EXPLORING THE ROLE OF COGNITIVE-MOTOR FUNCTION IN BIOMECHANICAL RISK FACTORS FOR PRIMARY AND SECONDARY ANTERIOR CRUCIATE LIGAMENT INJURIES

by

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DEDICATION

I dedicate this dissertation to my family, my parents and my sister. Thank you for your sacrifices, your endless love, and the unwavering support that carried me through every challenge. Your belief in me made this work possible.

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ABSTRACT

Non-contact anterior cruciate ligament (ACL) injuries continue to present major challenges in sports medicine, with long-term consequences for physical function and quality of life. A growing body of evidence indicates that these injuries frequently occur in dynamic environments where athletes must rapidly interpret visual cues and make decisions under pressure. Such cognitive demands may impair neuromuscular control and elevate injury risk, yet current screening and rehabilitation practices often fail to address the cognitive-motor processes that influence movement performance.

This dissertation investigates how cognitive load alters biomechanical and neural mechanisms related to ACL injury risk in both healthy and ACL-reconstructed (ACLR) athletes. Dual-task paradigms integrating visual decision-making with jump-landing tasks were used to evaluate knee mechanics and cortical activation under increasingly complex conditions. Additionally, this work uniquely incorporates trials with unbalanced landings and incorrect responses, performance outcomes typically discarded in prior research, to better reflect real-world scenarios in which athletes fail to react appropriately.

Through combined analysis of neuromuscular control, decision-making performance, and cortical activation, this research characterizes the interplay between cognitive demands and movement adaptation. Findings from this work advance a more comprehensive framework for ACL injury risk assessment and post-ACLR rehabilitation by highlighting the importance of cognitive-motor function in restoring safe and effective movement during challenging movements. Ultimately, this dissertation contributes evidence to support injury-prevention strategies and return-to-sport criteria that reflect the cognitive complexity of athletic environments.

CHAPTER ONE

INTRODUCTION

Introduction to the non-contact ACL injury

Having joined Manchester City from Everton, 23-year-old Chloe Kelly made an immediate impact, contributing 16 goals and 14 assists in 34 appearances during the 2020/21 FA Women's Super League season. In the penultimate match against Birmingham City, however, a routine attacking play resulted in a collision that left her with a season-ending anterior cruciate ligament (ACL) injury [3]. The diagnosis not only halted an outstanding debut season but also threatened her upcoming Olympic opportunity. Kelly's experience reflects a broader challenge in sport: ACL injuries abruptly disrupt careers and initiate long, demanding periods of rehabilitation and psychological recovery [3].

One year after her ACL injury, Kelly's return to play marked a significant milestone, yet her journey reflects the broader complexities of ACL rehabilitation [3]. Even after medical clearance, athletes may continue to experience deficits in neuromuscular coordination, decision-making under pressure, and confidence during high-demand movements. These challenges highlight the importance of understanding how cognitive load and neuromuscular control interact during sport-like tasks, not only for athletes following ACL reconstruction (ACLR) but also for healthy athletes who may be vulnerable to injury. This dissertation examines these interdependent components to inform more comprehensive strategies for injury prevention and successful return to high-level performance.

The ACL is a critical structure for knee stability and works alongside with the menisci, cartilage, and other ligaments to support knee joint function. It links the femur (thigh bone) to the tibia (shin bone) and runs diagonally within the knee and forms a cross with the posterior cruciate ligament (PCL) (Figure 1). Measuring roughly 38 mm in length and 10 mm in diameter, the ACL is composed of dense collagen fibers and consists of two key functional bundles, the anteromedial and posterolateral, which help control anterior tibial movement, excessive rotation, and hyperextension [4]. Its blood supply comes from the middle genicular artery, but due to limited vascularization, healing after injury is challenging. It is vital role in dynamic activities makes it susceptible to injuries, especially in high-impact sports.

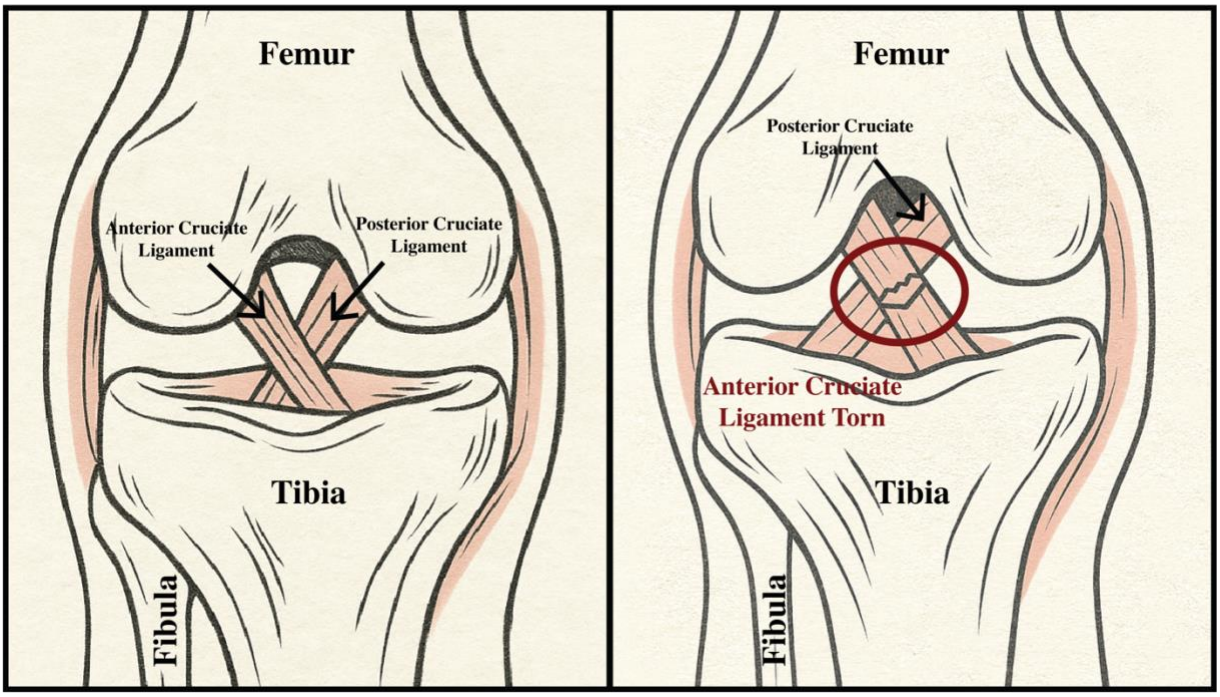


Figure 1: Anatomy of Knee joint (Left) and Torn ACL (Right) [5]

ACL injuries can result from both contact and non-contact mechanisms (Figure 2). Contact ACL injuries occur when external forces, such as direct impact or collision with another player or object, exceed the ligament's ability to stabilize the knee joint, leading to partial or complete rupture [6]. Non-contact ACL injuries usually happen when the knee is nearly or fully extended[7, 8], combined with excessive medial collapse[9]. ACL reconstruction (ACLR) is the most common procedure to restore joint stability, with the frequency of surgeries increasing fourfold over a 15-year period [10]. The economic burden of ACL injuries in the U.S. surpasses $5.3 billion annually [11, 12]. The long-term effects of these injuries, particularly in young athletes [13], include an elevated risk of osteoarthritis[14], obesity[15], and heart disease[16].



Figure 2: Contact and non-contact ACL injuries [1, 2]

Nearly 75% of ACL injuries are non-contact [7, 17], typically occurring when athletes are distracted by external factors such as opponents or the ball [18], similar to the case of Kelly Chlo's injury. These injuries occur within a very short window, approximately 50 milliseconds after ground contact [19], which does not give athletes enough time to adjust their knee position after making initial contact with the ground to avoid injury. Because non-contact injuries occur when attention is diverted externally [19], improving athletes' knee pre-positioning and motor control is critical to reducing ACL load and preventing injury. Effective pre-position training should incorporate insights into how individual athletes respond to distractions that divert attention from preventive movement strategies. Previous efforts in understanding these distractions have involved various visual methods to induce unanticipated situations, such as responding to directional cues or jumping toward an overhead goal [20-22]. The clinical significance of cognitive challenges in sports is supported by evidence indicating that scenarios leading to ACL injuries frequently involve visual distractions or reacting to opponents [23]. However, most of the previous literature has focused on performance of athletes during movements such as drop vertical jump (DVJ) and single-leg jump to effort on risk of ACL injury without considering cognitive performance during those tasks [24, 25]. Therefore, these evaluations allow athletes to focus only on the motor task and disregard potential alterations in neuromuscular function that arise when these movements are executed with added cognitive demands. This disconnect might elucidate their limited efficacy in adequately understanding the injury. Hence, it is important to investigate cognitive-motor function in these assessments as previous literature showed the neuroplastic and cognitive changes following ACLR [26-30].

Musculoskeletal injury risk is inherently multifactorial [31], and although epidemiological evidence suggests that cognitive factors contribute to injury susceptibility [32-34], current screening methods fail to adequately capture the role of cognition in neuromuscular deficiencies that lead to injury. The importance of investigating cognitive-motor interactions is further highlighted by findings that demonstrate persistent neuroplastic and cognitive changes following ACLR [35]. These alterations are rarely addressed in rehabilitation or evaluated during standard return-to-sport testing, leaving athletes potentially vulnerable to deficits in common cognitive-motor scenarios [36].

Dual-task screening provides a promising avenue to uncover these deficits by simultaneously challenging cognitive and motor systems. For example, ACLR patients increase their attentional investment in postural control during cognitive-motor balance tasks, adopting compensatory cognitive strategies not observed in single-task conditions [37]. This underscores the value of dual-task paradigms in revealing deficits that remain undetected in traditional assessments. Building on this framework, it is essential to integrate dual-task paradigms into dynamic, sport-specific assessments that replicate the conditions under which ACL injuries typically occur. Jump-landing tasks provide an ecologically valid platform to evaluate neuromuscular control and biomechanical patterns under both single-task and dual-task conditions, thereby bridging the gap between controlled laboratory testing and real-world sport scenarios.

Athletes demonstrate natural variability in movement performance, particularly during dynamic and unpredictable tasks [38]. In jump-landing assessments, some attempts may be well controlled while others involve balance errors, delayed reactions, or incorrect responses to sport-

like demands. Traditionally, biomechanical analyses focus only on the most successful trials to reduce variability and improve data consistency [38-40]. However, this approach may overlook the most meaningful moments: when coordination breaks down and injury-risk mechanics are most likely to emerge [41]. Considering both optimal and suboptimal performances may provide a more complete understanding of how athletes adapt under cognitive and mechanical stress, and how these adaptations contribute to ACL injury vulnerability.

In psychology studies, the concept of the "worse performance rule" suggests that on multitrial cognitive tasks, the trials where an individual performs the worst can be better predictors of general intelligence than those where they perform their best [41, 42]. In other words, instead of focusing solely on an individual's optimal performance, the worse performance rule argues that examining the trials in which the individual struggles the most may provide a more accurate reflection of their overall cognitive abilities. This concept challenges the conventional idea that best performance is the most informative indicator of cognitive capability and implies that understanding how someone handles difficulties may reveal deeper insights into their cognitive functioning.

A parallel idea may apply to athletic movements. Cognitive challenges can be a key factor in successful decision-making during sport-related reactions and dynamic tasks, and variability in performance can reveal critical weaknesses in neuromuscular control. Some studies have begun to explore differences between successful and failed jump-landing trials [40, 41], showing that athletes exhibit distinct movement patterns during these more challenging moments. For example, failed landings have been linked to altered trunk and pelvis motion at initial contact and reduced postural stability, mechanical changes associated with elevated ACL injury risk [40, 41]. Evidence

suggests that such failed trials may signal impaired neuromuscular control and potentially increased vulnerability to injury [40, 43].

Neurological changes in regions related to decision-making and visual-cognition related to ACL injury are important due to previous literature supported this evidence by studying on individuals' cognitive-motor functions related to ACL injury and ACLR [35, 43-46]. From previous studies, athletes who sustain ACL injuries had alternations in brain activities specifically in sensorimotor regions [29, 47, 48]. Studies have reported altered brain activation during isolated, fMRI-compatible motor, as well as impaired biomechanics during movement scenarios involving concurrent cognitive and motor demands [37, 43, 46, 49, 50]. Together, these findings suggest that ACL injury may influence both neural processing and neuromuscular control, particularly during sport-like challenges that require rapid decision-making. However, these studies did not focus on the combination of both motor and cognitive task on neural activation as well as the neural activation patterns of decision-making in the cognitive-motor function in sport-related tasks associated with risk of ACL injury. This gap underscores the need to integrate neural, cognitive, and biomechanical perspectives to better understand how brain function contributes to movement performance and injury vulnerability.

The prefrontal cortex plays an essential role in cognitive functions, including decision-making and executive function [51]. Monitoring neural activation in the prefrontal cortex during sport reaction tasks, such as trying to go towards the ball and hesitate to go towards the defender, can shed light on the cognitive demands placed on an individual. Moreover, it can provide insights into how neural activation influences the risk of errors in jump landing tasks related to focusing

on risk of ACL injury. Identifying neural correlates of mistakes in dual-task conditions can enhance our understanding of how the brain and body interact during dynamic movements.

Statement of Purpose

ACL injuries remain a significant clinical and scientific challenge, with persistent neuromuscular deficits and high rates of reinjury following reconstruction. While biomechanics has provided substantial insight into injury mechanisms, emerging evidence highlights the role of cognitive and neural processes, particularly attention control and decision-making, in shaping motor performance and failed movement responses. Current paradigms of dual-task assessment in ACLR individuals, however, are limited by their reliance on low-demand physical tasks and may overlook important diagnostic information.

Cognitive-motor demands, variability in performance, and neural contributions to movement all play critical roles in how athletes adapt to challenging situations. The overarching objective of this dissertation is to clarify how cognitive load influences neuromuscular control and cortical activation during jump-landing tasks in both healthy and ACLR athletes, with particular attention to the moments when performance breaks down. Hence, this dissertation expands knowledge on the relationship of these failed movements with biomechanics risk factors, cognitive performance, and brain activity related to ACL injury. Including failed decision-making trials during DVJ in the data set allows identification of additional information related to ACL injuries, as these failed movements are an example of scenarios in which ACL injury can occur. Moreover, this dissertation aims to fill the gap in knowledge of the connection of the pattern of neural activations during both cognitive functions and cognitive-motor functions in sport-related tasks related to ACL injury risk and individuals' ability to make decisions quickly during the jump-

landing task. Through this multi-domain approach, the dissertation aims to advance a more comprehensive understanding of ACL injury mechanisms and inform improved screening and rehabilitation strategies.

The central purpose of the research conducted for this dissertation is to advance a comprehensive model of cognitive-motor function in ACL injury by integrating biomechanics, cognition, decision-making during movements, and neural activation measures. Specifically, I aim to (1) evaluate dual-task impairments that persist following ACLR during challenging jump-landing tasks, (2) determine the ability of low-cost, accessible cognitive-motor tests (i.e., clinical tests) to capture clinically relevant information, specifically biomechanical second ACL injury risk factors, (3) determine the influence of variability in performance on knee mechanics in unanticipated jump-landing movements, and (4) understand the role of cognitive ability and neural activation patterns on successful decision-making during jump-landing.

By combining dynamic motor assessment with neural and cognitive measures, this dissertation introduces a novel approach to characterizing failed movement as a neurocognitive as well as biomechanical phenomenon. The expected outcomes will inform more precise therapeutic targets, enhance return-to-sport criteria, and ultimately contribute to rehabilitation strategies that address the full spectrum of deficits (i.e., neural, cognitive, and biomechanical) associated with ACL injury.

Review of Relevant Literature

Anterior Cruciate Ligament (ACL) Injuries: Mechanisms and Risk Factors

The ACL is the ligament in the middle of the knee joint, connecting femur to tibia and restraining anterior translation of tibia with respect to femur (Figure 3). Evidence shows that most ACL injuries in professional soccer players occur without direct contact, with nearly two-thirds of indirect or noncontact injuries taking place during tackles [52]. Recent video syntheses and epidemiologic studies emphasize that the mechanisms of ACL loading are highly sport-specific [53-55]. For instance, in women's soccer, more than 80% of noncontact ACL injuries occurred during defensive tackling, regaining balance after kicking, or being tackled [53]. Similarly, analyses of ACL injuries in the NBA identified picking up the ball while attacking, landing, and jump stops as the main mechanisms [54]. In women's Australian football, ACL injuries were most frequently observed in defensive scenarios requiring rapid change of direction (CoD) or in situations of indirect contact that placed players in unbalanced positions [55]. These findings suggest that players may benefit from targeted agility and perturbation training that incorporates unplanned sidestep cutting and strategies to manage contact or landing loads [55]. Collectively, these observations highlight the importance of body kinematics in this injury pattern, mainly hip abduction and trunk tilt towards the injured leg on initial contact and increases in knee valgus and knee flexion following initial contact [54], and increasing knee flexion and minimizing valgus collapse [55].

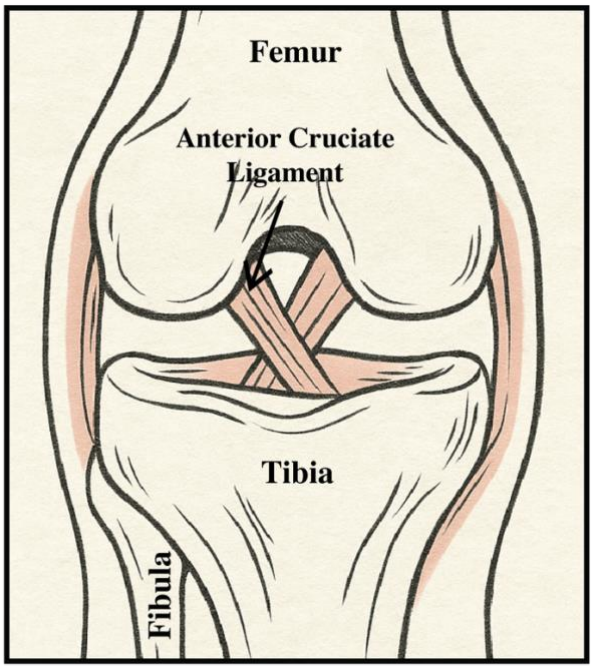


Figure 3: Anatomy of Anterior Cruciate Ligament [5]

Biomechanical factors are important to consider when focusing on ACL injuries, including stiff-legged extended landings [56-61], greater hip flexion angles sustained longer than in males [19, 62, 63], higher knee abduction, and shorter stance times during vertical drop jumps [56]. Recent video analyses of women's professional soccer players revealed four recurrent patterns of ACL injury: 1) non-contact "pressing" injuries, 2) indirect contact injuries during parallel sprinting and tackling, 3) direct contact "knee-to-knee" injuries, and 4) non-contact "landing" injuries [64]. The combination of strengthening balance, endurance, stability, and neuromuscular training may reduce ACL injury risk in female athletes by up to 90% [65], and individualized programs focusing on neuromuscular control, strength, and technique may prevent up to 65% of non-contact ACL injuries [19, 66].

Sex differences in ACL risk remain a critical point, but the reasons are being re-examined. Female athletes are at 2- to 8-fold greater risk of ACL injuries than male athletes [67-69]. Reasons for this high risk include anatomical characteristics such as smaller femoral notch [70], reduced tensile strength [71], the position of the tibia relative to the femur and ligamentous laxity [72, 73], as well as hormonal factors such as fluctuations in estrogen during the menstrual cycle [74]. Beyond biological and biomechanical differences, sex disparities in training opportunities and sport-specific equipment may also contribute to ACL risk [75]. Female athletes often have less access to structured training environments and use footwear designed primarily for male anatomy, leading to discomfort and potentially elevated injury risk [76-79]. In addition, pitch quality, artificial turf, and shoe-surface traction have been recognized as environmental factors that may further increase risk 83 [76, 80-82]. Taken together, these findings suggest that sex differences in ACL injury risk extend well beyond anatomy and biomechanics, encompassing hormonal influences, neuromuscular control, training exposure, and sport-specific environments. Addressing these multifactorial disparities through targeted prevention programs and sex-specific innovation may be essential to narrowing the injury gap between female and male athletes.

