant the sum of GRFv on both force platforms was <10 N and landing was defined as the first instant the sum of GRFv on both force platforms was >10 N after take-off. CoM vertical velocity was used to define phases of interest: The eccentric deceleration phase was defined as the time interval from maximum negative velocity to zero velocity (lowest CoM position). Impulse was calculated as integral of the force-time curve and divided by body mass.
	$Impulse_{(normalized)}$ concentric	the concentric phase was defined from zero velocity to the instant of take-off. Impulse was calculated as integral of the force-time curve and divided by body mass.

	Impulse$_{(normalized)}$ landing	the landing phase was defined as the time interval from landing to zero velocity (lowest CoM position). Impulse was calculated as integral of the force-time curve and divided by body mass
	Jump Height	Jump height was calculated from the vertical velocity of the center of body mass (CoM) at take-off, as derived from the impulse-momentum relationship
Mohammadi 2012	CoP AP displacement	Not operationalized
	CoP AP velocity	Not operationalized
	CoP ML displacement	Not operationalized
	CoP ML velocity	Not operationalized
	CoP mean velocity	Not operationalized
	Eccentric peak vGRF$_{(normalized)}$	participants were asked to drop off a 40-cm platform and immediately jump as high as they can (takeoff phase) and then contact the center of the force plate again (landing phase)
	Concentric peak vGRF$_{(normalized)}$	participants were asked to drop off a 40-cm platform and immediately jump as high as they can (takeoff phase) and then contact the center of the force plate again (landing phase)
	Eccentric loading rate$_{(normalized)}$	Peak vGRF normalized to body weight divided by time to reach peak vGRF
Moya-Angeler 2017	Eccentric peak vGRF$_{(normalized)}$	Mentioned in the paper as fallen maximum vertical force. According the graph, it means eccentric peak vGRF. Forces were normalized to body weight.
	Concentric peak vGRF$_{(normalized)}$	Mentioned in the paper as impulse maximum vertical force. Operated on the graph as concentric peak vGRF. Forces were normalized to body weight.
	Contact time	Not operated
O'Malley 2018	Jump Height	Jump height was determined using the impulse-momentum relationship
	Peak power$_{(normalized)}$	Peak power was measured and normalized to body weight during the propulsion phase of the single-leg CMJ. Peak power was selected due to its reported relationship to jump height.
Ortiz 2008	Peak vGRF$_{(normalized)}$	The ground-contact phase: from initial contact as identified by the force plate to push off from the force plate into the vertical jump. Forces were normalized to body weight.
Paterno 2007	Eccentric Peak vGRF$_{(normalized)}$	Eccentric: Take off phase. Forces were normalized to body weight.
	Concentric peak vGRF$_{(normalized)}$	Concentric: Landing phase. Forces were normalized to body weight.

	Eccentric loading rate$_{(normalized)}$	loading rate during landing was calculated as the peak vGRF normalized to body weight divided by time to reach peak vGRF
Read 2020	Jump height asymmetry	Asymmetry calculation was not operationalized. Jump height was calculated using the athletes centre of mass velocity via the following equation: $(\text{COM velocity})^2$ / (9.81 x 2).
	RSI asymmetry	Asymmetry calculation was not operationalized. Reactive strength index (RSI) was quantified using the equation jump height/ground contact time. contact time was defined as the time from which the vGRF exceeded 20 N to the instant of take-off
Read 2020a	Jump height	The initiation of the jump was defined by a 20-N change from body weight calculated during the quiet standing period. Jump height was calculated from the impulse-momentum relationship–derived take-off velocity and equation of constant acceleration
	Peak power	Not operationalized
	Impulse concentric	Concentric phase, from zero velocity to the instant of take-off
	Impulse concentric asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left + right) x 100 for ACLR and Healthy Controls, respectively
	Impulse eccentric deceleration	Eccentric phase, the time from initiation of the jump to zero center of mass velocity. The eccentric deceleration phase was defined as the time interval from the maximum negative velocity to zero velocity. Eccentric deceleration was calculated via time integration of the force-time curve during the eccentric deceleration phase
	Impulse eccentric deceleration asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left + right) x 100 for ACLR and Healthy Controls, respectively
	Concentric peak vGRF	Not normalized to body weight (based on the values)
	Concentric Peak vGRF asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left + right) x 100 for ACLR and Healthy Controls, respectively
	Eccentric deceleration RFD	Not operationalized
	Eccentric deceleration RFD asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left + right) x 100 for ACLR and Healthy Controls, respectively
	Eccentric mean GRF	Not normalized to body weight (based on the values)
	Eccentric mean GRF asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left +

		right) x 100 for ACLR and Healthy Controls, respectively
	Peak vGRF (Landing)	Not normalized to body weight (based on the values)
	Peak vGRF (Landing) asymmetry	Asymmetry was calculated as: (involved – uninvolved) / (involved + uninvolved) x 100 and (left – right) / (left + right) x 100 for ACLR and Healthy Controls, respectively
Schmitt 2015	Eccentric peak $vGRF_{(normalized)}$	During the landing phase. Forces were normalized to body weight.
	Eccentric loading $rate_{(normalized)}$	Peak vGRF divided by the time to reach peak; BW/seconds
Shimizu 2019	Peak $vGRF_{(normalized)}$	All data were analyzed during the landing phase of the task (stance phase). The stance phase of the task was defined as initial contact to toe off (vGRF > 20 N) and was time normalized to 101 points. Forces were normalized to body weight.
Shimizu 2020	Eccentric peak $vGRF_{(normalized)}$	The stance phase of the task was defined as initial contact to toe-off and was time normalized to 101 points. All data were analyzed during the landing phase of the task (stance phase). The peak vGRF was calculated during the (first 50% of stance phase). Forces were normalized to body weight.
Shimizu 2019a	Eccentric peak $vGRF_{(normalized)}$	The stance phase of the task was defined as initial contact to toe off and was time normalized to 101 points. All data were analyzed during the landing phase of the task (stance phase). The peak vGRF was calculated during the (first 50% of stance phase). Forces were normalized to body weight.
	vGRF Impulse	The vGRF impulse during the stance phase of the drop-jump task was calculated as the time-based integral of the vGRF

vGRF: vertical ground reaction force; ACLR: anterior cruciate ligament reconstruction; GRF: ground reaction force; CMJ: countermovement jump; hGRF: horizontal ground reaction force; CoP: center of pressure; TTS: time to stabilization; SD: standard deviation; BCM: body center of mass; m/s: meter per second; IC: initial contact; g: gravity; N: newton; RSI: reactive strength index; RSR: reactive strength ratio; S: second; DJ: drop jump; mlGRF: medial lateral ground reaction force; CoM: center of mass; AP: anterior posterior; ML: medial lateral; RFD: rate of force development; BW: body weight

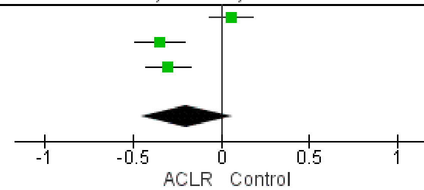
APPENDIX 4.4: Meta-analyses – Non-discriminatory parameters during double-leg drop jumps

Concentric peak vGRF$_{\text{(normalized)}}$ (involved side)

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Kuntze 2021	1.15	0.28	48	1.09	0.33	48	33.7%	0.06 [-0.06, 0.18]
Mohammadi 2012	1.1	0.1	15	1.45	0.26	15	32.9%	-0.35 [-0.49, -0.21]
Paterno 2007	1.1	0.1	14	1.4	0.25	18	33.5%	-0.30 [-0.43, -0.17]
Total (95% CI)			**77**			**81**	**100.0%**	**-0.20 [-0.45, 0.06]**

Heterogeneity: Tau² = 0.05; Chi² = 23.79, df = 2 (P < 0.00001); I² = 92%
Test for overall effect: Z = 1.48 (P = 0.14)

Mean Difference IV, Random, 95% CI

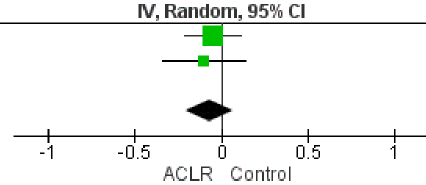


Concentric peak vGRF$_{\text{(normalized)}}$ (uninvolved side)

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Mohammadi 2012	1.4	0.2	15	1.45	0.26	15	67.5%	-0.05 [-0.22, 0.12]
Paterno 2007	1.3	0.4	14	1.4	0.25	18	32.5%	-0.10 [-0.34, 0.14]
Total (95% CI)			**29**			**33**	**100.0%**	**-0.07 [-0.20, 0.07]**

Heterogeneity: Tau² = 0.00; Chi² = 0.11, df = 1 (P = 0.74); I² = 0%
Test for overall effect: Z = 0.95 (P = 0.34)