Fatigue has been associated with a higher risk of ACL injury in female athletes due to reductions in hip flexion and ankle dorsiflexion, leading to unstable landings during drop jumps [83]. It is another essential contributor to ACL injury risk due to its connection to neuromuscular control and altering lower-limb mechanisms [37, 84-86]. Under fatigued states, athletes demonstrate reduced knee flexion, increased knee valgus, and elevated ground reaction forces, which are factors that collectively increase ACL loading [87-89]. A meta-analysis reported that fatigue significantly increases peak knee valgus during double-leg drop jumps [87]. Sport-specific

studies further highlight this risk. In female basketball players, neuromuscular fatigue did not always produce a statistically significant increase in dynamic knee valgus, but valgus angles rose under sharper change-of-direction demands, underscoring the interaction between fatigue and task complexity [88]. Similarly, in female soccer players, fatigue during pivot turns increased ground reaction forces and disturbed knee and hip moments, while anticipation demands further exacerbated knee flexion loads [89]. Structural predispositions may magnify this effect based on a study in individuals with genu valgum showed that running-induced fatigue decreased knee stiffness and amplified ACL strain responses [90]. A recent review concluded that although methodological heterogeneity exists across fatigue protocols, localized neuromuscular fatigue should be considered a modifiable risk factor for ACL injury [91]. Collectively, these findings suggest that fatigue does not act in isolation but interacts with task demands, sex, and individual biomechanics to heighten ACL injury risk.

Collectively, the reviewed literature demonstrates that ACL injury risk is multifactorial, influenced by the interaction of anatomical, biomechanical, neuromuscular, hormonal, and environmental factors. Taken together, these findings highlight the need for comprehensive, individualized prevention and rehabilitation programs that integrate neuromuscular training, fatigue management, and sport-specific cognitive-motor challenges to mitigate ACL injury risk and improve long-term outcomes following ACLR.

Return-to-Sport (RTS) Criteria After ACL Reconstruction

Evidence suggests that meeting return-to-sport (RTS) criteria can reduce anterior cruciate ligament (ACL) re-injury rates [11, 92]; however, the absence of standardized RTS assessments

remains a persistent limitation [93, 94]. A recent review summarized six main domains related to RTS clearance [94]: time, strength, jump and hop performance, biomechanical assessment, change of direction and agility, and patient-reported outcome measures (PROMs). These domains highlight the complexity of RTS decision-making and emphasize the need for a comprehensive, criteria-based approach rather than reliance on arbitrary timelines or single test outcomes.

Time since surgery has traditionally been considered the primary factor of RTS readiness. Historically, some rehabilitation protocols set a six-month target for RTS; however, mounting evidence has changed recommendations toward at least nine months. RTS earlier than nine months has been associated with a sevenfold higher risk of sustaining a second ACL injury [12], while delaying clearance by each additional month between six and nine months reduces reinjury risk by 51% [11]. Nagelli and Hewett [95] further suggested extending RTS timelines up to two years in certain high-risk groups, such as female athletes, given their increased susceptibility to second injuries. Thus, while time is an important factor, it should not serve as the sole factor but rather as one element of a broader, individualized readiness profile.

Strength testing is another cornerstone of RTS decision-making. Restoration of muscular strength is critical for stabilizing the knee joint and reducing the risk of graft failure. Isokinetic dynamometry remains the gold standard due to its ability to provide standardized, objective measures of quadriceps and hamstring strength. When isokinetic dynamometry is unavailable, portable force devices can provide an acceptable alternative in clinical and field settings. However, research shows that achieving the commonly used ≥90% limb symmetry index (LSI) cutoff may not fully capture recovery [96]. For example, Wellsandt and Failla [97] reported that only 28.6%

of athletes who achieved 90% LSI post-ACLR actually reached their estimated pre-injury capacity. These findings suggest that higher LSI cutoffs may be necessary, particularly for level I and elite athletes returning to pivoting sports [96], where 100% symmetry has been recommended [98]. Moreover, reliance on LSI alone can be misleading; therefore, additional benchmarks such as ≥2× body weight in unilateral leg press one-repetition maximum or comparison with pre-injury baselines should be integrated to ensure more robust strength assessment [99].

Jump and hop performance provides valuable insight into functional recovery. While hop tests are commonly used in clinical practice, evidence indicates that single- and triple-hop tests may be more effective than using a battery of four horizontal hop tests [100]. Importantly, the landing phase of these tasks appears to be especially sensitive to detecting deficits in energy absorption at the knee [101], which is critical for safe return to high-impact sports. In addition, the incorporation of dual-task or reactive conditions during hop testing is essential to replicate sport-specific cognitive demands. Research shows that exceeding a 10% dual-task cost may reflect heightened neurocognitive reliance and correspond to a higher risk of reinjury [102]. Beyond hop testing, vertical jump assessments using force platforms have revealed significant deficits in the "explode" and "drive" phases of the force–time curve in post-ACLR athletes [103], indicating reduced capacity to generate, sustain, and transfer force during explosive movements. These deficits may compromise athletic performance and elevate injury risk if RTS clearance is granted prematurely.

Biomechanical assessments further enhance the sensitivity of RTS protocols. Several studies have demonstrated interlimb asymmetries in the sagittal plane during drop jump tasks

[104]. Di Stasi et. al. [105] observed significant sagittal plane deficits in athletes who failed RTS assessments at six months post-ACLR, underscoring that biomechanical inefficiencies may persist even when standard functional tests are passed. Such asymmetries highlight the importance of incorporating biomechanical analysis, as they may predispose athletes to reinjury despite acceptable clinical performance. Although advanced technology such as 3D motion capture offers detailed insights, more accessible tools can be practical for clinical application, allowing clinicians to evaluate movement quality without costly equipment.

Change of direction (CoD) and agility are particularly relevant given that most ACL injuries occur during non-contact CoD movements [106-108]. Traditional RTS assessments may not adequately reflect the demands of pivoting sports, raising concern about their sensitivity [109]. Evidence suggests that unplanned CoD maneuvers generate nearly twice the knee loads compared to planned CoD tasks [109], which emphasizes the need to incorporate reactive agility testing into RTS batteries. Planned assessments such as the T-test provide useful performance baselines, but reactive tasks like the Reactive Agility Test or reactive 90° CoD test better replicate sport-specific conditions [94]. In resource-limited environments, clinicians can simulate these demands using reactive hop drills or dual-task CoD tasks, which introduce neurocognitive load and more closely mirror competitive play [94].

Patient-reported outcome measures (PROMs), particularly those assessing psychological readiness, are critical in determining whether athletes are prepared for RTS. Tools such as the Anterior Cruciate Ligament–Return to Sport after Injury scale (ACL-RSI) [110] and the International Knee Documentation Committee (IKDC) [111] questionnaire are among the most

reliable PROMs. Higher ACL-RSI scores have been consistently associated with successful RTS at 12 months [112], whereas athletes who fail to return often report significantly lower ACL-RSI scores at both six and twelve months [113]. Fear of reinjury is one of the most common barriers to RTS, with several studies identifying it as a key reason for unsuccessful return [114-116]. A clinical threshold of ACL-RSI ≥65–70 has been proposed as a guideline, with lower scores suggesting the need for psychological interventions or gradual exposure to sport-specific tasks [94]. Incorporating PROMs alongside physical and biomechanical testing ensures a more holistic evaluation of athlete readiness.

In conclusion, RTS following ACLR should be determined through an individualized, criteria-based, and multidisciplinary approach [94]. Decisions should not rely on arbitrary timelines or single metrics but instead reflect a composite profile integrating physical, functional, biomechanical, and psychological domains. Surgeons, physiotherapists, sports physicians, psychologists, and the athlete must work collaboratively to weigh these factors in context. By combining time-based milestones with strength testing, functional hop and jump assessments, biomechanical analysis, CoD and agility testing, and PROMs, clinicians can create a more comprehensive and individualized RTS framework. Such an approach not only minimizes reinjury risk but also promotes safer, more sustainable return to sport for diverse athletic populations.

Cognitive-Motor Function in ACL Rehabilitation

Rehabilitation following ACL injury has traditionally emphasized restoring biomechanical factors such as strength, range of motion, and neuromuscular control of the knee joint [117]. However, a growing body of evidence indicates that cognitive–motor function is also affected by

ACL injury and may remain impaired even after standard physical rehabilitation [28, 86, 118-120]. Jiménez-Martínez et al. [119] tracked athletes at three time points of pre-surgery (within 15 days after injury), post-surgery (within four months following ACLR), and at the end of rehabilitation (approximately 1.3 years post-surgery). They found that reaction times and accuracy on tasks such as the Flanker and Multiple Object Tracking tests improved significantly from pre- to post-surgery but remained below the levels of healthy controls [119]. This suggests that while cognitive recovery occurs alongside physical rehabilitation, standard protocols may not fully restore cognitive processing capacities.

Building on this concept, Chaput et al. [121] introduced the Visual–Cognitive Control-to-Chaos Continuum (VC-CCC) as a progressive rehabilitation model that transitions athletes from highly controlled, predictable exercises to chaotic, game-relevant environments that challenge perception, attention, and decision-making. The framework highlights that following ACLR, athletes often rely excessively on visual input and exhibit increased cortical activation during movement, indicating a compensatory shift from automatic to consciously driven motor control [121]. This compensatory behavior aligns with findings showing that ACLR athletes demonstrate slower reaction times, greater postural sway, and increased knee valgus or reduced flexion when performing motor tasks under added cognitive load [30, 37, 86]. Such impairments reflect reduced automaticity and inefficient neural resource allocation, precisely the limitations targeted by the VC-CCC model. Therefore, integrating graded dual-task (DT) challenges and progressively chaotic, sport-specific demands throughout rehabilitation may be critical for restoring full functional readiness.

Cognitive-Motor Function and ACLR Injury Risk Assessment

The cognitive domains most frequently implicated in ACL injury risk include visual and verbal memory, processing speed, and reaction time, which are skills essential for adapting to the rapidly changing and unpredictable environment of competitive sport. Swanik et al. [34] reported medium-to-large discrepancies in these domains between injured and uninjured athletes, while Wilkerson et al. [28] found that reaction times slower than 0.545 s were associated with nearly threefold higher odds of sustaining a lower-extremity injury. Athletes with slower processing speed or reduced working memory capacity are thought to have less time to adapt motor responses to external stimuli, which can lead to maladaptive knee mechanics and elevated ACL loading [86].

The inclusion of dual-task and cognitive–motor challenges in functional testing has gained attention as researchers explore more ecologically valid assessments. For example, studies using a triple hop test under single- versus dual-task conditions revealed that both surgical and non-injured limbs exhibited reduced hop distance when a cognitive task was added, with the healthy limb showing the greater percentage decline [122]. Moreover, Strong et al. [123] reported significantly greater cognitive–motor interference in ACLR patients, performance degradation under cognitive load that could not be explained by isolated cognitive or motor deficits alone. This suggests that integration difficulty, rather than isolated impairments, drives many of the observed decrements in function. Similarly, individuals with ACLR who demonstrated optimal single-task landing mechanics and high PROMs exhibited the largest shift toward riskier biomechanics when an unanticipated cognitive challenge was introduced [124]. These findings imply that current RTS

criteria may fail to capture cognitive–motor deficits that become evident under realistic sport conditions.

Early evidence using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery supports this notion. Athletes who sustained non-contact ACL injuries scored lower on all four ImPACT subscales compared to matched controls [34]. More recently, Monfort et al. [26] found that poorer ImPACT visual-memory scores correlated with greater peak knee valgus angles during dual-task run-to-cut movements in healthy soccer players. These results reinforce that cognitive demand and visual distraction directly influence perception–action coupling, thereby impairing the neuromuscular strategies needed for safe joint stabilization.

Building on this work, compelling evidence showed that ACL injury and ACLR disrupt sensorimotor integration at both peripheral and central levels [46, 121, 125]. A recent scoping review identified persistent alterations in the somatosensory and visual systems long after surgery [125]. ACLR individuals exhibit deficits in gaze tracking [126], visual attention [46], and reaction time to dynamic stimuli [44]. These impairments are highly relevant to sport environments that require rapid attentional shifts and precise visual-motor coordination. Moreover, previous studies examining the visual contribution to motor control reported that removing or perturbing visual input caused disproportionate declines in balance and movement precision among ACLR participants [30, 46, 127-130]. These findings reflect increased visual dependence and compensatory reliance on control strategies. Supporting this interpretation, Chaput et al. [46] found that superior visual–motor integration on neurocognitive testing correlated with faster time-to-

stability during a jump-landing task in ACLR athletes, but not in healthy controls, highlighting the central role of multisensory integration in dynamic stability.

Collectively, this literature underscores that motor recovery alone is insufficient to ensure safe return to play. Athletes must be capable of processing external cues, reacting under pressure, and maintaining attention despite distractions. Post-ACLR motor performance deficits cannot be attributed solely to peripheral muscle weakness or joint instability. Rather, they reflect broader disruptions in the sensorimotor performance, including impaired proprioceptive feedback, altered visual processing, and diminished automaticity of motor control [125]. Therefore, rehabilitation programs should incorporate dual-task paradigms, inhibitory control exercises, anticipation and reaction training, and perceptual-motor challenges early and progressively throughout the recovery timeline [94]. Transitioning from isolated strength or balance exercises to dynamic, cognitive-motor integrated tasks can better simulate real-sport conditions, improve detection of residual deficits during RTS testing, and ultimately reduce re-injury risk. In summary, successful return to play following ACLR requires not only physical restoration but also the re-establishment of cognitive-motor synergy essential for adaptive and resilient athletic performance.

Failed and Unbalanced Performance During Dual-Task Paradigms in ACL Injury Risk

Dual-task (DT) paradigms which are when individuals simultaneously perform a cognitive and motor task, have become a foundation of contemporary research examining the neurocognitive contributions to ACL injury risk. However, a recurring methodological challenge across these studies is the high frequency of failed or unsuccessful trials when the task becomes challenging. These failed trials are usually removed due to reducing the variability in the data set [131].

However, they might be informative indicators of impaired cognitive-motor integration and may themselves signify heightened injury vulnerability.

Relatively few studies explicitly compare successful vs. failed trials under decision-based or unplanned landing protocols. Giesche et al. [38] examined cognitive function and postural stability in unplanned single-leg landings and found that higher rates of landing errors (e.g., the other foot touches the ground during landing) were associated with poorer working memory, cognitive flexibility, and decision-making speed [38]. This suggests that failures in reactive landings are not random but tied to cognitive capacity. Nishino et al. [39] contrasted successful and failed single-leg medial drop landings and reported that failed trials showed significantly greater trunk and pelvic lean at initial contact which are inked to ACL risk. Romanchuk [40] et al. extended this notion to unanticipated landings, demonstrating that failures often begin in the flight phase (prior to ground contact) and are associated with altered trunk and pelvis kinematics, indicating anticipatory control deficits [40].

These findings suggest that failed performances can reveal important information. They often occur when the athlete's attention, perception, and movement control are overloaded. Instead of viewing failed trials as outliers, recent research recommends including them in dual-task performance measures that combine both cognitive errors and movement stability for better understanding of individuals performance [132].

Functional Near-Infrared Spectroscopy (fNIRS) and ACL Injury Research

Functional near-infrared spectroscopy (fNIRS) is a portable and non-invasive neuroimaging technique that has gained prominence for examining cortical activity during valid tasks. Unlike fMRI, which is limited to laboratory settings, fNIRS allows for measurement of neural activation during natural movement, making it well suited for biomechanics and rehabilitation research [133]. This mobility is particularly valuable for ACL injury studies, where unanticipated and dual-task conditions must be replicated to capture the cognitive–motor demands of sport.

Functional near-infrared spectroscopy (fNIRS) offers a promising approach to gain insight into underlying neural mechanisms of the relationship between attention control and injury-relevant biomechanics. fNIRS is a portable, non-invasive neuroimaging technique that enables the measurement of cortical activity during dynamic tasks. It has been validated against fMRI and provides better spatial resolution than EEG, while remaining suitable for ambulatory movement paradigms [133-138]. Prior research has successfully applied fNIRS to gait and resistance exercise tasks, demonstrating sensitivity to changes in cognitive load and motor complexity [139-143]. fNIRS signals are highly susceptible to physiological noise and motion artifacts, which can overlap with hemodynamic frequencies [144-148]. Although filtering and statistical approaches mitigate some artifacts, the use of short-separation channels to regress extracerebral signals shows promise [149-153]. These features make fNIRS well suited for examining the relationship between neural contributions during cognitive tasks and making decisions during dual-task or unanticipated movements.

Most fNIRS research employs block design paradigms alternating between rest and task periods, though event-related and single-trial designs have also been applied [134, 135]. These designs align well with biomechanics protocols and facilitate controlled assessment of task-related activation. fNIRS has been validated against fMRI, demonstrating high correlations in concurrent activation patterns [136, 137]. Measurement depth is limited to 3–4 cm, allowing assessment of superficial cortical regions but not deeper structures [154]. Despite these limitations, fNIRS demonstrates reproducibility across age groups, establishing its reliability for longitudinal and developmental research [155].

A substantial body of work supports the feasibility of fNIRS during dynamic tasks. Studies have reported cortical activation during walking [139-142], backward and precision stepping [141, 142], and dual-task gait paradigms [139, 140]. Increased cortical recruitment has also been observed during resistance exercise, such as squatting under progressively greater loads [143]. These findings demonstrate the sensitivity of fNIRS to both motor complexity and cognitive load. For research related to ACL injury, this is critical as non-contact injuries often occur under precisely these dual-task, high-demand conditions where attention control and neuromuscular coordination interact [18].

Mechanistically, fNIRS relies on neurovascular coupling, quantifying changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) to infer local cortical activation [156-158]. Direct result of increased neuronal activation is hyperemia which is the increased cerebral blood flow. Generally, increasing neural activation is associated with an increased hemodynamic response, which is increased oxygenated hemoglobin and decreased deoxygenated hemoglobin

[158]. Using the modified Beer–Lambert Law, optical density changes are converted into chromophore concentrations [159], which are analyzed via general linear modeling (GLM) to estimate task-related coefficients, β values [160].

Multichannel fNIRS is setup with placing sources (light emitting) and detectors (light detecting) optodes around the head in order to forming source-detector pairs [138]. Photons, which are infrared light, are scattered from the sources and absorbed by detectors as they penetrate through the scalp, skull, and cerebral tissue [156]. The fNIRS measurement is based on photons that reach the detectors. The penetration depth of a given source–detector pair is directly related to the distance separating the two optodes [135]. In general, a larger source–detector distance allows for deeper tissue interrogation compared with shorter separations. This applies as long as photons emitted from the source can still be detected; however, in the adult human head, the practical measurement depth is typically restricted to approximately 3–4 cm, which is sufficient to access cortical regions but not deeper brain structures [154]. At greater distances, the signal-to-noise ratio (SNR) increases because fewer photons successfully reach the detector [149]. Following acquisition, the detected signals are processed and expressed as optical density (Equation 1) [159]. Optical density is defined as a function of the ratio between the emitted light intensity from the source optode (I_o) and the detected light intensity at the detector optode (I).

$$OD_\lambda = -\log\left(\frac{I}{I_o}\right) \quad (1)$$

The concentrations of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) are determined by applying the modified Beer–Lambert Law (Equation 2) [159]. This law

provides a linear relationship between changes in the measured optical signal and the corresponding changes in chromophore concentrations within biological tissue. Specifically, changes in hemoglobin concentration (Δc) are computed from the changes in optical density (ΔOD_λ). In Equation 2, the term ε_λ represents the molar extinction coefficient of human brain tissue, which characterizes how strongly hemoglobin absorbs light at a given wavelength. Because HbO and HbR absorb light differently across wavelengths, using multiple wavelengths enables separation of their individual concentration changes. The parameter L is the pathlength that light travels through the tissue, while the differential pathlength factor (DPF) is the differential pathlength factor, which is used to estimate the actual path length of a photon. By incorporating differential pathlength factor, the modified Beer–Lambert Law provides a more accurate estimate of the effective distance light travels before reaching the detector.