Mean Difference IV, Random, 95% CI

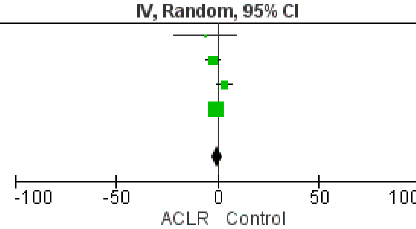


Eccentric loading rate$_{\text{(normalized)}}$ (involved side)

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Funk 2016	44.67	18.79	12	50.73	19.08	11	2.3%	-6.06 [-21.56, 9.44]
Mohammadi 2012	20.9	5.8	15	22.95	3.9	15	26.5%	-2.05 [-5.59, 1.49]
Paterno 2007	22.3	5.9	14	18.75	5.24	18	23.4%	3.55 [-0.38, 7.48]
Schmitt 2015	10.91	4.57	68	11.3	4.5	47	47.7%	-0.39 [-2.07, 1.29]
Total (95% CI)			**109**			**91**	**100.0%**	**-0.04 [-2.44, 2.36]**

Heterogeneity: Tau² = 2.41; Chi² = 5.15, df = 3 (P = 0.16); I² = 42%
Test for overall effect: Z = 0.03 (P = 0.97)

Mean Difference IV, Random, 95% CI

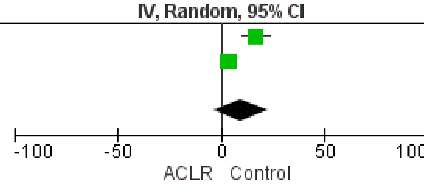


Eccentric loading rate$_{\text{(normalized)}}$ (uninvolved side)

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Paterno 2007	35.4	12	14	18.75	5.24	18	46.9%	16.65 [9.91, 23.39]
Schmitt 2015	14.73	6.55	68	11.3	4.5	47	53.1%	3.43 [1.41, 5.45]
Total (95% CI)			**82**			**65**	**100.0%**	**9.63 [-3.30, 22.56]**

Heterogeneity: Tau² = 80.95; Chi² = 13.58, df = 1 (P = 0.0002); I² = 93%
Test for overall effect: Z = 1.46 (P = 0.14)

Mean Difference IV, Random, 95% CI

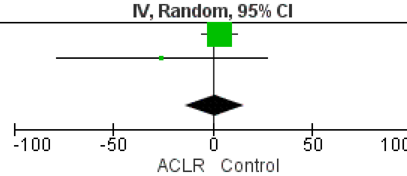


Eccentric loading rate$_{\text{(normalized)}}$ asymmetry

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Chang 2020	3.46	13.44	18	-0.11	11.68	12	92.3%	3.57 [-5.50, 12.64]
Huang 2021	-41.85	91.87	19	-16.31	74.78	19	7.7%	-25.54 [-78.80, 27.72]
Total (95% CI)			**37**			**31**	**100.0%**	**1.33 [-13.87, 16.53]**

Heterogeneity: Tau² = 43.73; Chi² = 1.12, df = 1 (P = 0.29); I² = 10%
Test for overall effect: Z = 0.17 (P = 0.86)

Mean Difference IV, Random, 95% CI

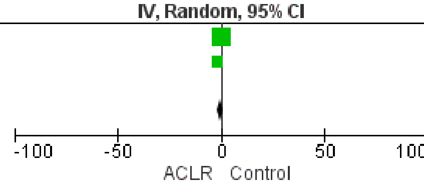


Eccentric peak vGRF$_{\text{(normalized)}}$ asymmetry

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Chang 2020	0.17	0.49	18	-0.08	0.47	12	63.7%	0.25 [-0.10, 0.60]
Huang 2021	-2.52	3.15	19	-0.86	3.11	19	36.3%	-1.66 [-3.65, 0.33]
Total (95% CI)			**37**			**31**	**100.0%**	**-0.44 [-2.24, 1.36]**

Heterogeneity: Tau² = 1.29; Chi² = 3.43, df = 1 (P = 0.06); I² = 71%
Test for overall effect: Z = 0.48 (P = 0.63)

Mean Difference IV, Random, 95% CI



APPENDIX 5.1 – Sensitivity Analysis – TTS Outcomes

Table A - Comparisons of TTS variables among ACLR and Healthy Control groups using parametric and non-parametric analysis according to data distribution.