Through this process, ΔOD values obtained from each source–detector pair are transformed into quantitative estimates of ΔHbO and ΔHbR. These values form the basis for examining cerebral hemodynamics, as increases in HbO and decreases in HbR are typically associated with localized neural activation.

$$\Delta c = \frac{\Delta OD_\lambda}{\varepsilon_\lambda \cdot L \cdot DFP} \tag{2}$$

Concentrations of HBO and HBR are used to infer neural activation from the hemodynamic response following a stimulus or task onset. fNIRS results are either reported as changes in these chromophores (oxygenated and deoxygenated hemoglobin) or fitted to an expected hemodynamic response function (e.g. canonical or delta functions) [161]. If fitted to a hemodynamic response

function, the strength of activation is typically described as a coefficient value. Oftentimes, neural activation is reported as β (Equation 3), a multiplier of the hemodynamic response function, or a t-statistic value which compares activation during task and baseline periods [160]. Mechanistically, fNIRS relies on neurovascular coupling, quantifying changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) to infer local cortical activation [156-158]. In Equation 3, Y represents the observed fNIRS signal as a column vector containing one measurement per time point. The design matrix X encodes the timing and type of experimental events, including stimulus onset, task blocks, and nuisance regressors (e.g., motion artifacts, signal drift, and mean signal level). The parameter vector β contains the regression coefficients that quantify how strongly each regressor in X contributes to the observed signal. The residual term ε represents random noise and unmodeled variance in the data, capturing deviations between the predicted and actual signals. Together, these components form the general linear model used to estimate task-related hemodynamic changes in cortical activation.

$$Y = X \cdot \beta + \varepsilon \tag{3}$$

However, the application of fNIRS to sport-like tasks faces significant challenges. Signals are vulnerable to motion artifacts and physiological noise (e.g., heartbeat, respiration, blood pressure fluctuations), which overlap with hemodynamic frequencies and obscure true neural activation [144-148]. Although approaches such as wavelet filtering and principal component analysis can reduce noise [145-147], they are not always effective in highly dynamic conditions where large artifacts are present. Thus, the ability to isolate neural activation in tasks involving

rapid landings, cuts, or unanticipated maneuvers, those most relevant to ACL injury, remains limited.

Recent methodological advances in functional near-infrared spectroscopy (fNIRS) have sought to improve signal specificity and applicability during dynamic tasks. Short-separation channels, which use closely spaced optode pairs (~8 mm), primarily capture extracerebral signals originating from the scalp and skull. These superficial signals can then be modeled as nuisance regressors, thereby enhancing the accuracy of cortical activation estimates [149-153]. In studies involving movement-based activities, fNIRS offers a practical, portable, and non-invasive neuroimaging option to assess brain activation in ecologically valid contexts [133]. Moreover, fNIRS has been extensively validated against the gold standard, functional magnetic resonance imaging (fMRI), demonstrating strong correlations in concurrent activation measurements [136, 137]. Although fNIRS provides limited penetration depth compared with fMRI due to its light-based nature, it offers significant advantages in portability, cost, and experimental flexibility. Finally, fNIRS has been validated across diverse populations, including adults, infants, and children, and has demonstrated good reproducibility across repeated assessments [155].

Because of its portability, fNIRS enables researchers to study brain activation cortical activation in naturalistic and task-specific settings that were previously challenging for traditional neuroimaging modalities. This capability allows researchers to investigate the neural mechanisms underlying attention, decision-making, and cognitive control in experimental conditions that closely mimic sport-relevant information processing demands encountered during performance assessment. Non-contact ACL injuries are strongly associated with failures of cognitive–motor

integration during unanticipated sport movements. Athletes must rapidly shift attention, process environmental cues, and coordinate neuromuscular control within milliseconds of ground contact [162]. While biomechanical factors contributing to ACL injury risk are well established, the neural and cognition mechanisms underlying these failures remain poorly characterized. fNIRS offers a unique opportunity to address this gap by enabling the measurement of cortical activation during cognitive tasks and see their correlation with biomechanics variables during challenging tasks.

Current Knowledge Gaps in ACL Injury and Rehabilitation

Despite decades of research, ACL injury remains a persistent challenge in sports medicine and rehabilitation. Traditional approaches have primarily emphasized biomechanical and musculoskeletal recovery, such as restoring joint stability, strength, and range of motion [163]. While these efforts have improved short-term outcomes, long-term data continue to show elevated rates of reinjury and suboptimal return-to-sport performance following ACLR [94, 113, 164]. Emerging evidence suggests that these persistent deficits extend beyond mechanical restoration, reflecting unresolved impairments in cognitive-motor integration and neural control that influence how athletes perceive, plan, and execute movements under pressure [121, 125].

Although the biomechanical mechanisms of ACL injury, such as excessive knee valgus, reduced flexion, and asymmetrical loading, are well established, the neural and cognitive mechanisms underlying these risky motor patterns remain poorly characterized. In particular, attention control, decision-making, and dual-task processing have been shown to modulate lower-limb mechanics [85, 86], yet these domains are rarely assessed in clinical or research settings. Current rehabilitation and return-to-sport (RTS) paradigms rely predominantly on low-demand, predictable physical tasks that fail to capture the real-world cognitive demands of sport. As a result,

athletes may achieve apparent neuromuscular readiness under controlled testing conditions but still lack the cognitive-motor adaptability required to respond safely to unanticipated events during gameplay.

Another critical limitation in the current literature lies in the assessment methods used to evaluate recovery and reinjury risk. Dual-task and cognitive-motor studies in ACLR populations have typically utilized standing balance [30, 37] weight-shifting tasks [165] and gait [166, 167], which may underestimate the extent of persistent deficits. Moreover, the influence of failed performance, such as errors or missed responses during high-demand dual-task conditions, on knee biomechanics and neural activation remains largely unexplored. Understanding how performance breakdowns emerge during complex, reactive movements is crucial for identifying athletes who are at highest risk for second ACL injury.

Finally, the integration of neuroimaging and cognitive testing into biomechanics research remains limited. Techniques such as fNIRS now provide the opportunity to examine cortical activation patterns during sitting or walking, but still few studies have combined these neural measures during cognitive tasks. As a result, the field lacks a unified framework linking cognitive ability, neural activation, and motor control (Figure 4).

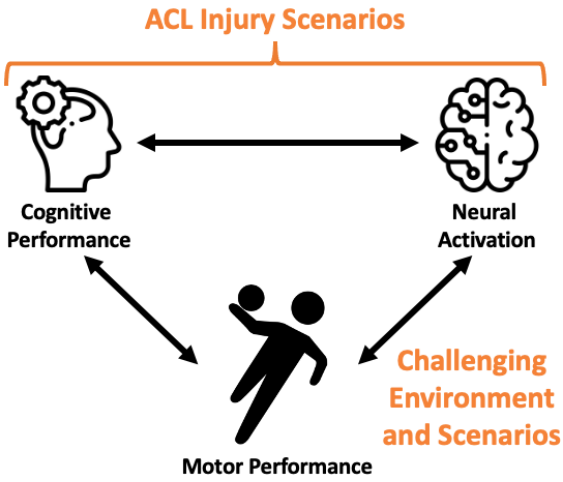


Figure 4: Connection of Motor performance, Cognitive performance, and Neural activation for better understanding of ACL injury scenarios

Addressing these gaps requires a paradigm shift from isolated biomechanical assessment toward a comprehensive neurocognitive model of ACL injury scenarios. The research presented in this dissertation aims to advance this integration by (1) evaluating persistent dual-task impairments following ACLR during challenging jump-landing tasks, (2) assessing whether low-cost clinical cognitive-motor tests can predict biomechanical risk factors for reinjury, (3) determining how failed performance influences knee mechanics under unanticipated conditions, and (4) exploring the neural and cognitive correlates of successful decision-making during dynamic landings. Together, these objectives will help redefine failed movement as both a biomechanical and neurocognitive phenomenon, guiding more precise therapeutic interventions, enhancing return-to-sport assessments, and ultimately improving long-term outcomes for athletes recovering from ACL injury.

CHAPTER TWO

COGNITIVE-MOTOR FUNCTION DURING JUMP LANDINGS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

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Contributions: Conceptualization, Testing, Data collection, Formal analysis, Investigation, Visualization, Methodology, Writing – original draft, Writing – review and editing.

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Contributions: Study design, Data interpretation, Manuscript preparation

Co-Author: Keith A. Hutchison

Contributions: Data interpretation (particularly leveraging cognitive psychology literature to help interpret the cognitive test battery and the study findings), Manuscript preparation

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Contributions: Study design, Data collection, Data processing, Data analysis, Data interpretation, Manuscript preparation

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Original Research

Cognitive-Motor Function During Jump Landings After Anterior Cruciate Ligament Reconstruction

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Background: The risk of second anterior cruciate ligament (ACL) injury remains high after ACL reconstruction (ACLR), indicating the need to improve rehabilitation and return-to-sport assessment. Because ACL injuries frequently occur in cognitively demanding situations, dual-task screening provides a promising opportunity to detect movement impairments by testing cognitive and motor skills simultaneously.

Purpose/Hypothesis: The purpose was to evaluate cognitive-motor impairments that persist after ACLR. It was hypothesized that jump landing biomechanics would be impaired in athletes with previous ACLR versus controls and that these impairments would be exacerbated when the jump landings were performed with a cognitive challenge.

Study Design: Controlled laboratory study.

Methods: A total of 35 individuals who underwent primary ACLR (ACLR group) and 35 healthy controls (HC group), matched by sex, age, dominant limb, body mass index, sports activities, Tegner score, and Marx activity score, participated in this study. Participants performed jumping tasks under a variety of conditions, including with and without visual constraint, rapid decision-making, and visual-spatial challenges. Primary dependent variables included second ACL injury factors such as asymmetry of knee extensor moment at initial contact (KEM-Asym-IC). Second-level analysis focused on other variables associated with ACL loading and injury (eg, peak knee flexion angle [pKFA]). Mixed-effect models were tested for group and condition interactions as well as group and condition main effects.

Results: A total of 35 individuals (25 women and 10 men) who underwent ACLR (ACLR group) (age, 19.9 ± 1.7 years; height, 1.7 ± 0.1 m; mass, 69.9 ± 13.1 kg; years after ACLR, 1.5 ± 0.6 years; Tegner score, 6.8 ± 1.8; and Marx score, 10.6 ± 3.8) were matched with 35 (25 women and 10 men) HC individuals (HC group) (age, 20.1 ± 1.9 years; hight, 1.7 ± 0.1 m; mass, 67.1 ± 8.4 kg; Tegner score, 6.6 ± 1.6; and Marx score, 11 ± 3.9). No significant group and condition interactions were detected. A group effect for KEM-Asym-IC (HC group, –0.005 ± 0.8 % bodyweight–height vs ACLR group, 0.43 ± 0.82 % bodyweight–height; $P < .001$) indicated relatively more knee extensor moment in the uninvolved limb at initial contact for the ACLR group, regardless of condition. In addition, a condition effect for pKFA indicated that both groups demonstrated decreased knee flexion in response to rapid decision-making challenges (anticipated conditions, 79°-80° vs rapid decision-making conditions, 76°-78°; $P < .001$).

Conclusion: After return-to-sport clearance, the ACLR group showed increased presence of mechanics associated with second ACL injury compared with the HC group during jump landing movements, with rapid decision-making conditions also eliciting reduced pKFA during landing for both groups.

Clinical Relevance: The extent to which these multivariable outcomes may compound injury risk after ACLR requires further research to more precisely understand opportunities for neurocognitive challenges to augment ACLR return-to-sport assessment.

Keywords: anterior cruciate ligament; dual-task; injury prevention; knee ligaments; kinesiology; rapid decision-making; general biomechanics; motion analysis

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About half of all children and adolescents in the United States are involved in team sports.[10] However, within these sports, musculoskeletal injuries are common and significantly reduce participation.[15,48] Anterior cruciate ligament (ACL) injury is a common musculoskeletal injury among athletes, with about 250,000 annual injuries in the United States.[22] The most common treatment for this injury is ACL reconstruction (ACLR). Although many adolescents return to sports after ACLR, nearly a quarter of athletes who are <25 years and return to sports sustain a second ACL injury.[58] The high risk of a second ACL injury may indicate that current return-to-sport approaches do not fully capture the risk for a second injury.

Many ACL injuries occur when an athlete's attention is directed externally (opponent, ball, etc).[57] Furthermore, poorer cognitive performance is linked to riskier biomechanics and altered muscle activation patterns during cognitively challenging movements[8,20,26,40,50] as well as risk of ACL injury.[54] Despite the evidence for the relevance of visual-cognitive challenges to injury risk and biomechanics, athletes' cognitive-motor function (ie, the ability to meet simultaneous cognitive and motor demands) is not routinely used as a criterion for return-to-sport (RTS) after ACLR.[12] The disconnect between isolated physical RTS tests and attention-demanding real-world sport scenarios likely contributes to the inconsistent association between passing RTS criteria and second ACL injury risk.[12,33]

Previous research on musculoskeletal injuries has explored a variety of stimuli, such as unexpected directional cues,[9,11] visual targets,[26] sport-specific tasks,[38] and arithmetic tests,[14] primarily in healthy populations.[2] Although dual-task protocols have been used with ACLR patients,[1,17,45,52,53] they have primarily focused on standing balance,[37,41] weight-shifting tasks,[13] and gait,[44,45] revealing impaired cognitive-motor performance after ACLR. More recent studies have begun to incorporate sport-relevant tasks such as jumping and cutting in dual-task paradigms.[17-19,42,53] However, these efforts remain limited by using only singular cognitive tasks,[17-19] not involving reactive challenges,[42] or lacking a control group.[53] Recently, Strong et al[52] reported magnified cognitive-motor interference in those who had ACLR compared with controls; however, the motor outcomes (eg, jump height) had unclear relevance to injury risk.[52] Building upon existing evidence to demonstrate the injury relevance of cognitive-motor interference after ACLR remains an important knowledge gap.

Although prospective studies provide the strongest evidence to demonstrate relevance to injury risk, these study designs are time-intensive and costly. These studies require strong preliminary data to obtain the necessary resources to conduct an extensive, prospective study. Alternatively, previous studies have identified potential biomechanical risk factors that can ground cross-sectional studies in clinically relevant outcomes related to the risk of second ACL injury. For example, in a study of 56 young male and female athletes, Paterno et al[46] found that less external rotator moments at the uninvolved hip (odds ratio [OR], 8.4), greater asymmetry in knee extensor moments at initial contact (OR, 3.3), and increased frontal plane knee motion (OR, 3.5) were associated with a higher likelihood of sustaining a second ACL injury. More recently, King et al[28] conducted a larger study into jump landing biomechanical predictors of a contralateral ACLR injury in male athletes 9 months after ACLR. Several biomechanical variables distinguished between participants who did and did not sustain a contralateral ACL injury within the 2-year follow-up of the study, including contact time, center of mass stiffness, and sagittal plane kinematics at the hip and knee. Although replicating the predictive value of these outcomes is needed to demonstrate the robustness of the findings and demonstrating generalizability requires additional work (eg, do King et al[28] findings extend to female patients?), these biomechanical risk factors for second ACL injuries provide feasible outcomes for a cross-sectional study that can provide preliminary clinical relevance of cognitive-motor function after ACLR that can then be explored more rigorously through a prospective study.

To understand the extent to which cognitive-motor deficits go undetected and/or unaddressed in standard ACLR rehabilitation, this cross-sectional study was conducted to evaluate dual-task impairments that persist after ACLR. We hypothesized that jump landing biomechanics would be impaired in athletes with previous ACLR versus controls and that these impairments would be exacerbated when the jump landings were performed with a cognitive challenge.

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Ethical approval for this study was obtained from Montana State University (protocol No. SM081818).

METHODS

Participants

A total of 36 athletes who had undergone primary ACLR surgery and cleared to RTS (ACLR group) and 36 healthy controls (HC group) who were matched at an individual level on sex, age, dominant limb, body mass index (BMI), sports activities, Tegner score,[55] and Marx activity score[36] participated in this study. Eligibility for the ACLR group required having a single ACLR that occurred within 2.5 years of participating in the study, completing rehabilitation, and being cleared to return to unrestricted activity. HC participants were targeted to match an individual in the ACLR group for sex, dominant limb, sport activity, and match an ACLR individual within ~2 units for age, BMI, Tegner, and Marx activity scales. HC participants had no previous lower-extremity surgeries, no time-loss lower body injuries within the previous year, no concussions in the last year, no known neurologic or lower body musculoskeletal disorder, and no pain during movement. All the participants signed a consent form approved by the institutional review board of Montana State University (protocol No. SM081818). One pair was omitted because they were an outlier regarding agreement in age compared with the rest of the pairs (3.8 years age difference compared with the mean age difference of 0.8 ± 0.6 years), leaving data for 35 matched pairs. This analysis is based on data collected in a single ~2.5-hour data collection.

Those with a primary ACLR were recruited from orthopaedic and physical therapy clinics in the Bozeman area. Matched healthy control participants were recruited from the university campus and surrounding community, including recreational and collegiate sports teams, local fitness centers, and teammates of enrolled ACLR participants. To support effective matching on key demographic and activity-level criteria, a prescreening survey was distributed widely, with approximately 1400 individuals responding. From these responses, control participants who matched the ACLR group on sex, age, dominant limb, BMI, sports activities, Tegner score, and Marx activity score were selected.

Jump-Land-Jump Task

A total of 75 reflective markers were attached to the participants to measure their whole-body motion. This marker set included a point-cluster distribution of markers on the thighs and shanks, covering a large area of the respective segments. It was designed to reduce the influence of soft tissue motion artifact on segment pose estimation.[4,40] Four medial markers were removed (left/right medial femoral epicondyle, and the left/right medial malleolus) after capturing the static calibration trial. A 10-camera motion capture system was used to record the kinematic data at 250 Hz (Motion Analysis Corp) and 4 force plates to record ground-reaction force data at 1000 Hz (OPT464508-2K; Advanced Mechanical Technology Inc). Before starting the jump-landing protocol, participants did 2 sets of 8 bodyweight squats and 5 maximal effort vertical jumps as a warm-up.[3]

For the jumping protocol, participants jumped from a 30-cm box over a distance of half of their height to land bilaterally on force plates, where they immediately performed a secondary bilateral jump in 1 of 3 directions (straight up, 45° to the right, or 45° to the left).[26] The movement was performed under 6 conditions. The convention of the condition abbreviation uses the first character to indicate the stimulus type (N, no stimulus; A, auditory stimulus; and V, visual stimulus). The second character indicates whether the condition was anticipated (A) or unanticipated (U). The third letter indicates whether participants' gaze was fixed (F) at a fixation target in front of them, directed toward a visual-spatial memory (M) cue in front of them, or unconstrained so they could look down (D) at their landing area. Conditions included were as follows: (1) baseline (NAD, no cognitive task; anticipated direction; no visual gaze constraint); (2) baseline with visual constraint (NAF, same as NAD but with constraining visual gaze forward); (3) visual unanticipated with visual constraint (VUF, secondary jump direction cue (arrow) was presented ~250 ms before initial contact while looking at the fixation cross [Figure 1]); (4) auditory unanticipated (AUD, secondary jump direction verbal cue was completely played ~250 ms before initial contact [Figure 1]); (5) auditory unanticipated with visual constraint (AUF, same as AUD but with constraining visual gaze forward); (6) and visual memory[16,56] (VAM, anticipated secondary direction with visual working memory task) (Figure 1). In addition, 250 ms of available time to react was chosen for unanticipated conditions to align with previous research[16,26] and with evidence that available time to react being <300 ms facilitates jump landing tasks to be unplanned.[51] The visual constraint factor was chosen because of previous reports of altered visual reliance after ACLR[23-25] and potential for visual stimuli to alter neuromuscular control.[24] The auditory component was chosen to enable decoupling of the visual constraint and rapid decision-making factors. The unanticipated factor was included because of the large body of literature identifying deleterious effects of rapid decision-making on knee mechanics,[3,7,8,16,26,49] lack of literature on the response of those who had ACLR to rapid decision-making challenges during demanding sport movements, and evidence of visual-cognitive compensatory strategies after ACLR that could exacerbate cognitive-motor impairments in this clinical population. The visual memory task was used to decouple cognitive domain-specific effects (ie, visual-cognitive challenge from rapid decision-making versus working memory). Although additional conditions could be feasible, we chose this set of conditions because it targeted the factors of interest, provided several levels of control (eg, visual gaze vs stimulus modality), and was feasible to be completed within a ~3-hour collection period.

Five successful trials for the "straight up" secondary jump direction were collected for each participant and condition (Supplemental Table 1). Successful trials were defined as those in which participants responded correctly to the cognitive task and both feet made contact with

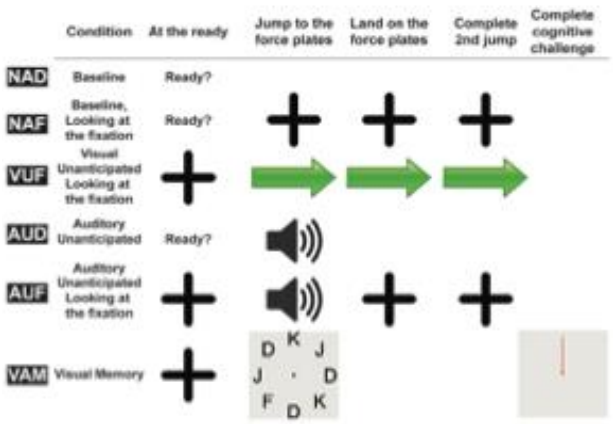


Figure 1. Jump-land-jump task progression for all conditions. AUD, auditory unanticipated; AUF, auditory unanticipated looking at the fixation; NAD, baseline, no visual constraint; NAF, visual unanticipated looking at the fixation; auditory unanticipated looking at the fixation; VAM, visual memory; VUF, visual unanticipated looking at the fixation.

separate force plates (ie, feet did not share the same plate). The focus of analysis for this study was on the landing from the initial jump off the box for trials with a straight-up secondary jump direction. Five-trial averages for each biomechanical outcome variable for each condition and participant were used for statistical analysis.

Data Processing

Motion capture and force plate data were analyzed using Visual3D (HAS-Motion). Marker and force data were filtered using a fourth-order, zero-lag, low-pass Butterworth filter with a 15 Hz cutoff frequency.[30] Kinematic and kinetic data were computed using a Quasi-Newton optimization method and an inverse kinematics model.[33] The CODA pelvis definition was applied, and hip joint centers were estimated using the Visual3D implementation of the equations of Bell et al.[6] The knee and ankle joint centers were identified as the midpoints between markers placed on the femoral epicondyles and the malleoli, respectively. The lower extremity segments were defined with the z-axis oriented from the distal to the proximal joint centers, the y-axis pointing anteriorly, and the x-axis directed to the participants' right. An inverse kinematics model was employed, constraining lower-extremity degrees of freedom to 3 rotational degrees at the hip and knee and 2 rotational degrees at the ankle.[16] A Cardan x-y-z rotation sequence, corresponding to (+) flexion/(-) extension, (+) adduction/(-) abduction, and (+) internal/(-) external rotation, respectively, was used to calculate the hip and knee joint angles. Net reaction moments were resolved within the proximal joint segment. For kinetic variables, forces were normalized to participant weight, and moments were normalized to both weight and height. Initial contact was defined as the first frame in which the force plate reading exceeded 10 N after the initial jump off the box. Custom MATLAB code Version R2022b (MathWorks) was used to calculate the second ACL injury risk factors and prepare outcome variables for statistical analysis.

Outcome Variables

Primary outcomes for the study were based on biomechanical predictors of second ACL injuries that were published at the time of design/onset of the present study.[46] To provide a more comprehensive understanding of biomechanical adaptations regarding cognitive-motor function after ACLR, additional outcomes were also included.

Primary Outcomes—Second ACL Injury Predictors

Previously reported biomechanical predictors of a second ACL injury were used as the primary outcomes.[46] Specifically, these outcomes were (1) uninvolved hip rotation net moment impulse during the initial 10% of landing (Uni-HRot-Imp); (2) knee extensor moment asymmetry at initial contact (KEM-Asym-IC) normalized to body weight and height, calculated as involved limb minus uninvolved limb variables (internal extensor moment defined positive, with more uninvolved extensor moments leading to negative values for KEM-Asym-IC); and (3) range of knee abduction angle for the involved limb, defined as the absolute difference between the maximum and minimum values from initial contact to the point of minimum center of mass (Inv-KAbA-range). In summary, the previous study[46] found that lower external rotation moments at the uninvolved hip, increased asymmetry in knee extensor moments at initial contact (indicating relatively lower extensor moments at the involved knee), and increased

frontal plane knee motion were associated with a higher risk of sustaining a second ACL injury. These findings correspond to greater Uni-HRot-Imp and Inv-KAbA-range and lower KEM-Asym-IC values using our convention, which were interpreted as "risky" in our study.

Secondary Outcomes—General ACL Injury Risk Factors

Previous video analysis has identified additional biomechanical factors linked to primary ACL injuries that occur within the first 100 ms after initial contact with the force plate during jump landing tasks.[31] Three additional outcomes were added as secondary outcomes to provide a more complete evaluation of the data. Specifically, the secondary outcomes were peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and externally defined peak knee abduction moment. Less knee flexion and increased abduction were interpreted as risky given their association with increased ACL loading.[32,35,36]

Exploratory Outcomes—Contralateral ACL Injury Risk Factors After ACLR

A post-hoc analysis, including biomechanical risk factors for contralateral injury after ACLR[28] that were reported during the progress of our study, was also incorporated for broader insight. Specifically, we included the mean of contralateral limb knee and hip flexion angles (CL-KFA and CL-HFA, respectively) during the portions of the stance phase of the initial jump landing that were delineated between the contralateral injured and the no contralateral injury groups.[28] To define the phases, variables were first normalized to 101 women corresponding to the initial contact to the minimum center of mass position (0%-100%). Then, time-normalized ranges of 14% to 94% for CL-KFA and 14% to 95% for CL-HFA were extracted. Additionally, vertical center of mass stiffness was calculated as the peak ground-reaction force measured from the force plate solely in contact with the contralateral limb during the stance phase, divided by the magnitude of change in the vertical position of the center of mass from initial contact to its minimum vertical position. Finally, contralateral limb contact time for the first jump (ie, elapsed time with ground-reaction force >10 N) was also included.

Power Analysis

GLIMMPSE (Version 3.1.3, SampleSizeShop.org)[29] was used for the power analysis to obtain 80% statistical power to detect within-within interactions of Group (ie, matched pairs) and condition factors with a repeated-measure design using the Hotelling-Lawley trace test. Given the paucity of data for our primary outcome variables across the novel set of experimental conditions of this study, we based our sample size on available, but sparse, information to inform expected group and condition means. Literature values from Paterno et al[46] were used as a basis for the baseline (NAD) condition estimates, with the previously published "first injury" and "second injury" group values used as approximations for anticipated baseline (NAD) performance for our HC and ACLR groups, respectively. We then scaled this clinically meaningful difference (ie, no injury vs second injury from Paterno et al[46]) to inform group-specific condition estimates in response to visual gaze fixation, visual memory, and rapid decision-making challenges, with the ACLR group hypothesized to be more greatly impacted by visual and unanticipated difficulties. Standard deviation and covariance across groups and conditions were based on actual variability in our dataset. Percent changes for anticipated versus unanticipated conditions of 8% to 310% were within previously reported[9,11] ranges (6%-370%). Specific inputs regarding the means and standard deviations used in the power analysis are provided in the supplemental content.

Statistical Analysis

The primary analysis was done using linear mixed-effect statistical models, with matched pairs as a random factor and group, condition, and group × condition interaction as fixed factors. The primary comparison of interest was in the group × condition interaction. Significance level was set at $\alpha = .0166$ to account for multiple comparisons across 3 primary dependent variables (0.05/3). Dependent variables related to second ACL injuries were given the highest priority, with general and contralateral ACL injury risk factors included for additional context.

To evaluate the robustness of the findings from the primary analysis to statistical assumptions, we performed an additional sensitivity analysis using variations of this approach. Specifically, we included clinical and performance covariates (age, sex, height, time since surgery, Marx activity score, and jump height) and repeated the analyses (with and without covariates), with individual participants as random effects rather than matched pairs. Outcomes of the primary analysis are reported in the manuscript alongside a summary of the sensitivity analysis, with details of the sensitivity analyses provided in Supplemental Tables 4, 5, and 6.

Upon completion of the primary and sensitivity analyses, a post-hoc analysis was deemed necessary to evaluate potential additive effects that spanned primary and secondary outcome variables. A post-hoc multivariable analysis was done to provide greater context on the collective relationships. Specifically, the means of KEM-Asym-IC and pKFA were subtracted from individual values in their respective data sets. Then, these zero-mean data sets were normalized by their respective standard deviations, yielding z-scores for the 2 variables. The component z-scores were then averaged to obtain a composite outcome based on both KEM-Asym-IC and pKFA. The "riskiest" combined outcome corresponded to the most negative values, resulting from asymmetric extensor moments and decreased knee flexion. The post-hoc multivariable analysis is provided in Supplemental Tables 8 and 9.

RESULTS

The available data included 210 means (35 participants × 6 conditions) for the HC group and 207 for the ACLR group, as 3 means were removed due to a taring issue with the force plates during the data collection. The total available dataset was based on approximately 97% of the total expected trials (Supplemental Table 1). The timing of the directional cues was verified in a post-hoc test (Supplemental Table 2). Paired *t* tests indicated no significant group differences for matched pairs in age, height, body mass, Tegner values, or Marx activity values between ACLR and HC groups (all $P > .05$) (Table 1).

For the primary outcome variables, the most robust finding was a significant group effect for KEM-Asym-IC (HC group, 0.005 ± 0.8 [% bodyweight–height]; ACLR group, –0.43 ± 0.82 [% bodyweight–Height]; $P < .001$) (Supplemental Table 3), with the ACLR group having greater asymmetry than the HC group (Table 2 and Figure 2). This finding persisted regardless of including covariates and using a paired versus unpaired analysis approach (Supplemental Table 4). Additionally, a significant group effect was observed for Uni-HRot-Imp for the primary analysis (HC group, 0.006 ± 0.003 [N.m.s/Kg]; ACLR group, 0.005 ± 0.004 [N.m.s/Kg]; $P < .001$) with the HC group having relatively more internal rotation moment (Table 2 and Figure 2); however, this result was sensitive to the statistical model and did not persist when using an unpaired analysis (Supplemental Table 4). There were no significant group and condition interactions for any primary outcome variables.

For the general ACL injury outcomes, the most robust finding was a significant condition effect for pKFA, in which a post-hoc test revealed a significant decrease in knee flexion for rapid decision-making conditions, with a range of 76° to 78°, compared with anticipated conditions, with a range of 79° to 80° for all participants, regardless of group (Table 3 and Figure 3). Other initially significant findings (group effects for pKFA and pKAbA) did not remain through the iterative statistical analysis (Supplemental Table 5).

For the exploratory outcomes, the most robust findings were a condition effect for all variables and a group effect for CL-HFA (Table 4, Supplemental Tables 6 and 7). Post-hoc analysis revealed that anticipated conditions had higher values for CL-KFA, CL-HFA, and contact time compared with cognitively challenging conditions. In contrast, the difference between conditions was opposite for vertical stiffness, with higher values for cognitively challenging conditions. For group differences, the ACLR group had more contralateral limb hip and knee flexion compared with the HC group (Table 4, Supplemental Tables 6,7). Other initially significant findings did not persist through the iterative statistical analysis (Supplemental Table 7).

The post-hoc multivariable analysis using a composite *z*-score derived from both pKFA and KEM-Asym-IC yielded significant group ($P < .001$) and condition ($P = .002$) effects, but not a group × condition ($P = .28$). The ACLR group had lower composite z-scores than the HC group ($P < .001$), and unanticipated conditions had lower composite *z*-scores than anticipated conditions ($P < .03$) (Table 4, Supplemental Tables 8–9).

TABLE 1
Cohort Characteristics[a]

	ACLR	HC
Female/male	25/10	25/10
Age, years	19.9 ± 1.7	20.1 ± 1.9
Height, m	1.7 ± 0.1	1.7 ± 0.1
Mass, kg	69.9 ± 13.1	67.1 ± 8.4
Time since surgery, years	1.5 ± 0.6	-
Tegner score	6.8 ± 1.8	6.6 ± 1.6
Marx activity score	10.6 ± 3.8	11 ± 3.9
Graft type		
Quadriceps tendon autograft	14	
Hamstring tendon autograft	12	
Bone-patellar tendon-bone autograft	8	
Allograft	1	
Matched sport participation		
Running, recreational	11	11
Down-hill skiing	7	7
Basketball	4	4
Soccer	3	3
Volleyball	2	2
Other	8	8

[a]Data are presented as mean ± SD or number. Some participants played multiple sports. ACLR, anterior cruciate ligament reconstruction; HC, healthy controls.

DISCUSSION

This study evaluated cognitive-motor impairments that persist after ACLR rehabilitation, even after RTS clearance was achieved using standard criteria. A robust group main effect, but not group and condition interaction, was detected, with the ACLR group demonstrating more asymmetry in knee extensor moments during landing compared with the HC group. Counter to our hypothesis, the primary outcomes were not impacted by the presence or absence of a cognitive challenge. In contrast, unanticipated conditions elicited a reduced pKFA for landing compared with anticipated conditions, regardless of group. Also, the unanticipated conditions caused significant differences for contralateral ACL injury factors when compared with conditions expected, with the most robust effect indicating increased contralateral hip flexion angle for the ACLR group, which has previously been linked to elevated contralateral injury risk.[28] Therefore, rapid decision-making may represent a particularly salient challenge to neuromuscular control. Further prospective studies are required to determine the different aspects of cognitive-motor function and the most meaningful sets of outcomes that can serve as a therapeutic target in assessing second ACL injury risk.

Findings across outcome variables suggest that a multivariable perspective may provide insight into high-risk

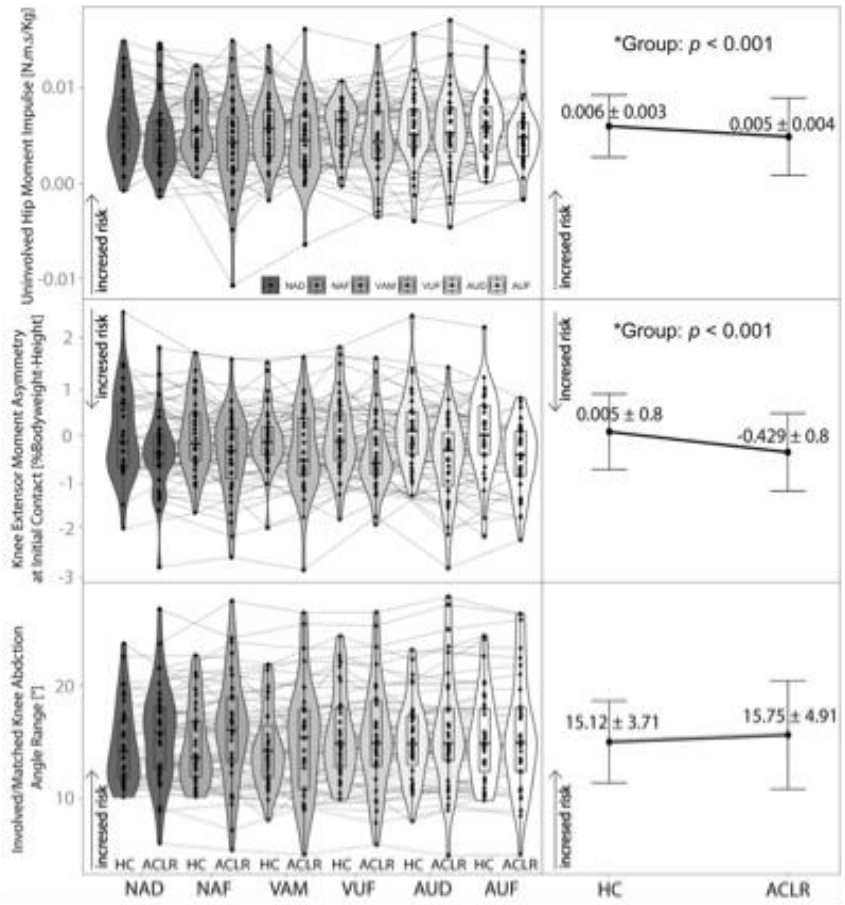


Figure 2. Left: Violin plots for the second ACL injury predictors for ACLR and HC groups for each condition. Right: Main effects of group showing ACLR and HC groups' means and standard deviations for each second ACL injury predictor. The asterisk indicates significant differences. ACLR, anterior cruciate ligament reconstruction group; AUD, auditory unanticipated; AUF, auditory unanticipated with visual constraint; HC, healthy control group; NAF, baseline with visual constraint; NAD, baseline, no visual constraint; VAM, anticipated secondary direction with visual working memory task; VUF, visual unanticipated.

scenarios. Considering the main significant findings, the ACLR group exhibited riskier loading patterns based on greater knee extensor moments asymmetry across all conditions. One plausible reason for the lack of a group × condition effect for this variable is that the asymmetric landing strategy was already demonstrated in the baseline conditions and may indicate that the ACLR group was already at a performance "floor," making further increases in asymmetry less likely even under the other condition challenges. Alternatively, unanticipated conditions elicited reduced pKFA during landing patterns for both groups. The post-hoc test for pKFA revealed a significant decrease in this variable for rapid decision-making conditions compared with anticipated conditions for all participant regardless of their group. Notably, the interaction between group and condition was not significant, suggesting that the ACLR group did not demonstrate an exaggerated detrimental response to the unanticipated conditions. However, it may be insightful to consider that their effects could be additive. When considered concurrently from a multivariable perspective (ie, pKFA and KEM-Asym-IC on the same plot), the riskiest combination of outcome variables occurs for the ACLR group under unanticipated conditions (Figure 4). Therefore, even though unanticipated

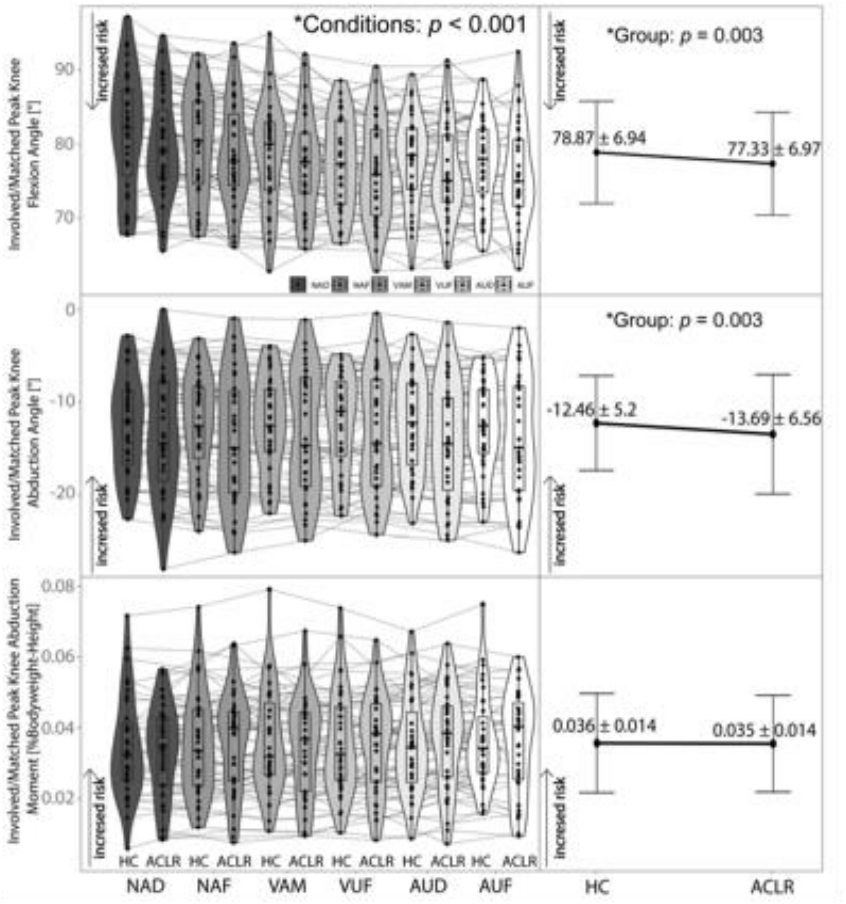


Figure 3. Left: Violin plots of ACLR and the HC group for means of each condition for primary ACL injury predictors. Right: Main effects of group for each primary ACL injury predictor (means and standard deviations). The asterisk indicates significant differences in conditions for pKFA.ACLR, anterior cruciate ligament reconstruction group; AUD, auditory unanticipated; AUF, auditory unanticipated with visual constraint; HC, healthy control group; NAD, baseline, no visual constraint; NAF, baseline with visual constraint; VAM, anticipated secondary direction with visual working memory task, VUF, visual unanticipated.