OUTCOMES	ACLR (n = 21)	Healthy Control (n = 20)	P-value	ES (95% CI)
APTTS-C†	2.01 (0.28)	2.04 (0.23)	0.80	
MLTTS-C†	2.29 (0.27)	2.16 (0.42)	0.38	
VTTS-C†	1.61 (0.16)	1.57 (0.1)	0.07	
RVTTS-C†	2.31 (1.02)	2.03 (0.26)	**0.03***	**0.40 (0.04, 0.67)**
APTTS-op†	1.97 (0.29)	1.87 (0.27)	0.28	
MLTTS-op	2.04±0.47	2.19±0.29	0.18	
VTTS-op†	1.76 (0.27)	1.6 (0.19)	**0.02***	**0.96 (0.84-0.99)**
RVTTS-op†	2.87 (0.35)	2.87 (0.35)	1.00	
APTTS-nop	2.15±0.28	2.19±0.3	0.68	
MLTTS-nop†	1.95 (0.4)	1.84 (0.4)	0.16	
VTTS-nop†	1.66 (0.18)	1.63 (0.16)	0.53	
RVTTS-nop	2.97±0.06	2.89±0.36	0.44	
APTTS-Asy	-0.02±0.27	0.01±0.24	0.70	
MLTTS-Asy	0.01±0.24	0.03±0.15	0.81	
VTTS-Asy†	0.03 (0.27)	0.07 (0.2)	0.90	
RVTTS-Asy†	0.02 (0.35)	0.01 (0.18)	0.72	

† Data reported in median and inter-quartile range (IQR). APTTS-G: anterior-posterior time to stabilization combined from both force plates. MLTTS-G: medial-lateral time to stabilization combined from both force plates. VTTS-G: vertical time to stabilization combined from both force plates. RVTTS-G: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APTTS-Asy: asymmetry in anterior-posterior time to stabilization between the two legs. MLTTS-Asy: asymmetry in medial-lateral time to stabilization between the two legs. VTTS-Asy: asymmetry in vertical time to stabilization between the two legs. RVTTS-Asy: asymmetry in resultant vector time to stabilization between the two legs.

Table B – Sex differences within and between groups using parametric and non-parametric analysis according to data distribution.- TTS outcomes

OUTCOMES	ACLR		Healthy Control		df	F or X^2	p-value
	Female (n=10)	Male (n=11)	Female (n=10)	Male (n=10)			
APTTS-C	1.97±0.17	2.15±0.25	2.05±0.22	2.11±0.23	1	0.85	0.36
MLTTS-C†	2.33 (0.27)	2.27 (0.35)	2.35 (0.66)	2.09 (0.31)	3	4.72	0.19
VTTS-C†	1.56 (0.12)	1.71 (0.15)	1.53 (0.10)	1.56 (0.14)	3	12.76	**0.01***
RVTTS-C†	2.09 (0.91)	3.03 (1.03)	2.04 (0.52)	2.02 (0.27)	3	9.87	**0.02***
APTTS-op†	2.13 (0.42)	1.97 (0.70)	2.15 (0.21)	2.22 (0.40)	3	3.05	0.38
MLTTS-op	1.87±0.24	2.06±0.32	1.89±0.26	1.86±0.29	1	1.69	0.20
VTTS-op†	1.59 (0.13)	1.87 (0.26)	1.58 (0.13)	1.68 (0.25)	3	16.94	**<0.01***
RVTTS-op	2.93±0.34	2.98±0.48	2.88±0.19	2.94±0.39	1	0.00	0.95
APTTS-nop†	2.02 (0.52)	2.19 (0.16)	2.18 (0.28)	2.36 (0.61)	3	1.20	0.75
MLTTS-nop†	1.80 (0.55)	2.03 (0.38)	1.86 (0.24)	1.80 (0.62)	3	3.94	0.27
VTTS-nop†	1.59 (0.15)	1.72 (0.11)	1.59 (0.11)	1.66 (0.15)	3	5.99	0.11
RVTTS-nop†	2.93 (0.37)	2.99 (0.45)	2.92 (0.21)	2.98 (0.85)	3	1.87	0.60
APTTS-Asy†	0.03 (0.19)	-0.01 (0.44)	0.01 (0.12)	0.01 (0.44)	3	0.62	0.89
MLTTS-Asy†	0.08 (0.23)	0.05 (0.27)	0.06 (0.26)	-0.01 (0.13)	3	0.43	0.93
VTTS-Asy†	0.03 (0.16)	0.05 (0.40)	0.06 (0.18)	0.07 (0.23)	3	0.08	0.99
RVTTS-Asy†	0.05 (0.37)	-0.07 (0.53)	0.01 (0.10)	0.01 (0.37)	3	0.79	0.89

† Data reported in median and inter-quartile range (IQR). APTTS-G: anterior-posterior time to stabilization combined from both force plates. MLTTS-G: medial-lateral time to stabilization combined from both force plates. VTTS-G: vertical time to stabilization combined from both force plates. RVTTS-G: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APTTS-Asy: asymmetry in anterior-posterior time to stabilization between the two legs. MLTTS-Asy: asymmetry in medial-lateral time to stabilization between the two legs. VTTS-Asy: asymmetry in vertical time to stabilization between the two legs. RVTTS-Asy: asymmetry in resultant vector time to stabilization between the two legs.