TABLE 2
P Values for Linear Mixed Effect Models for the Second ACL Predictors[a]

	Group	Condition	Group*Condition	R^2_{adj}, %
Uni-HRot-Imp	**<.001**	.902	.712	42
KEM-Asym-IC	**<.001**	.995	.794	51
Inv-KAbA-range	.036	.856	.711	32

[a]Presented outcomes are based on statistical models with "pair" as a random effect and not including covariates. Bold *P* values indicate statistical significance. Inv-KAbA-range, range of knee abduction angle for the involved limb; KEM-Asym-IC, limb asymmetry in knee extensor moment at initial contact normalized to body weight and height; Uni-HRot-Imp, uninvolved hip rotation net moment impulse.

TABLE 3
P Values for Linear Mixed-Effect Models for General ACL Risk Factors[a]

	Group	Condition	Group × Condition	R^2_{adj}, %
pKFA	**.003**	**<.001**	≥.999	44
pKAbA	**.003**	.993	.993	52
pKAbM	.857	.876	.959	47

[a]Presented outcomes are based on statistical models with "pair" as a random effect and not including covariates. Bold *P* values indicate statistical significance. pKAbA, peak knee abduction angle; pKAbM: peak knee abduction moment normalized to body weight and height; pKFA, peak knee flexion angle.

TABLE 4
P Values for Linear-Mixed Effect Model Analysis for Contralateral ACL Risk Factors and Multivariable Perspective of Injury Risk[a]

	Group	Condition	Group × Condition	R^2_{adj}, %
CL-KFA	**<.001**	**<.001**	.964	37
CL-HFA	**<.001**	**<.001**	.984	40
Contact Time	**<.001**	**.004**	.376	46
Stiffness	.298	**<.001**	.666	38

[a]Presented outcomes are based on a statistical model iteration with "pair" as a random effect and not including covariates. Values are presented as *P* values. Bold *P* values indicate statistical significance. CL-HFA, contralateral limb hip flexion angle; CL-KFA, contralateral limb knee flexion angle.

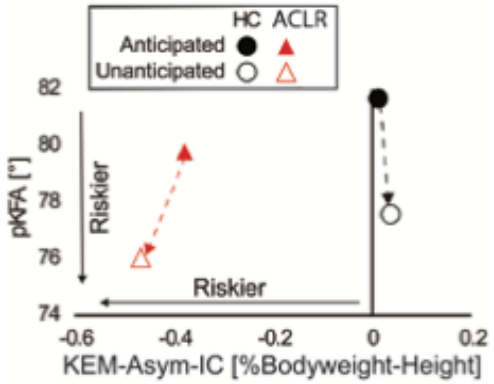


Figure 4. Multivariable perspective of injury risk of the current dataset. pKFA and asymmetry of KEM-Asym-IC during anticipated and unanticipated conditions (means of 3 unanticipated conditions) for the ACLR and HC groups. Arrows indicate group-specific shifts in outcome variables between anticipated and unexpected situations. ACLR, anterior cruciate ligament reconstruction; HC, healthy control; KEM-Asym-IC, knee extensor moment at initial contact; pKFA, peak knee flexion angle.

conditions elicit stiffer landing strategies for both ACLR and HC groups, this added effect may be particularly problematic for those in the ACLR group who already have other biomechanical patterns associated with second ACL injury risk (ie, asymmetric knee extensor moment) across a range of conditions.

Precedence for multivariate interactions in the context of ACL loading exists, where the most significant risk of ACL injury occurs from a combination of high knee flexion moments, knee compression forces, internal tibial torque, and knee abduction moments during movements such as jump landings or sudden direction changes.[5] However, future work is needed to validate the extent and nature of potential multivariable interactions with respect to second ACL injury risk. Alternatively, estimating loading in the ACL graft may enable more direct outcomes related to potential graft failure.[43] Despite ongoing opportunities to refine the outcome measures, the current findings provide novel data to support the potential value of cognitive-motor function as a therapeutic target to enhance rehabilitation outcomes after ACLR.

The riskier performance of the ACLR group compared with the HC group for KEM-Asym-IC at initial contact is consistent with previous research reporting that patients who underwent ACLR demonstrate high-risk knee mechanics even after RTS. An earlier study observed asymmetry in sagittal-plane knee moments at initial contact among participants who later suffered a second ACL injury compared with those who underwent ACLR but did not sustain a second injury within 1 year.[46] This observation highlighted that unbalanced force absorption strategies during the initial phase of the drop vertical jump task may contribute to an increased risk of future injuries. Our results extend this analysis to compare the ACLR group with the matched HC group, which indicates that those

in the ACLR group still tend to adopt riskier landing strategies even after they are cleared to RTS. This finding further supports the potential need for further rehabilitation or more sensitive RTS testing to address these unresolved neuromuscular adaptations.

Previous research has shown that the risk of ACL injury to the contralateral limb is higher than to the ipsilateral limb.[59] Our exploratory analysis of contralateral limb ACL injury parameters aligns with findings from a previous study on male participants[28] that found that those with a contralateral ACL injury exhibited lower stiffness, longer contact time, and greater CL-HFA and CL-KFA. Similarly, our results showed that the ACLR group had higher CL-KFA and CL-HFA values and longer contact times compared with the HC group. However, unlike King et al,[28] we did not observe significant group differences in vertical stiffness. Instead, we observed that these stiffness values can vary by condition, with lower stiffness values in anticipated conditions compared with rapid decision-making conditions. These findings suggest that cognitive load may influence parameters related to contralateral ACL injury risk. Further studies are needed to determine whether these findings apply to a broader population and whether they align with the higher risk observed in the contralateral limb.

More recently, research has supported that adding a secondary cognitive task to drop jump landing on ACLR group assessments may enhance the identification of movement patterns linked to increased ACL injury risk and insufficient rehabilitation.[39,53] Our study expanded these findings of reduced pKFA by showing the same results when adding not only visual cognitive challenges, but also auditory cognitive tasks during jump landing movement. Notably, rapid decision-making appeared to be the dominant challenge that elicited differences in pKFA, regardless of the directional cues being implemented with visual or auditory stimulus modalities. Decision-making and divided attention have been identified as key factors influencing several biomechanical risk factors for ACL injury.[27] Biomechanical adaptations in response to rapid decision-making in an ACLR cohort performing a jump landing task have also been reported by others.[53] The present study provides novel data supporting this point in the context of second ACL injury risk, with performance during rapid decision-making demands representing a particularly salient scenario to target rehabilitation and assessment efforts.

When considering Uni-HRot-Imp, we found a lower rotational impulse at the hip in the ACLR group compared with the HC group, corresponding with less risky biomechanics for the ACLR group. However, the significance of this finding was contingent upon the statistical analysis approach, specifically losing significance when using an unpaired analysis. Although many factors were intentionally matched, considerable person-specific variance cannot be completely accounted for in a case-control study design. The iterative statistical analysis aimed to evaluate the robustness of our findings to statistical assumptions, with robust findings being those that persisted regardless of assumption and inclusion of covariates. The source of the sensitivity of the Uni-HRot-Imp to the paired versus unpaired assumption is not known; however, it may be related to the enhanced statistical power of the paired analysis or other person-specific variability that is not adequately modeled through a paired design. In contrast, findings for KEM-Asym-IC were more robust, which may partially result from the KEM-Asym-IC outcome targeting asymmetry rather than a limb-specific metric. By comparing relative values between limbs, aspects of overall performance (eg, higher jump height) may be mitigated, supporting broader evaluation across ACLR and HC groups.

It is important to acknowledge the limitations of this study. We focused on specific jump landing tasks with a variety of cognitive challenges; however, these are not representative of all movements related to second ACL injury, including single-limb landings and cutting maneuvers. Notably, the group comparisons used in this study do not allow for potential patient-specific responses to be determined. For example, a subset of ACLR patients may demonstrate more detrimental responses to certain cognitive challenges, which are averaged out through group analyses. Future work that elucidates individualized injury risk profiles is warranted. Although the sample size was sufficient for this study's purposes, it may limit the generalizability of the findings. We examined second ACL injury predictors with high sensitivity and specificity from a previous study; however, these variables are now without their critiques (eg, unknown reliability of small knee extensor moments at initial contact, Supplemental Table 3).[46] Further research is necessary to investigate the ability of cognitive-motor function to predict injury recurrence and athletic performance prospectively, which is not feasible through our cross-sectional study design. However, our findings provide novel data to corroborate growing perspectives on the relevance of cognitive-motor function as an area that can augment ACLR rehabilitation efforts.[12,21,47]

CONCLUSION

The study results suggest that those in the ACLR group exhibit riskier biomechanics compared with those in the HC group during jump landing movements, regardless of the presence of additional cognitive challenges. Real-world demands, such as rapid decision-making, adversely influence landing kinematics. The extent to which these multivariable outcomes may compound injury risk after ACLR requires further research to more precisely understand the opportunities for neurocognitive challenges to impact ACLR return-to-sport assessment, ensuring that ACLR patients are adequately prepared for the demands of their sport environment.

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CHAPTER THREE

COGNITIVE-MOTOR FUNCTION AND ACL INJURY RISK: EXPLORING RELATIONSHIPS BETWEEN CLINICAL AND LAB-BASED ASSESSMENTS

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ORIGINAL RESEARCH REPORT

Cognitive-Motor Function and Anterior Cruciate Ligament Injury Risk: Exploring Relationships Between Clinical and Lab-Based Assessments

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Assessing cognitive-motor function following anterior cruciate ligament reconstruction may enable a more comprehensive assessment of readiness to return to sport. The primary purpose of this study was determining the relationship between measures of clinical cognitive-motor interference and laboratory-based second injury relevant biomechanics through a cross-sectional study. ***Methods:*** Thirty-six individuals following anterior cruciate ligament reconstruction (26 females/10 males, 19.8 [1.8] y; 1.7 [0.1] m; 69.6 [12.8] kg, Tegner activity level 6.8 [1.8], 1.5 [0.6] y post anterior cruciate ligament reconstruction) participated in the study. We assessed 2 clinically feasible tests of cognitive-motor function: single (ST) and dual tasks (DT) for triple hop and medial-side hop. Laboratory-based tests involved motion capture assessment of jump landings from a 30-cm box followed immediately by a secondary jump. Conditions included, ST (anticipated secondary jump direction) and DT (unanticipated secondary jump direction). Primary outcome variables included DT change (DTC) of second anterior cruciate ligament injury predictors (limb asymmetry in knee extensor moment at initial contact, range of knee abduction angle for the involved limb, and uninvolved hip rotation net moment impulse). Correlations were used to identify associations between lab- (biomechanics) and clinic-derived (hop distance) outcomes. Secondary analyses with other risk-associated knee mechanics and patient-reported outcome measures were also performed. ***Results:*** No significant correlations were found between DTC clinical variables and DTC second anterior cruciate ligament predictors. However, significant relationships were observed between clinical and lab outcomes when considering ST or DT in isolation, such as ST range of knee abduction angle for the involved limb correlating with ST for triple hop for both limbs (Inv: $r = -.436$, $P_{adj} = .04$; Uninv: $r = -.453$, $P_{adj} = .04$). ***Conclusions:*** Associations between cognitive-motor interference (ie, DTC) in clinical and lab tests were not found, but significant fair strength correlations appeared between clinical and lab variables when examining ST and DT performance, separately. Future prospective studies are needed to determine the predictive value of cognitive-motor function for injury rehabilitation decision making.

Keywords: anterior cruciate ligament reconstruction, cognitive-motor performance, clinical assessments, return to sport

Key Points

- Dual-task change between hop distance on motor versus cognitive-motor clinical hop test was largely unrelated to dual-task changes of second anterior cruciate ligament injury predictors in unanticipated jump landings.
- Injury-relevant biomechanics tended to be more related to clinical hop distance, albeit with limited strength, when considering single- and dual-task scenarios separately.
- Insight for anterior cruciate ligament reconstruction return-to-sport assessment may be complementarily gained through measures of single-, dual-task performance, and cognitive-motor interference to more fully evaluate patient function and guide personalized rehabilitation.

Following rehabilitation for anterior cruciate ligament reconstruction (ACLR), return-to-sport (RTS) decision making relies on a combination of time from surgery, self-reported measures of physical and psychological function, and functional tests.[1–3] Functional tests include muscle strength, and a variety of hop or jump assessments.[4] However, after testing these criteria and returning to sport, about 30% of young athletes sustain a second anterior cruciate ligament (ACL) injury to the reconstructed or contralateral limb.[5] Despite numerous studies aimed at better understanding ACL injuries, the connection between meeting the RTS criteria and the risk of a second ACL injury remains unclear.[6]

Recent findings regarding the neurological alterations following lower-extremity injuries highlight the critical necessity of integrating visual-cognitive challenges within RTS assessments.[7,8]

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Notably, up to 70% of second ACL injuries happen when athletes' attention is directed externally (eg, an opponent, ball, or other environmental factors).[9] Additionally, poorer visual-spatial performance is linked to riskier biomechanics during cognitively challenging movements.[10] Despite the prevalence of cognitive-motor demands in ACL injury scenarios, cognitive-motor function is not routinely a criterion for RTS following ACLR. Assaying cognitive-motor function may provide more complete information for RTS decision making and reduce secondary injury risk.[7,8] However, there is a gap in knowledge regarding the extent that clinically feasible tests can be adequate surrogates for injury relevant cognitive-motor interference. To address this gap, dual-task (DT) clinical hop tests (triple hop [TH] and medial-side hop [MSH] combined with visual-cognitive tasks), which have established high test–retest reliability in prior research,[11,12] have been proposed as practical tools for assessing cognitive-motor interference.

Therefore, the purpose of this study was to determine the ability of low-cost, accessible cognitive-motor tests (ie, clinical tests) to capture clinically relevant information, specifically biomechanical second ACL injury risk factors, obtained from a biomechanics laboratory (ie, lab tests). We hypothesized that clinical measures of cognitive-motor interference would be highly correlated with motion capture laboratory-derived second ACL injury risk biomechanics. Accepting the hypothesis would provide support for clinical tests that relate to biomechanical risk factors of a second ACL injury following ACLR and support efforts to augment RTS decision making. Rejecting the hypothesis would emphasize that hop distance during clinical tasks is not a reliable indicator of patients' biomechanics in cognitive-motor scenarios following ACLR.

Methods

Participants

Eligibility included: (1) one prior ACL injury and reconstruction, (2) ACLR surgery occurred within 2.5 years prior to the time of testing, (3) cleared to return to sport by their clinical team, (4) no concussion or lower body musculoskeletal injury following ACL injury, and (5) no known neurologic or musculoskeletal disorder.

Thirty-six persons (Table 1) who completed rehabilitation from a primary ACLR participated. All participants provided written informed consent and assent for those under 18 years old (Montana State University Institutional Review Board protocol no. SM081818). For all tasks, participants wore their preferred athletic shoes for testing. Motion capture testing of jump landing tasks occurred prior to participants performing the hop tests.

Lab-Based Testing: Motion Capture Assessment of Jump Landing Biomechanics

Seventy-five reflective markers attached to participants captured their motion and force plates recorded ground reaction forces during the lab tasks (Figure 1A). The marker set followed a point-cluster distribution on the thighs and shanks.[10,13] A plug-in gait marker set was used for the upper body, with additional markers on the iliac crests used to assist pelvis tracking during the jumping tasks (Figure 1A). We used a 10-camera motion capture system to record the kinematic data at 250 Hz (Motion Analysis Corp) and 4 force plates to record ground reaction force data at 1,000 Hz (OPT464508-2K, Advanced Mechanical Technology, Inc). Before starting the lab-based test, participants did 2 sets of 8 bodyweight squats and 5 maximal effort vertical jumps as a warm-up.

Table 1 Cohort Characteristics (Average [SD])

Female/male	26/10
Age, y	19.8 (1.8)
Height, m	1.7 (0.1)
Mass, kg	69.6 (12.8)
Time since surgery, y	1.5 (0.6)
Tegner score	6.8 (1.8)
Marx activity score	10.6 (4.1)
Graft type	
Quadriceps graft	14
Hamstring graft	12
Bone-Patella-bone graft	9
Allograft	1
Primary sport participation	
Down-hill skiing	13
Soccer	6
Basketball	6
Volleyball	3
Running (recreational)	3
Weightlifting	2
Other	3

The lab-based test was jumping from a 30-cm box placed a distance of half of their height from the force plates and had a secondary jump in one of the 3 directions of straight up, 45° to the right, or 45° to the left (Figure 1B).[14] The jumping task was performed in 2 conditions: ST and DT (Figure 1C), with 5 successful trials for the straight up direction collected for each participant with the average of biomechanical variables for the 5 trials used in analyses. The single-task (Lab-ST) condition involved an anticipated direction (up secondary jump direction) with no cognitive task. In this task, participants' visual gaze was not constrained, and they were instructed to jump as high and hard as they could immediately upon landing from the initial jump from the box. The dual-task (Lab-DT) condition presented a secondary jump direction cue ~250 milliseconds prior to initial contact to keep the task unanticipated.[14] Timing of the cue was based on a signal from a force sensitive resistor on the box and a previously described procedure to calibrate presentation timing to individual participants' jumping strategies to maintain a consistent ~250-millisecond reaction time for all participants.[15] Time to react (ie, cue presentation until initial contact) was verified post hoc (249 [90] ms). The secondary tasks were conducted using E-Prime 3.0 software (Psychology Software Tools) and presented on a 1.5-m television screen positioned about 5-m away from the primary landing zone. Participants were asked to look at the fixation in front of them during the entirety of the jump landing. Directional cues were random for both participant and examiner. Only trials with a secondary jump direction of straight up were analyzed for this study. Successful trials were defined as reacting correctly to the arrow and not looking down during the entirety of the jump landing.

Data Processing for Lab Tests

Data processing was performed in Visual 3D (HAS-Motion) and MATLAB (version R2022b, MathWorks). A Visual3D CODA pelvis was employed, and hip joint centers were estimated using the Visual3D implementation of the prediction equations from Bell

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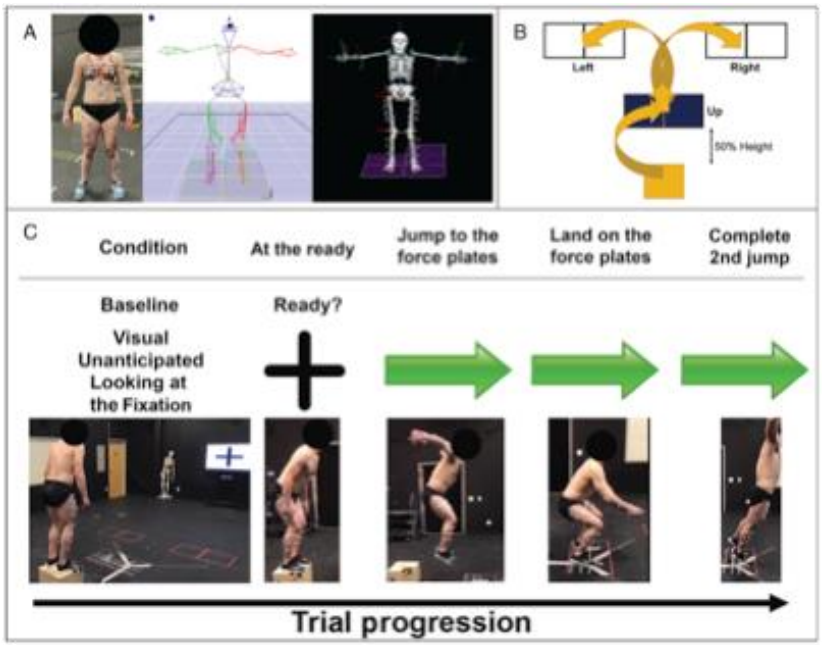


Figure 1 — (A) Picture of a participant with marker set, 3-dimensional model in Cortex, and Visual 3D for motion analysis (A, from left to right), (B) secondary jump directions, (C) jump landing task progression.

et al.[16] The knee joint centers were defined as the midpoints between markers on the femoral epicondyles, and the ankle joint centers as the midpoints between markers on the malleoli. Segments were defined with the *z*-axis directed from distal to proximal joint centers, the *y*-axis oriented anteriorly, and the *x*-axis oriented to the participants' right. Kinematic and force plate data were filtered using fourth-order, zero-lag, low-pass Butterworth filters with cutoff frequencies set at 15 Hz.[17] Kinematic data were computed using a Quasi-Newton optimization method and an inverse kinematics model with limiting the degrees of freedom to 3 rotational degrees at the hip and knee and 2 rotational degrees at the ankle. Kinetic data were computed using the model with the inertial and ground reaction force data to solve for the internal net joint forces and moments.[15] For kinetic variables, forces normalized to the mass, and moments normalized to both mass and height of each participant.

Joint kinematics were estimated using *X*–*Y*–*Z* Cardan rotation with *X*-, *Y*-, *Z*-axis rotations corresponding to (+) flexion/ (−) extension, (+) adduction/ (−) abduction, and (+) internal/ (−) external rotation, respectively, for the hip and knee joints. Internally defined net reaction moments resolved in the proximal joint segment were also calculated, with the knee and hip following similar conventions as previously stated for the kinematics. Initial contact was the frame where the vertical ground reaction force first exceeded 10 N.

Lab-Based Biomechanical Outcomes

Previously reported biomechanical predictors of second ACL injuries were calculated for the landing from the initial jump.[18] We calculated the range in knee abduction angle for the involved limb (Inv-KAbA-range) within a window starting from the initial contact to the minimum of the body's center of mass, with larger values reflecting more frontal plane motion and interpreted as riskier.[18] Limb asymmetry in knee extensor moment at initial contact was calculated and normalized to body weight and height (KEM-Asym), with negative values reflecting a greater knee extension moment in the uninvolved limb compared with the involved limb and interpreted as riskier for second injury.[18] Uninvolved hip rotation net moment impulse was calculated during the initial 10% of the chosen window (Uni-HRot-Imp), with larger values reflecting less external rotator moments and interpreted as riskier.[18] To quantify cognitive-motor interference, we calculated dual-task change (DTC = DT − ST) for each of the variables. A pure difference, rather than a percent change, was used due to the kinematic/kinetic outcomes spanning zero and therefore being overly sensitive when dividing by values near zero.

Clinic-Based Testing: Hop Distance

The clinical tasks were the TH[11] and MSH[12] for distance, assessed without biomechanics laboratory equipment. Participants were asked to do these tasks with (DT) and without visual-cognitive challenges (ST), as described below.

Traditional and Visual-Cognitive Triple Hop[11]

The order of ST-TH and DT-TH was randomized. In the ST, the participants hopped 3 times consecutively on the same leg, maximizing distance and maintaining balance on the final hop for 3

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seconds. In the visual-cognitive task, we used the FitLight system (FITLIGHT Sports Corp.) following the same protocol as Farraye et al.[11] Participants did 2 practice trials. In the visual-cognitive task, participants were required to respond to specific-colored peripheral lights as their "GO" signal and hopping forward 3 times while keeping their focus on a light in front of them and then recalling a sequence of colors flashed by the central light during the hopping (Figure 2A). The peripheral lights randomly displayed different colors, with one designated as the "GO" signal (Figure 2B). A successful trial required the participant to trigger the reaction time FitLight while executing the same TH task, as described for the ST condition. If the participant lost their balance, added extra hops, or switched legs during the trial it was considered a physical miss, and the trial was repeated. Three successful trials were completed on each limb, starting with the uninjured side.

Traditional and Visual-Cognitive Medial Side Hop[12]

Participants also performed a MSH for distance as a ST (ST-MSH), and with simultaneous visual-cognitive task as a DT (DT-MSH) in a randomized order (Figure 2C). For the ST, participants stood on one leg, hands on hips, and hopped medially as far as possible, holding the landing for 30 seconds, and starting on their uninjured limb. After one practice trial for each limb, 3 successful trials were completed for each limb, with success defined by maintaining balance without foot shifts, opposite foot use, or hand movement. In the visual-cognitive task, participants stood 2-m away from a 1.5-m television in a relaxed position. They were shown a circular array of 8 letters (D, F, J, K) around a central dot on the screen for 100 milliseconds (Figure 2D). After the letters disappeared, a line appeared for 1.9 seconds, prompting participants to recall the letter at the corresponding location. A 10-second practice trial and two 30-second trials were completed of the visual-cognitive task in isolation (ie, no hopping) prior to completing the DT. Participants were then asked to do the same visual-cognitive task, while they performed the MSH for distance (DT-MSH).

Clinical Test Outcomes: Hop Distance

To avoid the need for specialized biomechanics lab equipment, clinical test outcomes focused solely on hop distance. The maximum distance among 3 successful trials normalized to leg length (%L) were used for analyses. DTC for triple hop (DTC-TH) and DTC-MSH distances for involved and uninvolved limbs were primary outcomes of the clinical tests. Reliability for these metrics are intraclass correlation coefficient ($ICC_{3,1}$) = .62 for DTC-MSH and $ICC_{3,1}$ = .94 for DTC-TH based on reanalysis of data of prior studies for the DTC metric.[11,12] For consistency with the lab-based outcomes, we used a difference score rather than percent change to capture the cognitive-motor interference; however, difference scores and percent changes yielded high correlations (r = .95–.97) for hop distances.

Supplemental Outcomes

Our primary analysis focused on the ability for clinical test outcomes to correlate with previously reported biomechanical predictors of second ACL injuries measured via motion capture in a biomechanics laboratory.[18] To provide additional perspective regarding the clinical relevance of the clinical cognitive-motor tests, we added exploratory outcomes focused on primary ACL injury risk factors of the involved limb, such as peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and peak knee abduction moment (defined externally and normalized to body weight and height [pKAbM]), as well as a metric of overall task performance (ie, jump height) for the lab

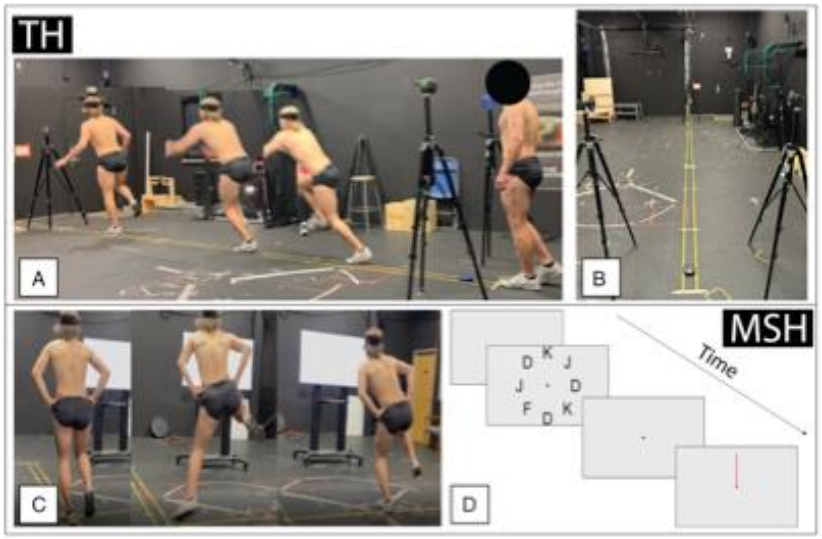


Figure 2 — (A) Time–lapse picture of a participant reacting to "GO" color on the peripheral lights and initialized TH while looked at the light in front of them to memorize the 3 colors in order, (B) set up of the triple hop task, (C) picture of a participant performing a MSH and focused on the task on television, (D) overview of the visual-cognitive task presented on television during MSH. MSH indicates medial side hop; TH, triple hop.

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tasks. Additionally, we performed correlations between the clinical cognitive-motor test outcomes and patient-reported outcomes (PROs) related to physical function, quality of life, psychological readiness, and fear. Specifically, participants completed the following surveys: International Knee Documentation Committee subjective knee evaluation form,[19] Knee Injury and Osteoarthritis Outcome Score,[20] shortened Tampa Scale of Kinesiophobia-11,[21] ACL Return to Sport after Injury[22], and the Forgotten Joint Score-12 knee.[23] Analyses for these supplemental outcomes are provided in see Supplementary Table S1 and Supplementary Figures S1–S3 in Supplementary Materials (available online).

Statistical Analysis

Pearson correlations were used for normally distributed variables and Spearman correlations for variables not normally distributed according to the Anderson–Darling Normality test to identify significant associations between lab and clinical measures. The same approach was used for the supplemental outcomes. *P* values were adjusted within each set of correlations (eg, DTC lab-based and clinical variables, DT lab-based and clinical variables, and ST lab-based and clinical variables) between biomechanic variables and hop distance with Benjamini–Hochberg method to control the false discovery rate. For significant correlations, follow-up regression models were used to test for DTC lab-based variables as dependent variables with the DTC clinic-based variables as predictors and assess potential confounding factors (ie, gender and jump height) included as covariates. The Benjamini–Hochberg method was used for the *P* values of regressions for the same set of variables with significant results. The necessary sample size to provide 80% statistical power and $\alpha = .05$ to detect relationships with magnitudes of at least moderate strength ($r = .5$) was estimated to be n = 29 by using G*Power.

Results

The results are based on 36 clinical-ST and 36 clinical-DT data sets and 36 lab-ST data sets and 35 lab-DT data sets (number of missed trials and collected data in Supplementary Table S2 in Supplementary Materials [available online]). We excluded lab-DT data for one participant due to data collection issues (trials used: 160 out of 180 [36 participants × 5 trials] trials for lab-DT, and 179 out of 180 trials for lab-ST). Descriptive statistics and DTC for these trials are provided in Table 2.

Second ACL Injury Predictors

There were no significant correlations between DTC clinical variables and DTC second ACL injury predictors (Figure 3). When considering the ST conditions in isolation, clinical and lab outcomes had several significant relationships. Inv-KAbA-range was related to ST-TH hop distance for both involved and uninvolved limbs (Inv: $r = -.44$, $P_{adj} = .04$, Uninv: $r = -.45$, $P_{adj} = .04$; Figure 4A), and ST-MSH-Inv hop distance ($r = -.42$, $P_{adj} = .04$; Figure 4A), with farther clinical hop distance related to less frontal plane motion in the lab-based jump landing. In post hoc models, these results stayed significant with gender as a covariate (ST-TH-Inv: $P_{adj} = .034$, ST-TH-Uninv: $P_{adj} = .02$, ST-MSH-Inv: $P_{adj} = .037$). However, when adding lab testing jump height as a covariate, only the regression between Inv-KAbA-range and ST-TH-Uninv remained significant ($P_{adj} = .029$), with other previously significant relationships trending after controlling for multiple comparisons (ST-TH-Inv: $P_{adj} = .061$, ST-MSH-Inv: $P_{adj} = .074$). DT-TH-Inv was correlated with Lab-DT-Uni-HRot-Imp ($r = .432$,

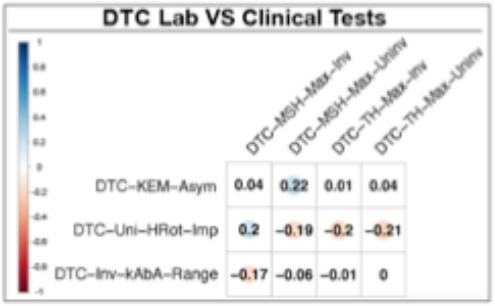


Figure 3 — Correlogram for DTC for second and primary ACL injury predictors, overall performance in drop vertical jump, and clinical tests. Numeric values shown are correlation coefficients. ACL indicates anterior cruciate ligament; DTC, dual-task change; Inv, involved; Inv-KAbA-range, range in knee abduction angle for the involved limb; MSH, medial side hop; TH, triple hop; Uni, uninvolved; Uni-HRot-Imp, uninvolved hip rotation net moment impulse; KEM-Asym [%BW-HT], limb asymmetry in knee extensor moment at initial contact normalized to body weight and height.

Table 2 Average (SD) of Clinical Tests and Lab Drop Vertical Jump Tests Variables

	ST	DT	DTC (DT – ST)
Clinical values			
MSH-Inv, %L	1.08 (0.30)	1.07 (0.30)	–0.005 (0.110)
MSH-Uninv, %L	1.12 (0.33)	1.1 (0.3)	–0.024 (0.100)
TH-Inv, %L	4.91 (0.99)	4.55 (0.89)	–0.36 (0.35)*
TH-Uninv, %L	5.03 (1.03)	4.73 (0.86)	–0.3 (0.5)*
Lab values			
Uni-HRot-Imp, N·m·s/kg	0.005 (0.004)	0.005 (0.004)	0.00005 (0.0031)
KEM-Asym, %BW-HT	–0.36 (0.83)	–0.36 (0.79)	–0.073 (0.64)
Inv-KAbA-range, °	15.9 (4.4)	15.5 (4.8)	–0.25 (2.03)

Abbreviations: BW, body weight; HT, height; Inv, involved limb; Inv-KAbA-range, range in knee abduction angle for the involved limb; KEM-Asym (%BW-HT), limb asymmetry in knee extensor moment at initial contact normalized to body weight and height; %L, normalized to the leg length; MSH, medial side hop; TH, triple hop; Uni-HRot-Imp (N·m·s/kg), uninvolved hip rotation net moment impulse; Uninv, uninvolved limb.
*Significant difference of $P < .05$.

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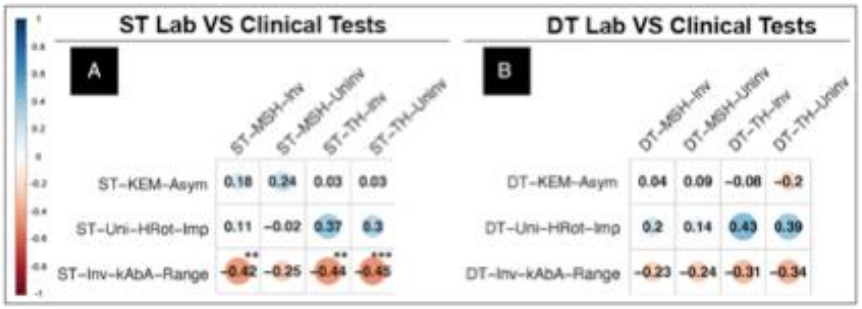


Figure 4 — (A) Correlogram for ST variables for second and primary ACL injury predictors, and overall performance in drop vertical jump in ST jump landing and clinical tests. (B) Correlogram for DT variables for second and primary ACL injury predictors, and overall performance in drop vertical jump in DT jump landing and clinical tests. $^{*}P_{adj}$ of correlation < .05. $^{**}P_{adj}$ of regression with gender as a covariate < .05. $^{***}P_{adj}$ of regression with gender and jump height as covariates < .05. ACL indicates anterior cruciate ligament; DT, dual task; Inv, involved; Inv-KAbA-range, range in knee abduction angle for the involved limb; MSH, medial side hop; ST, single task; TH, triple hop; Uni, uninvolved, Uni-HRot-Imp, uninvolved hip rotation net moment impulse.

$P = .01$; Figure 4B) before adjusting the P value; however, it no longer remained significant after correcting for multiple comparisons ($P_{adj} = .12$).

Summary of Supplemental Analyses

In summary, DTC for clinical variables did not significantly correlate with DTC for primary ACL predictors, DTC for overall performance (see Supplementary Figure S1 in Supplementary Materials [available online]), or PROs (see Supplementary Figure S2 in Supplementary Materials [available online]). In ST conditions, most clinical test variables correlated with primary ACL injury predictors, with greater distances in clinical tasks linked to increased knee flexion and abduction angles, and decreased abduction moments (Supplementary Figure S3A in Supplementary Materials [available online]). Similar correlations were observed in DT conditions (Supplementary Figure S3B in Supplementary Materials [available online]). The results related to ST-pKAbA and ST-pKAbM with ST-TH-Uninv stayed significant after running the regression modeling and adding both gender and jump height as covariates with adjusting P values, but the rest of correlations did not remain significant (see Supplementary Figure S3 in Supplementary Materials [available online]). Greater distances in clinical tasks were associated with greater jump heights in both ST and DT jump landing tasks. PROs showed significant correlations with ST and DT metrics for the clinical hop tests before correcting for multiple comparisons, suggesting that farther hop distances were linked to less fear (Tampa Scale of Kinesiophobia-11) and higher function (International Knee Documentation Committee); however, these correlations were not significant after correcting for multiple comparisons (see Supplementary Figure S2 in Supplementary Materials [available online]).

Discussion

This study aimed to determine the potential correlation between clinical DT tests relative to laboratory-acquired second ACL injury risk biomechanics for cognitive-motor interference. The results of this study did not support our primary hypothesis that cognitive-motor interference (ie, DTC) during 2 clinical cognitive-motor tests would be related to cognitive-motor interference of biomechanical second ACL injury predictors. However, significant, fair strength correlations existed between clinical and lab metrics when focusing on ST and DT performance in isolation, rather than the within-subject DTC. These correlations existed between clinically accessible outcomes (ie, hop distance) and select biomechanical predictors of second and primary ACL injury. The collective results highlight that DT performance is a potentially more robust clinical metric to identify biomechanical risk than DTC metrics to describe cognitive-motor function. Additional prospective studies are needed to clarify the predictive value of clinical tests of cognitive-motor function with rehabilitation outcomes and injury risk.