APPENDIX 5.2 – Sensitivity Analysis – PSI Outcomes

Table A- Comparisons of PSI variables among ACLR and Healthy Control groups using parametric and non-parametric analysis according to data distribution.

OUTCOMES	ACLR (n = 21)	Healthy Control (n = 20)	P-value
APSI-C	0.69±0.19	0.70±0.16	0.71
MLSI-C	0.60±0.18	0.68±0.15	0.07
VSI-C	0.24±0.04	0.25±0.03	0.22
DPSI-C†	0.94 (0.20)	1.06 (0.20)	0.25
APSI-op	0.56±0.21	0.71±0.18	0.35
MLSI-op	0.64±0.34	0.67±0.29	0.73
VSI-op†	0.24 (0.06)	0.25 (0.04)	0.21
DPSI-op	0.97±0.32	1.04±0.26	0.49
APSI-nop	0.72±0.24	0.71±0.17	0.85
MLSI-nop†	0.58 (0.40)	0.68 (0.45)	0.35
VSI-nop	0.26±0.05	0.26±0.04	0.59
DPSI-nop	1.05±0.28	1.08±0.28	0.74
APSI-Asy	0.04±0.24	0.04±0.16	0.96
MLSI-Asy	0.45±0.30	0.42±0.27	0.71
VSI-Asy	0.01±0.08	-0.01±0.06	0.35
DPSI-Asy†	0.41 (0.46)	0.21 (0.29)	0.77

† Data reported in median and inter-quartile range (IQR). APSI-G: anterior-posterior stability index combined from both force plates. MLSI-G: medial-lateral stability index combined from both force plates. VSI-G: vertical stability index combined from both force plates. DPSI-G: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. APSI-Asy: asymmetry in anterior-posterior stability index between the two legs. MLSI-Asy: asymmetry in medial-lateral stability index between the two legs. VSI-Asy: asymmetry in vertical stability index between the two legs. DPSI-Asy: asymmetry in dynamic postural stability index between the two legs.

Table B- Sex differences within and between groups using parametric and non-parametric analysis according to data distribution.- TTS outcomes – PSI outcomes

OUTCOMES	ACLR		Healthy Control		df	F or X^2	P-value
	Female (n=10)	**Male (n=11)**	**Female (n=10)**	**Male (n=10)**			
APSI-C†	0.70 (0.13)	0.69 (0.28)	0.66 (0.22)	0.77 (0.30)	3	2.37	0.50
MLSI-C	0.65±0.14	0.56±0.21	0.67±0.13	0.70±0.18	1	1.12	0.30
VSI-C	0.22±0.05	0.25±0.04	0.25±0.02	0.26±0.03	1	0.65	0.42
DPSI-C†	0.99 (0.14)	0.91 0.17)	1.00 (0.10)	1.13 (0.31)	3	3.08	0.38
APSI-op	0.66±0.13	0.64±0.27	0.65±0.16	0.76±0.19	1	0.98	0.33
MLSI-op†	0.63 (46)	0.58 (0.73)	0.80 (0.35)	0.51 (0.40)	3	2.28	0.52
VSI-op†	0.24 (0.08)	0.24 (0.05)	0.26 (0.03)	0.25 (0.04)	3	1.67	0.64
DPSI-op	0.97±0.23	0.98±0.40	1.05±0.23	1.03±0.30	1	0.01	0.91
APSI-nop	0.75±0.19	0.70±0.28	0.65±0.13	0.76±0.19	1	1.85	0.18
MLSI-nop†	0.61 (0.36)	0.58 (0.16)	0.68 (0.23)	0.86 (0.40)	3	2.35	0.50
VSI-nop†	0.22 (0.08)	0.27 (0.04)	0.26 (0.06)	0.28 (0.07)	3	7.82	**0.05***
DPSI-nop	1.08±0.30	1.02±0.27	0.96±0.20	1.21±0.31	1	3.37	0.07
APSI-Asy	0.04±0.28	0.05±0.21	0.04±0.14	0.04±0.19	1	0.01	0.91
MLSI-Asy	0.46±0.22	0.45±0.21	0.31±0.21	0.53±0.28	1	1.54	0.22
VSI-Asy	0.03±0.09	-0.01±0.08	-0.01±0.06	-0.01±0.06	1	0.61	0.44
DPSI-Asy†	0.39 (0.39)	0.41 (0.49)	0.24 (0.21)	0.18 (0.38)	3	0.24	0.97

† Data reported in median and inter-quartile range (IQR). APSI-G: anterior-posterior stability index combined from both force plates. MLSI-G: medial-lateral stability index combined from both force plates. VSI-G: vertical stability index combined from both force plates. DPSI-G: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. APSI-Asy: asymmetry in anterior-posterior stability index between the two legs. MLSI-Asy: asymmetry in medial-lateral stability index between the two legs. VSI-Asy: asymmetry in vertical stability index between the two legs. DPSI-Asy: asymmetry in dynamic postural stability index between the two legs.

APPENDIX 5.3 – PSI analyses results

Table 1- Between group comparisons of PSI outcomes

OUTCOMES	ACLR (n = 21)	Healthy Control (n = 20)	P-value
APSI-C	0.69 (0.16)	0.71 (0.22)	0.86
MLSI-C	0.63 (0.24)	0.64 (0.21)	0.25
VSI-C	0.24 (0.04)	0.25 (0.04)	0.29
DPSI-C	0.94 (0.20)	1.06 (0.20)	0.25
APSI-op	0.60 (0.17)	0.68 (0.25)	0.45
MLSI-op	0.61 (0.46)	0.62 (0.37)	0.60
VSI-op	0.24 (0.06)	0.25 (0.04)	0.21
DPSI-op	0.89 (0.39)	0.99 (0.30)	0.40
APSI-nop	0.72 (0.28)	0.70 (0.18)	0.67
MLSI-nop	0.58 (0.40)	0.68 (0.45)	0.35
VSI-nop	0.27 (0.06)	0.26 (0.05)	0.44
DPSI-nop	1.01 (0.39)	1.07 (0.31)	1.00
APSI-Asy	0.05 (0.25)	0.02 (0.18)	0.71
MLSI-Asy	0.48 (0.48)	0.37 (0.30)	0.77
VSI-Asy	0.01 (0.10)	-0.02 (0.09)	0.30
DPSI-Asy	0.41 (0.46)	0.21 (0.29)	0.77

Data reported in median and inter-quartile range (IQR). APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. APSI-Asy: asymmetry in anterior-posterior stability index between the two legs. MLSI-Asy: asymmetry in medial-lateral stability index between the two legs. VSI-Asy: asymmetry in vertical stability index between the two legs. DPSI-Asy: asymmetry in dynamic postural stability index between the two legs. Bonferroni adjustment was not made.[23, 27]

Table 2- Subgroups differences- PSI outcomes

OUTCOMES	ACLR		Healthy Conrtol		df	F or X^2	P-value
	Female (n=10)	Male (n=11)	Female (n=10)	Male (n=10)			
APSI-C	0.70 (0.13)	0.69 (0.28)	0.66 (0.22)	0.77 (0.30)	3	2.37	0.50
MLSI-C	0.66 (0.24)	0.58 (0.19)	0.66 (0.16)	0.63 (0.30)	3	2.36	0.50
VSI-C	0.23 (0.05)	0.24 (0.04)	0.24 (0.03)	0.26 (0.05)	3	4.32	0.23
DPSI-C	0.99 (0.14)	0.91 0.17)	1.00 (0.10)	1.13 (0.31)	3	3.08	0.38
APSI-op	0.59 (0.23)	0.63 (0.21)	0.63 (0.26)	0.69 (0.39)	3	2.59	0.46
MLSI-op	0.63 (0.46)	0.58 (0.73)	0.80 (0.35)	0.51 (0.40)	3	2.28	0.52
VSI-op	0.24 (0.08)	0.24 (0.05)	0.26 (0.03)	0.25 (0.04)	3	1.67	0.64
DPSI-op	0.99 (0.39)	0.84 (0.71)	1.02 (0.26)	0.96 (0.27)	3	0.81	0.98
APSI-nop	0.75 (0.19)	0.69 (0.37)	0.66 (0.20)	0.74 (0.20)	3	2.93	0.40
MLSI-nop	0.61 (0.36)	0.58 (0.16)	0.68 (0.23)	0.86 (0.40)	3	2.35	0.50
VSI-nop	0.22 (0.08)	0.27 (0.04)	0.26 (0.06)	0.28 (0.07)	3	7.82	**0.05***
DPSI-nop	1.08 (0.35)	1.01 (0.43)	0.95 (0.25)	1.18 (0.28)	3	3.39	0.34
APSI-Asy	0.16 (0.42)	0.00 (0.30)	0.05 (0.11)	-0.03 (0.20)	3	0.79	0.85
MLSI-Asy	0.49 (0.28)	0.41 (0.72)	0.37 (0.29)	0.46 (0.33)	1	2.31	0.51
VSI-Asy	0.05 (0.09)	0.00 (0.11)	-0.02 (0.07)	-0.02 (0.09)	1	2.43	0.49
DPSI-Asy	0.39 (0.39)	0.41 (0.49)	0.24 (0.21)	0.18 (0.38)	3	0.24	0.97