The rejection of the DTC correlation hypothesis may be grounded in properties of the difference score metric. Specifically, there was a high degree of association between single- and dual-task performance (ie, $r > .7$ for all clinical and lab testing in our study, see Supplementary Table S3 in Supplementary Materials [available online]). The stronger the correlation, the less predictable variance in change/cost measures (eg, DTC),[24] leading to null correlations with other measures. Therefore, DTC measures may generally be less reliable than the ST or DT performance in isolation, especially to the extent that ST and DT performance are correlated.[24] Considering the clinical tasks used in this study,[11,12] the test–retest reliability of MSH task was ICC = .88 for ST-MSH, ICC = .86 for DT-MSH, and ICC = .64 for DTC-MSH, and ICC = .96 for ST-TH, ICC = .92 for DT-TH, and ICC = .94 for DTC-TH. There was a pronounced decrease in reliability for MSH when measuring DTC instead of ST or DT separately. Differences in the level of difficulty of the individual cognitive and motor tasks may influence the extent that test–retest reliability is influenced for DTC metrics. More work is needed to elucidate what outcome(s) of cognitive-motor tests (eg, DTC or DT performance) are most robust and insightful to maximize clinical utility. A potential, albeit unexplored, area for ACLR RTS would be considering performance on multiple visual-cognitive augmented RTS assessments (Figure 5). By isolating shared variance of DT performance across multiple tests of cognitive-motor function, the underlying construct, rather than test-specific performance, may be more robustly assessed. This approach has yielded substantial benefits in

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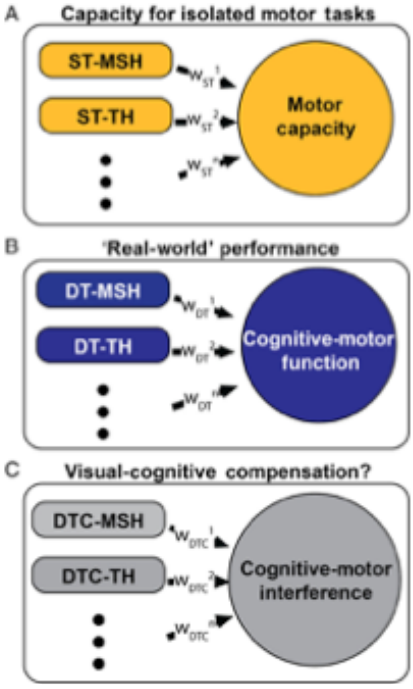


Figure 5 — Prospective theoretical framework for comprehensive evaluation of patient cognitive-motor function. Complementary perspectives from ST, DT, and dual-task cost outcomes, each defined by composite factors determined from performance on multiple clinically tests. (A) Evaluate motor capacity using various hop and strength tests (eg, ST-MSH, ST-TH, isokinetic strength), with hypothetical weightings defined by w_{ST}^{1}, and so on. (B) Assess "real-world" performance via a composite metric defined by performance on multiple cognitive-motor tests (eg, DT-MSH weighted by w_{DT}^{1}; DT-TH weighted by w_{DT}^{2}; additional tests having respective weightings [w_{DT}^{n}]). The approach may circumvent reliability and test-specific pitfalls of relying on DTC/cost metrics from isolated clinical tests to ultimately be more robust in understand cognitive-motor function in rehabilitation programs. (C) Probe for maladaptive visual-compensatory strategies using DTC outcomes across multiple cognitive-motor tests. Notably, insights afforded by B and C are likely enhanced by first ensuring adequate performance on A. Additionally, optimal sets of clinical tests and their relative weightings for each composite factor would need to be determined through future research. DT, dual task; DTC, DT change/cost; DT-MSH, DT medial side hop; DT-TH, DT triple hop; ST, single task; ST-MSH, traditional ST medial side hop; ST-TH, traditional ST triple hop.

improving reliability and identifying individual differences in other fields particularly in contrast to difference score metrics.[24]

Importantly, restricting assessment to even just DT performance likely provides an incomplete picture of patient function. For example, low DTC may be achieved by both the highest performers (eg, high performance on both ST and DT conditions leading to no DT-ST change) and lowest performers (eg, low performance on both ST and DT conditions leading to no DT-ST change) with no ability to distinguish between these scenarios if only considering a DTC outcome. Therefore, we theorize that complementary perspectives may be gained from expanding this composite approach for cognitive and motor ST performance (ie, assessing idealized performance capacity), cognitive-motor DT performance (ie, assessing "real-world" performance), and cognitive-motor interference (ie, DTC to probe compensation strategies) to more fully evaluate patient function and inform personalized rehabilitation and RTS decisions (Figure 5). This multifactorial strategy aligns with recent RTS frameworks that emphasize the importance of integrating physical, psychological, contextual, and sport-specific factors to more fully evaluate patient readiness and risk.[25] Notably, considerable research is needed to determine optimal sets of tests, timing of tests, and, ultimately, the clinical value of this approach for achieving appreciable impact on ACLR outcomes.

There were several fair-to-moderate strength correlations between clinical variables and second ACL injury predictors in ST and DT conditions separately (Figure 4). ST-TH for both limbs and ST-MSH-Inv were correlated with Lab-ST-Inv-KAbA-range with better performance in clinical tests related to reduced risk factor of Lab-ST-Inv-KAbA-range (Figure 4A). DT lab-based variables did not have any significant correlations with DT clinical variables after correcting for multiple comparisons (Figure 4B). The variable response to clinical versus lab DT challenges (ie, significant for ST but not for DT) may be partially due to differences in the specific DT demands elicited in the clinic versus lab scenarios. Although both clinic and lab conditions introduced visual-cognitive challenges, the lab test emphasized a reactive motor response to the directional cue in contrast to the Go/No-Go challenge of the clinical hop tests. The varying cognitive-motor response may highlight context- (eg, task objective, movement) and domain-specific response (eg, rapid decision making, response inhibition) to cognitive-motor challenges. Notably, prior work has demonstrated that different cognitive tasks can elicit divergent neuromuscular and biomechanical responses. For example, Fischer et al[15] reported that visual constraints led to altered jump landing biomechanics, whereas a visual-spatial memory task did not elicit biomechanical adaptations. Additionally, the selective response to specific aspects of cognitive-motor tasks may be exacerbated in different populations (eg, affected by neuroplasticity following ACLR). Individuals following ACLR exhibit increased postural instability during visual-cognitive DT conditions compared to motor DT, suggesting a heightened reliance on visual input for postural control.[26] Furthermore, ACLR patients demonstrated greater cognitive-motor interference than noninjured controls during drop vertical jumps combined with secondary cognitive tasks.[27] This interference was revealed by impaired performance in both cognitive and motor domains. Particularly these deficits were independent of isolated cognitive ability, suggesting specific challenges in cognitive-motor integration following ACLR.[27] Notably, rapid decision making and inhibitory control challenges appeared to have a more salient impact on ACLR individuals' biomechanics compared to a memory challenge.[28] These studies underscore the importance of considering the specific nature of cognitive challenges when assessing cognitive-motor interactions in ACLR populations. Future work is needed to determine whether more closely aligned cognitive demands would increase the strength of relationships between clinical and lab conditions and also what the most salient DT demands are regarding injury risk prediction.

Shortcomings of focusing on hop distances alone may be reflected in our correlations, suggesting the need for additional

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metrics during jumps. Notably, jump height was a significant covariate for a number of the relationships with clinical hop distances, which corroborates the extent that hop distance may reflect overall power/strength rather than more nuanced kinematic/kinetic variables (see Supplementary Figure S3 in Supplementary Materials [available online]). Burland et al[29] showed that there was increased variability and no agreement between hop distance symmetry and knee biomechanics on a trial-by-trial basis during TH, indicating that passing clinical tests does not necessarily reflect movement quality. Therefore, it is important for clinicians to consider that hop distance symmetry and performance may not reveal underlying biomechanical issues after ACLR and hop distance during clinical tasks is not a reliable indicator of patients' biomechanics. Studies have demonstrated that force-sensing insoles are closely linked with knee extension moment symmetry during stop jumps in ACLR patients and may enhance the ability to diagnose neuromuscular control deficits before RTS.[30] Enhancing clinical assessments with practical means to capture aspects of patients' kinematics and kinetics during the task may strengthen agreement with the kinematic/kinetic lab-based outcomes and cognitive-motor interference.

It is important to acknowledge the limitations of this study. This paper focused on specific jump landing tasks; however, these are not representative of all movements related to second ACL injury. Therefore, future studies can focus on different tasks, such as single-leg landing, or more similar cognitive-motor challenge tasks for both clinical and lab assessments. For the clinical tests, we focused on the hop distances, however there are some other factors that can be used in future projects, such as reaction time, cognitive errors (task prioritization), and physical errors (landing stability). Furthermore, investigating the optimal timing for integrating cognitive-motor function assessments into the rehabilitation process and return to sport decision making is an avenue worth exploring.

Conclusions

This study aimed to determine the ability of clinical DT tests to capture changes in DTCs in biomechanical risk factors during laboratory testing. Correlations were more pronounced when examining ST and DT performances separately, rather than focusing solely on within-subject DTCs. Our results underscore the importance of considering individual performance on clinical tests within specific conditions particularly in relation to hop performance. Furthermore, correlations between PROs and clinical test performance highlight the potential clinical relevance of subjective experiences in the rehabilitation process.

Acknowledgments

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CHAPTER FOUR

BIOMECHANICAL CONSEQUENCES OF UNBALANCED JUMP LANDINGS

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

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Contributions: Conceptualization, Testing, Data collection, Formal analysis, Investigation, Visualization, Methodology, Manuscript preparation

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Contributions: Study design, Data interpretation, Manuscript preparation

Co-Author: Keith A. Hutchison

Contributions: Data interpretation, Manuscript preparation

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Contributions: Study design, Data interpretation, Manuscript preparation

Co-Author: Scott M. Monfort

Contributions: Study design, Data collection, Data processing, Data analysis, Data interpretation, Manuscript preparation

Manuscript Information

Fatemeh Aflatounian, James N. Becker, Keith A. Hutchison, Corey A. Pew, and Scott M. Monfort

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Abstract

Background:

Anterior cruciate ligament (ACL) injuries often occur in dynamic sport situations requiring rapid, unanticipated decisions. Traditional laboratory assessments such as the drop vertical jump (DVJ) are limited by their predictable nature and may not capture the cognitive and temporal challenges that contribute to injury risk. Failed or unbalanced landings during cognitively demanding tasks are commonly discarded, yet they may provide critical insight into neuromuscular control breakdowns relevant to injury mechanisms.

Purpose:

To examine the relationship between unbalanced landing performance and knee biomechanics associated with ACL injury risk across varying levels of cognitive challenge and to determine whether available time to react (ATR) influences these outcomes.

Methods:

Forty-one physically active adults (17 female, 24 male; 23.7 ± 3.7 years) performed single-leg and double-leg jump landings from a 30 cm box under three conditions: Baseline (anticipated), Simple (directional cue, three choices), and Complex (contextual cue, five choices). Motion capture and force plate data quantified peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and peak knee abduction moment (pKAbM). Mixed-effects models tested effects of Condition (Baseline, Simple, Complex), Success (Successful vs. Unbalanced), and their interaction, with ATR evaluated as a covariate.

Results:

Unbalanced trials demonstrated significantly greater pKAbA ($p = 0.033$) and pKAbM ($p = 0.043$) than successful trials, indicating riskier frontal-plane knee mechanics. Cognitive-challenging conditions (Simple and Complex) produced increased pKFA, pKAbA, and pKAbM compared to Baseline ($p < 0.05$).

Conclusion:

Unbalanced landings under cognitive load reveal high-risk knee biomechanics that may be masked when only successful trials are analyzed. Including these trials provides a more comprehensive assessment of ACL injury risk and highlights the importance of decision-making and reaction-time constraints in dynamic sport environments. These findings support incorporating cognitive–motor challenges into screening and injury-prevention programs to better reflect real-world movement demands.

Introduction

Anterior cruciate ligament (ACL) injuries are among the most prevalent and costly sports-related injuries, with more than 120,000 cases occurring annually in the United States [1, 2]. Most ACL injuries occur through noncontact mechanisms, often during cutting, pivoting, or landing maneuvers that demand rapid responses to an external focus [3]. These injuries carry significant consequences, including long rehabilitation, risk of reinjury, and early-onset osteoarthritis [4].

To evaluate injury risk, researchers frequently use controlled laboratory tasks such as the drop vertical jump (DVJ) to assess neuromuscular control [5-11]. While informative, these tasks do not consider all aspects of human performance because they are performed in predictable, pre-planned environment. In contrast, real-world sport requires athletes to make rapid, unanticipated decisions while dividing attention among multiple external stimuli. This mismatch highlights a gap in current assessment approaches.

To better simulate game-like conditions, some protocols incorporate cognitive challenges, such as directional cues requiring rapid decision-making to jump in a secondary direction upon landing from the initial jump [5, 12, 13]. Notably, these protocols often yield “failed” or unbalanced trials, where participants respond incorrectly to the directional cue. Traditionally, such trials are discarded in an attempt to analyze a cohesive set of representative successful trials. Yet, excluding the failed trials may overlook critical insights. Failed trials may indicate poor neuromuscular control and increased re-injury risk [14]. These failures often reflect deficits in delayed muscle activation and reduced joint stabilization, rather than random occurrences or participant error [14]. These findings underscore the potential of failed landings to reveal impairments in dynamic postural control that may not be captured during successful trials [14].

Including these trials may therefore improve the understanding of the complexity of environmental validity in laboratory assessments and offer a more complete view of athletes' responses under cognitive load. Therefore, the purpose of this study was to examine the relationship between unbalanced landing trials and outcomes linked to ACL injury risk across varying cognitive challenges. We hypothesized that unbalanced trials, especially under higher cognitive demand, would be associated with riskier knee biomechanics related to risk of ACL injury, such as decreased peak knee flexion angle (pKFA), increased peak knee abduction angle (pKAbA), and increased peak knee abduction moment (pKAbM), compared to successful trials.

Methods

Participants

Forty-one active individuals 18 to 35 years old participated in this study (Table 1). Eligibility for participating in this study was having experience playing basketball, being right limb dominant (the preferred leg for kicking a ball [15]), being physically active by running, cutting and pivoting at least twice a week based on their Marx activity scale [16], and having a Tegner scale of more than 5 [17, 18], so that they were active athletes. Moreover, the participants did not have any prior lower-extremity surgeries or ligament tears, lower-extremity injuries within the past three months, or a concussion within the past six months. All the participants signed a consent form approved by the institutional review board of Montana State University (protocol No. #2024-1360). This analysis is based on data collected in a single ~2.5-hour data collection.

Table 1: Cohort characteristics (Average ± Standard deviation)

Female/Male	17/24
Age (years)	23.7±3.7
Height (m)	1.7±0.1
Mass (kg)	72.6±12.1
Tegner Score	6.8±1.3
Marx Activity Score	10.3±3.5

Drop Landing Task

Eight markerless motion capture cameras were used to record the data at 100 Hz (Qualisys Miqus Video cameras, Qualisys AB, Gothenburg, Sweden) and force plates to record ground reaction force data at 1000 Hz (OPT464508-2K; Advanced Mechanical Technology, Inc; Watertown, MA) by using Qualisys Track Manager (QTM-Qualisys AB, Sweden, v2024.3 and v2025.1). Before starting the jump-landing protocol, participants did two sets of 8 bodyweight squats and 5 maximal effort vertical jumps as a warm-up [7].

Kinematics and ground reaction force data were collected as participants performed a jump landing from a 30 cm box over a distance of one third of their height to the edge of the force plates, followed by landing on left, or right leg, or double-leg landing following by jump up as high as possible. The movement was performed under three conditions (Figure 5). Conditions included: Baseline (Baseline, anticipated landing, no cognitive task), Simple cognitive task (Simple, landing on the limb towards an image on one side of the screen), Complex cognitive task (Complex, landing on the limb towards a picture of a basketball or away from a picture of a simulated opponent, displayed on one side of a screen). Participants were given 450 ms for the Simple task

with having three options to react (i.e., left limb, right limb, or bilateral landing). For the Complex task, we used Hick's Law to adjust the reaction time with having five choices (i.e., left/right limb opposite of opponent image, left/right limb toward the ball, or bilateral) rather than three, therefore the given time was 582 ms for this condition. These times were chosen for unanticipated conditions based on pilot testing to achieve a task difficulty that allowed for a portion of decisions to be incorrect while not being too challenging and result in participants simply guessing. Because the single-leg task requires athletes to coordinate both the directional decision and the landing strategy, slightly longer cue durations were necessary compared to bilateral jump-landing protocols used previously in the literature [19]. This approach produced the error rates of 25.0% ± 16.8% for the Simple condition and 34.3% ± 16.9% for the Complex condition, compared to 23.6% ± 18% failure rates observed in a previous study involving bilateral jumps during unanticipated condition [20].

For the Simple condition, 15-20 trials, and for the Complex condition, 20-25 trials were targeted for each participant to have enough variety of data for unbalanced and good trials (Supplemental Table 1). The order of the drop jumping tasks was randomized for each participant.

After completing all jump-landing tasks, participants completed the NASA Task Load Index (NASA-TLX) to assess their perceived mental and physical demands, time pressure, perceived performance, and effort. Each factor was rated individually on a 21-point scale ranging from 0 (very low demand) to 20 (very high demand) [21].

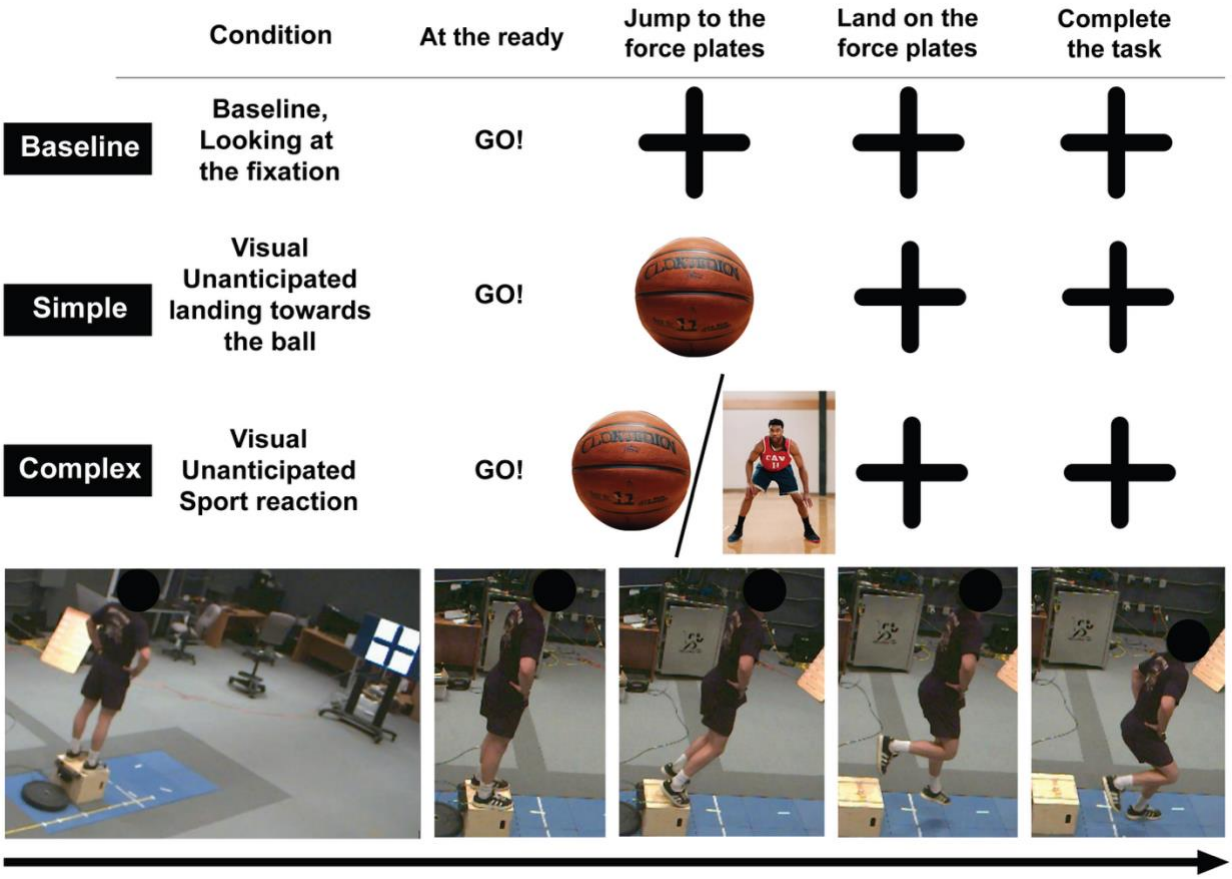


Figure 5: Jump-land-jump task progression for all conditions. The image sequence of participant demonstrates the response for landing on the limb (left) that aligned with the side of the screen that the ball image was displayed.

Trials Categorization: Successful, Unbalanced and Failed.

Trials were categorized as successful, unbalanced, or failed. Successful trials were described as trials in which participants were able to land on the correct limb and keep their balanced for 2 seconds while keeping their hands on their hips during single-leg landings or correctly complete a bilateral jump upon landing in response to the basketball hoop. Unbalanced trials were those when participants landed on the correct limb but were unable to maintain their

balance for 2 seconds, participants' hands did not remain on their hips, or participants' torso tilted more than 45 degrees relative to the lab coordinate system. Failed trials were those where participants reacted incorrectly to the cue (e.g., landing on the right limb but the correct response was to land on the left limb) or tried to land on the correct limb but touched the ground with the other limb in less than 0.25 seconds in single-leg landings.

Data Processing

Motion capture and force plate data were processed using Theia3D (Theia Markerless Inc., Kingston, ON, Canada, v2024.1.19) following by analyzing using Visual3D (HAS-Motion; Kingston, Ontario). Marker and force data were filtered using a fourth-order, zero-lag, low-pass Butterworth filter with 20 Hz cutoff frequency [22].

Kinematic and kinetic data were computed using the Theia3D full-body framework, using the Apollo model with enabling the internal/external rotation for knee joint, but not six degrees of freedom for shoulders and ankles. The lower extremity segments were defined with the z-axis oriented from the distal to the proximal joint centers, the y-axis pointing anteriorly, and the x-axis directed to the participants' right. A Cardan x-y-z rotation sequence corresponding to (+) flexion/ (-) extension, (+) adduction/ (-) abduction, and (+) internal/ (-) external rotation, respectively, was used to calculate the knee joint angles. For kinetic variables, forces were normalized to participant weight and moments were normalized to both weight and height. Initial contact was defined as the first frame in which the force plate reading exceeded 10 N following the initial jump off of the box.