Data reported in median and inter-quartile range (IQR). APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. APSI-Asy: asymmetry in anterior-posterior stability index between the two legs. MLSI-Asy: asymmetry in medial-lateral stability index between the two legs. VSI-Asy: asymmetry in vertical stability index between the two legs. DPSI-Asy: asymmetry in dynamic postural stability index between the two legs. Bonferroni adjustment was not made.[23, 27]

APPENDIX 6.1: Sensitivity analysis – TTS outcomes

Between conditions (stoop vs. no-stroop) differences of TTS outcomes in ACLR and Healthy Control individuals using parametric and non-parametric analysis according to data distribution.

TTS Variables	ACLR (n=21)			Healthy Contorl (n=20)		
	No-Stroop	Stroop	p-value	No-Stroop	Stroop	p-value
APTTS-C	2.07±0.23	2.09±0.19	0.66	2.04 (0.23) †	2.00 (0.26) †	0.74
MLTTS-C	2.30±0.17	2.34±0.27	0.51	2.16 (0.42) †	2.34 (0.48) †	0.58
VTTS-C	1.61 (0.16) †	1.63 (0.12) †	0.11	1.56±0.10	1.58±0.12	0.67
RVTTS-C	2.31 (1.02) †	3.19 (0.29) †	**<0.01***	2.03 (0.26) †	3.13 (0.55) †	**<0.01***
APTTS-op	2.04 (0.47) †	2.02 (0.44) †	0.23	2.19 (0.29) †	2.25 (0.39) †	0.84
MLTTS-op	1.93 (0.39) †	1.77 (0.44) †	0.05	1.87±0.27	1.83±0.26	0.49
VTTS-op	1.76 (0.27) †	1.72 (0.25)	0.53	1.62±0.14	1.66±0.15	0.31
RVTTS-op	2.87 (0.35) †	2.94 (0.33) †	0.74	2.91±0.30	2.88±0.27	0.60
APTTS-nop	2.15±0.28	2.15±0.22	0.91	2.19±0.30	2.11±0.32	0.39
MLTTS-nop	1.95 (0.40) †	1.88 (0.42) †	0.24	1.87±0.27	1.84±0.26	0.55
VTTS-nop	1.66 (0.18) †	1.69 (0.15) †	0.77	1.63 (0.16) †	1.65 (0.24) †	0.67
RVTTS-nop	2.97±0.29	2.90±0.30	0.38	2.89±0.36	2.80±0.36	0.38

† Data reported in median and inter-quartile range (IQR). APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg.

APPENDIX 6.2: Sensitivity analysis – PSI outcomes

Between conditions (stoop vs. no-stroop) differences of PSI outcomes in ACLR and Healthy Control individuals using parametric and non-parametric analysis according to data distribution.

Postural Stability Indices	**ACLR (n=21)**			**Healthy Control (n=20)**		
	No-Stroop	**Stroop**	**p-value**	**No-Stroop**	**Stroop**	**p-value**
APSI-C	0.69±0.19	0.71±0.23	0.43	0.71±0.16	0.76±0.15	**0.02***
MLSI-C	0.60±0.18	0.65±0.20	**0.01***	0.68±0.15	0.75±0.16	**<0.01***
VSI-C	0.24±0.04	0.24±0.04	0.49	0.25±0.03	0.25±0.04	0.69
DPSI-C	0.94 (0.20) †	1.01 (0.20) †	**0.04***	1.03±0.17	1.11±0.17	**<0.01***
APSI-op	0.65±0.21	0.70±0.25	0.13	0.71±0.18	0.73±0.17	0.34
MLSI-op	0.64±0.34	0.68±0.35	0.10	0.67±0.29	0.75±0.34	**0.02***
VSI-op	0.24 (0.06) †	0.23 (0.04) †	0.93†	0.25±0.07	0.25±0.07	0.95
DPSI-op	0.97±0.32	1.05±0.33	**0.01***	1.04±0.26	1.12±0.29	**0.04***
APSI-nop	0.72±0.24	0.72±0.22	0.91	0.71±0.17	0.80±0.18	**0.02***
MLSI-nop	0.58 (0.40) †	0.64 (0.36) †	**0.02***	0.74±0.30	0.80±0.37	0.11
VSI-nop	0.27 (0.06) †	0.25 (0.07) †	0.75†	0.26±0.04	0.27±0.06	0.69
DPSI-nop	1.05±0.28	1.09±0.31	0.33	1.08±0.28	1.20±0.31	**0.01***

† Data reported in median and inter-quartile range (IQR). APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg.

APPENDIX 6.3: Sensitivity analysis – Stroop effect

Comparisons of "Stroop Effect" on time to stabilization postural stability indices outcomes between individuals post-ACLR and Healthy Controls using parametric and non-parametric analysis according to data distribution.

TTS Variables	ACLR (n=21)	Healthy Control (n=20)	p-value
APTTS-C	0.02±0.20	-0.02±0.25	0.55
MLTTS-C	0.04±0.27	0.03±0.37	0.94
VTTS-C	0.03 (0.10) †	0.02 (0.17) †	0.66
RVTTS-C	0.61±0.60	0.98±0.46	**0.03***
APTTS-op	-0.07±0.34	-0.01±0.24	0.49
MLTTS-op	0.1 (0.28) †	0 (0.27) †	0.25
VTTS-op	-0.01 (0.18) †	0.06 (0.15) †	0.11
RVTTS-op	-0.12±0.39	-0.03±0.27	0.42
APTTS-nop	-0.01±0.32	-0.09±0.44	0.52
MLTTS-nop	-0.09±0.34	-0.03±0.25	0.58
VTTS-nop	0.01 (0.15) †	0.01 (0.24) †	0.84
RVTTS-nop	-0.05±0.40	-0.11±0.43	0.68
APSI-C	0.02±0.12	0.05±0.09	0.31
MLSI-C	0.05±0.08	0.07±0.09	0.46
VSI-C†	0.00 (0.01) †	0.00 (0.02) †	0.55
DPSI-C	0.06±0.11	0.09±0.10	0.37
APSI-op	0.05±0.16	0.02±0.11	0.48
MLSI-op†	0.02 (0.16) †	0.05 (0.12) †	0.40
VSI-op†	0.00 (0.02) †	0.00 (0.05) †	0.85
DPSI-op†	0.09 (0.16) †	0.07 (0.1) †	0.61
APSI-nop	0.00±0.16	0.09±0.16	0.06
MLSI-nop	0.06±0.11	0.06±0.17	0.91
VSI-nop	0.00±0.04	0.00±0.04	0.93
DPSI-nop	0.03±0.16	0.12±0.18	0.14

† Data reported in median and inter-quartile range (IQR). APTTS-C: anterior-posterior time to stabilization combined from both force plates. MLTTS-C: medial-lateral time to stabilization combined from both force plates. VTTS-C: vertical time to stabilization combined from both force plates. RVTTS-C: resultant vector time to stabilization combined from both force plates. APTTS-op: anterior-posterior time to stabilization on the operated leg. MLTTS-op: medial-lateral time to stabilization on the operated leg. VTTS-op: vertical time to stabilization on the operated leg. RVTTS-op: resultant vector time to stabilization on the operated leg. APTTS-nop: anterior-posterior time to stabilization on the non-operated leg. MLTTS-nop: medial-lateral time to stabilization on the non-operated leg. VTTS-nop: vertical time to stabilization on the non-operated leg. RVTTS-nop: resultant vector time to stabilization on the non-operated leg. APSI-C: anterior-posterior stability index combined from both force plates. MLSI-C: medial-lateral stability index combined from both force plates. VSI-C: vertical stability index combined from both force plates. DPSI-C: dynamic postural stability index combined from both force plates. APSI-op: anterior-posterior stability index on the operated leg. MLSI-op: medial-lateral stability index on the operated leg. VSI-op: vertical stability index on the operated leg. DPSI-op: dynamic postural stability index on the operated leg. APSI-nop: anterior-posterior stability index on the non-operated leg. MLSI-nop: medial-lateral stability index on the non-operated leg. VSI-nop: vertical stability index on the non-operated leg. DPSI-nop: dynamic postural stability index on the non-operated leg. Bonferroni adjustment was not made.[23, 26]