Outcome Variables: Primary ACL Injury Risk Factors

Previous video analysis has identified additional biomechanical factors linked to primary ACL injuries that occur within the first 100 ms after initial contact with the force plate during jump landing tasks [23, 24]. The outcomes were peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and externally defined peak knee abduction moment (pKAbM). Less knee flexion and increased abduction were interpreted as risky given their association with increased ACL loading [23, 25, 26]. All outcome variables were calculated for dominant limb (right limb) during successful and unbalanced trials on single-leg landing for the dominant limb. Custom MATLAB code (version R2024b; MathWorks, Natick, MA) was used to isolate the ACL injury risk factors and prepare outcome variables for statistical analysis.

Power Analysis

An a priori power analysis was conducted in GLIMMPSE (v3.1.3 [27]) for a within-within linear mixed effect model with a 3 × 2 repeated-measures design: Condition (Baseline, Simple, Complex) × Success (Successful, Unbalanced). Each participant contributed six repeated measurements per biomechanical outcome (pKFA, pKAbA, pKAbM). The test statistic was Hotelling's Lawley Trace, with $\alpha = 0.05$ and target power = 0.80. We specified mean patterns that reflected clinically meaningful differences across Condition × Success: approximately 4–5° in pKFA, 2–3° in pKAbA, and 2–3% in pKAbM [5, 7, 19]. These hypothesized cell means (and the assumed covariance) were entered directly into GLIMMPSE for each outcome to evaluate power for the Condition × Success interaction in the repeated-measures model. Under these assumptions, GLIMMPSE estimated that $n = 37$ participants would provide 80% power to detect the hypothesized within–within interaction at $\alpha = 0.05$.

Statistical Analysis

Mixed effect statistical models tested for Condition*Success interactions as well as main effects of Condition and Success. The individual was considered as a random factor. Condition, Success, and Condition*Success interaction were fixed factors. The primary comparison of interest was in the Condition*Success interaction. Significance was set at $\alpha=0.05$. Clinical and performance factors such as age, height, Marx activity score, and Effort factor from NASA TLX were considered as potential covariates.

The data underwent an initial evaluation to check for assumptions such as normality and homogeneity of variance, as well as the presence of outliers and systematic bias to ensure the validity of the analyses. We calculated the variables of dominant limb of the participants (right limb) during successful and unbalanced trials of the dominant-limb single-leg landings.

For post-hoc analyses, participants with more than 60% failed trials in the Complex condition or unusually long reaction times (indicating delayed movement after seeing the cue) were excluded to ensure expected task engagement and reduce bias from guessing or slow responses. After removing four participants, the model was re-run to confirm consistency of results. In a separate exploratory model, the difference between actual available time to react (ATR), the time measured from seeing the cue until initial contact with force plates, and the target time (450 ms for Simple, and 582 ms for Complex condition), considered as ART-Target, was added as a covariate to assess its effect on performance outcomes. This model was designed to examine whether participant-specific differences in ATR better explained variability in performance outcomes during unanticipated tasks.

Results

The results are based on averages of good trials and unbalanced trials for each biomechanical outcome variable for each condition and each participant (Supplemental Table C1). The available data were 219 averages trials remained for analysis. The initial dataset included 246 trials (41 participants × 3 conditions × 2 success levels). 18 participants in the Baseline condition and 6 participants in the Simple task had not existed because participants did not perform unbalanced trials during these tasks, and 3 data points were removed due to participants' feet landing outside the force plates upon post-processing review (Supplemental Table C2).

No significant Condition*Success interactions were detected. Significant differences between unbalanced and successful trials were observed for pKAbA ($p=0.033$) and pKAbM ($p=0.043$). Post-hoc analysis (Figure 6) indicated more pKAbA for the unbalanced trials (-4.04±0.37) compared to successful trials (-3.26±0.36), and greater pKAbM for the unbalanced trials (5.63±0.24% BW-HT) compared to successful trials (5.27±0.20% BW-HT). Condition differences were observed for all biomechanics factors, pKFA ($p=0.027$), pKAbA ($p<0.001$), and pKAbM ($p<0.001$) (Table 2). Post-hoc analysis (Figure 6) indicated an increase for pKFA (more flexion), a decrease for pKAbA (more abduction), and increase in pKAbM for cognitive-challenging conditions compared to Baseline, specifically between Complex and Baseline for pKFA (Complex: 55.00±6.36° and Baseline: 53.14±5.94°), pKAbA (Complex: -3.69±0.42° and Baseline: -2.92±0.41°), and pKAbM (Complex: 5.89±0.26% BW-HT and Baseline: 4.58±0.22% BW-HT), and between Simple and Baseline for pKAbA (Simple: -4.10±0.49° and Baseline: -2.92±0.41°) and pKAbM (Simple: 5.66±0.28% BW-HT and Baseline: 4.58±0.22% BW-HT). However, there were no significant differences between Simple and Complex conditions for any

of the variables (pKFA: p=0.525; pKAbA: p=0.102; pKAbM: p=0.609). These findings persisted regardless of including covariates in mixed effect models (Table 3).

Table 2: *p*-values for mixed effect models for main analysis. Presented outcomes are based on statistical models without covariates.

	Success	**Condition**	**Success*Condition**	**R^2_{adj}**
pKFA	0.223	**0.027**	0.375	85%
pKAbA	**0.033**	**<0.001**	0.258	90.5%
pKAbM	**0.043**	**<0.001**	0.848	70%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment.

Table 3: *p*-values for mixed effect models for main analysis. Presented outcomes are based on statistical models with 'age, height, Marx activity score, and Effort factor from NASA TLX" as covariates. There was no significant effect from the covariates.

	Success	**Condition**	**Success*Condition**	**R^2_{adj}**
pKFA	0.282	**0.037**	0.459	85%
pKAbA	**0.047**	**<0.001**	0.240	90.5%
pKAbM	**0.035**	**<0.001**	0.894	70%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment.

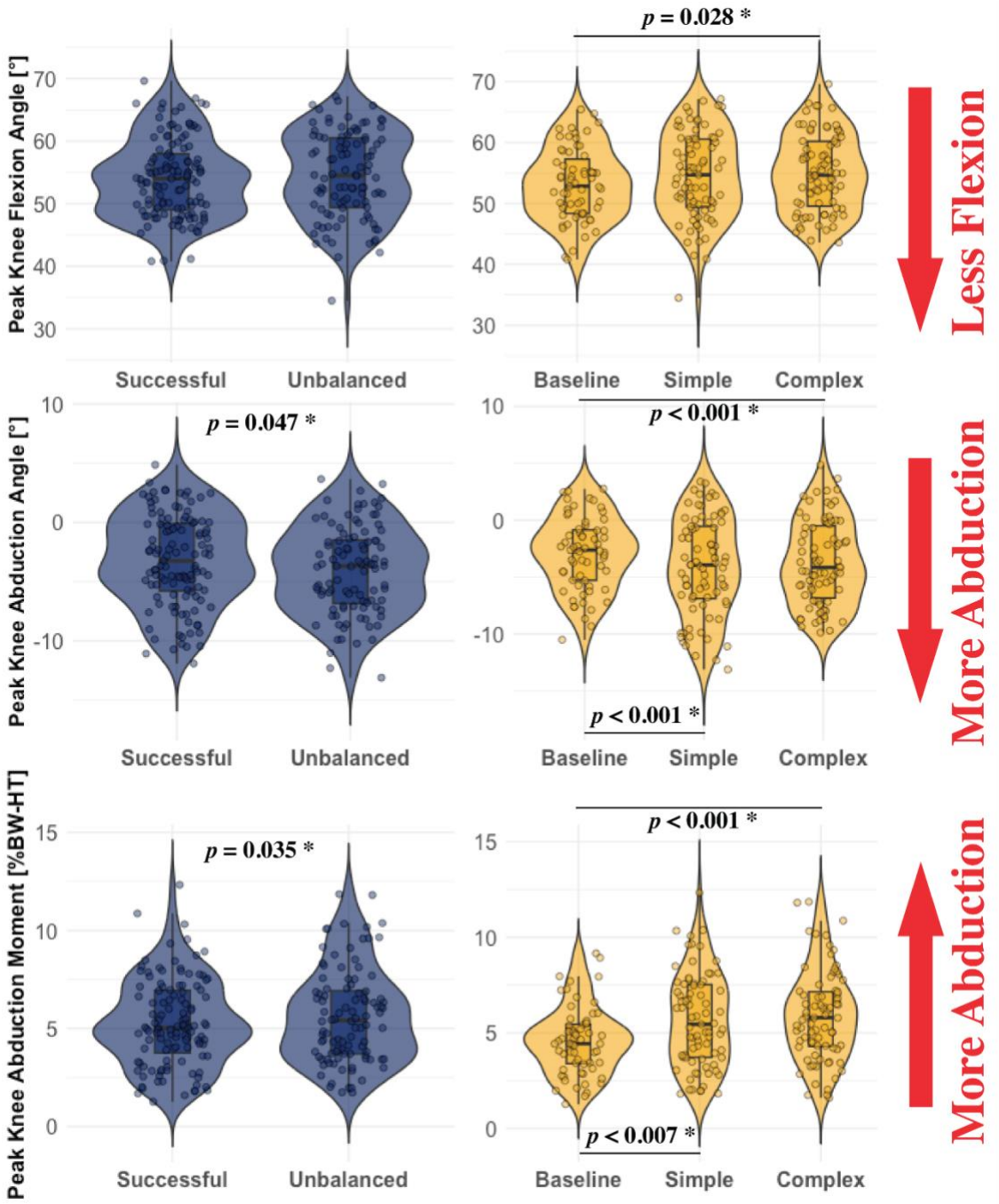


Figure 6: Left: Violin plots for the effect of Success on ACL injury risk factors; Right: Violin plots for effect of Condition on ACL injury risk factors. Abbreviation: %BW-HT: Normalized to body weight and height.

After running the post-hoc analysis with removing 4 participants, the significant results stayed the same, except losing condition effect for pKAbA without covariates ($p = 0.111$, Table 4) and same with considering covariates ($p = 0.151$, Table 5, Figure 7).

Table 4: p-values for mixed effect models for post hoc analysis with removing 4 participants due to 60% failing or delayed movement. Presented outcomes are based on statistical models without covariates

	Success	**Condition**	**Success*Condition**	**R^2_{adj}**
pKFA	0.127	**0.001**	0.512	86%
pKAbA	0.111	**<0.001**	0.112	90.5%
pKAbM	**0.036**	**<0.001**	0.851	69%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment.

Table 5: p-values for mixed effect models for post hoc analysis with removing 4 participants due to 60% failing or delayed movement. Presented outcomes are based on statistical models with 'age, height, Marx activity score, and Effort factor from NASA TLX" as covariate. There was no significant effect from the covariates.

	Success	**Condition**	**Success*Condition**	$\mathbf{R^2_{adj}}$
pKFA	0.173	**0.001**	0.637	86%
pKAbA	0.151	**<0.001**	0.094	90.5%
pKAbM	**0.029**	**<0.001**	0.820	68%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment.

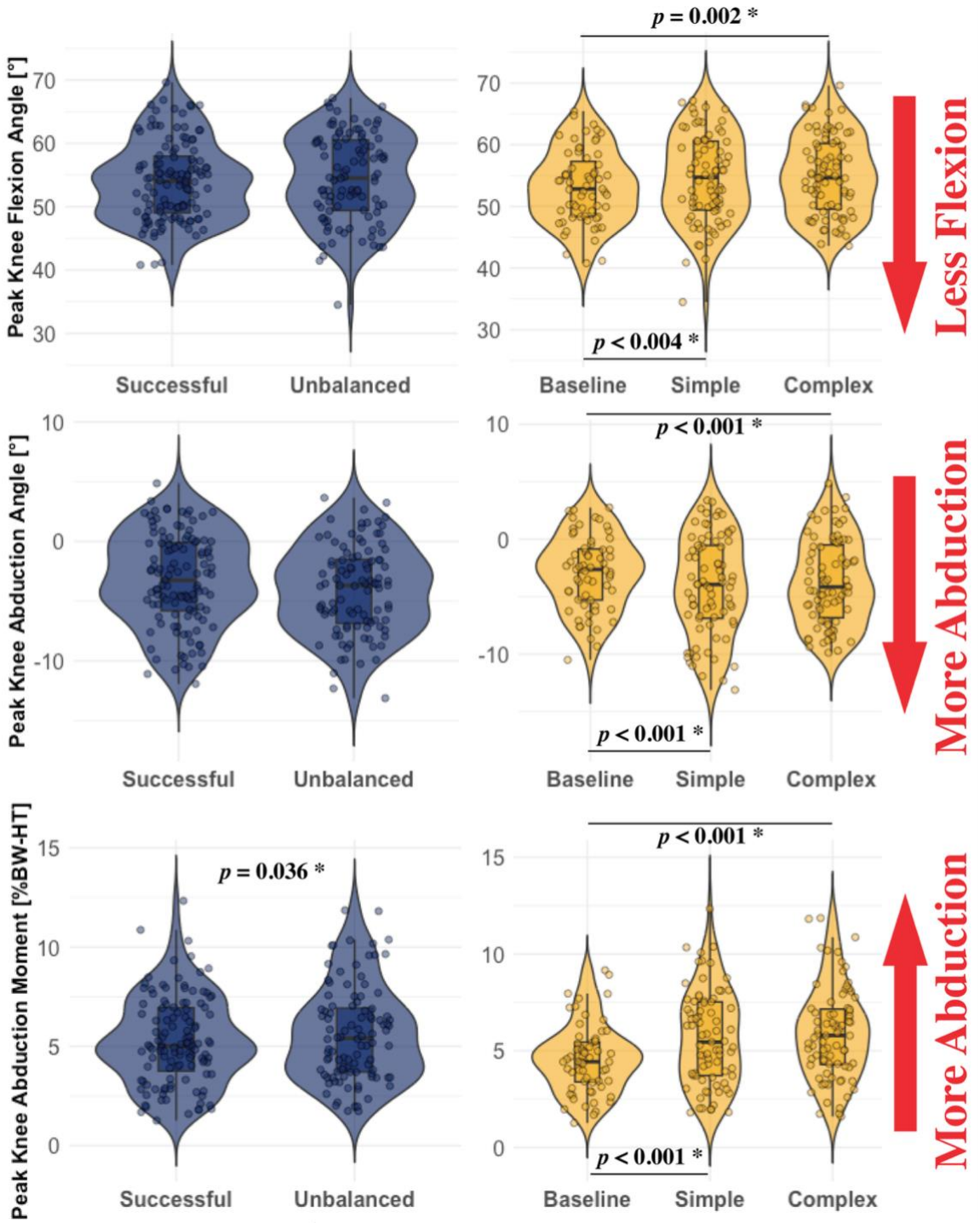


Figure 7: Left: Violin plots for the effect of Success on ACL injury risk factors with removing 4 participants due to 60% failing or delayed movement; Right: Violin plots for effect of Condition on ACL injury risk factors with removing 4 participants due to 60% failing or delayed movement. Abbreviation: %BW-HT: Normalized to body weight and height.

Table 6: Average and standard deviation of biomechanics variables for each condition

	Condition	Successful trials (Average ± Standard deviation)	Unbalanced trials (Average ± Standard deviation)
pKFA [°]	**Baseline**	53.04 ± 5.82	53.31 ± 6.27
	Simple	54.82 ± 6.40	54.11 ± 7.89
	Complex	54.44 ± 6.54	55.57 ± 6.21
pKAbA [°]	**Baseline**	-2.71 ± 3.47	-3.28 ± 2.74
	Simple	-3.77 ± 4.29	-4.44 ± 4.34
	Complex	-3.31 ± 3.85	-4.09 ± 3.57
pKAbM [%BW-HT]	**Baseline**	4.59 ± 1.79	4.56 ± 1.77
	Simple	5.46 ± 2.47	5.85 ± 2.43
	Complex	5.76 ± 2.19	6.03 ± 2.55

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment; BW-HT: normalized to body weight and height.

When ATR–Target was used as a covariate, only the pKAbA Success and Condition effects remained (Table 7), showing more pKAbA for unsuccessful trials (-4.5±4.0°, Figure 6) than successful trials (-3.7±4.1°, Figure 6). ATR-Target additionally explained a significant amount of variance for pKAbA ($p = 0.008$) and pKAbM ($p = 0.038$). These findings suggest that frontal-plane knee mechanics during unanticipated landings may be more sensitive to fluctuations in available reaction time.

Table 7: p-values for mixed effect models for post hoc analysis with removing 4 participants due to 60% failing and delay in response. Presented outcomes are based on statistical models with ATR-Target as covariate.

	Success	**Condition**	**Success*Condition**	**ATR-Target**	**R^2_{adj}**
pKFA	0.87	0.16	0.236	0.084	86.5%
pKAbA	**0.021**	**0.003**	0.942	**0.004**	94.4%
pKAbM	0.166	0.997	0.976	**0.038**	73.0%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment; ATR: available time to react.

Discussion

The present study investigated the effects of unbalanced landings and cognitive challenge on outcomes related to ACL injury risk across challenging cognitive tasks. The main findings revealed that unbalanced trials were characterized by riskier knee mechanics, including higher pKAbA and pKAbM, compared with successful trials. Similarly, cognitive-challenging conditions (Simple and Complex) were associated with greater pKAbA and pKAbM relative to the baseline condition, suggesting that increased cognitive demand influences single-leg jump landing in a way that elevates ACL injury risk. Conversely, there was reduced pKFA for the baseline condition compared to cognitive-challenging conditions, which likely reflects a more smoother landing strategy when cognitive resources are redirected toward decision-making. However, when participants' ATR-Target was included as a covariate, all previously significant condition effects

became non-significant, except for effect of success for pKAbA. This result suggests that ATR is an important factor to consider in cognitive-motor demand tasks. Overall, this study demonstrated clear biomechanical differences between successful and unbalanced landings, as well as between baseline and cognitive-challenging conditions. Importantly, unbalanced trials consistently exhibited higher-risk knee mechanics across all conditions (Table 5), indicating that removing these trials from analysis may mask an athlete's injury-relevant performance. The general pattern of biomechanics was preserved between successful and unbalanced trials, suggesting stable individual tendencies (high correlation between successful and unbalanced trials: pKFA: $r = 0.85$, $p < 0.001$; pKAbA: $r = 0.88$, $p < 0.001$; pKAbM: $r = 0.685$, $p < 0.001$), but the magnitude of risk increased when cognitive load or decision-making demands were added. Thus, including a broader range of trial outcomes provides a more realistic representation of how ACL injury risk emerges under true sport demands.

The present results demonstrate that unbalanced trials exacerbated frontal plane biomechanical factors linked to ACL loading. This finding extends previous work emphasizing the value of analysing unsuccessful trials rather than discarding them. Nishino et al. [28] observed that failed single-leg medial drop landings demonstrated greater thoracic and pelvic lean at initial contact, that these kinematic deviations linked to increased ACL strain. Another study, by Romanchuk et al. [29], reported that failures during unanticipated landings often originated mid-air, implying deficiencies in anticipatory control rather than reactive balance alone. Our study adds another aspect to the findings of these studies by analysing unbalanced movement and suggest that including unbalanced trials in biomechanical analyses may offer a more comprehensive picture of cognitive–motor performance boundaries that may predispose athletes to primary ACL injury.

Condition differences between cognitive challenges and baseline movements further highlight the effects of cognitive challenges on influencing biomechanics during jumping tasks, which may better reflect performance during real-world sport performance. Across conditions, greater cognitive challenge produced increased pKFA and increased pKAbA and pKAbM, adding more evidence to growing literature that cognitive load and attention demand meaningfully alter neuromechanical control during dynamic tasks [30-32]. Monfort et al. [32] reported increased peak knee valgus angle during run-to-cut tasks with dual-task demands, while Hughes and Dai [31] similar changes during jump landings that required quick visual decisions. Decision-making demands during the jump-landing task were associated with biomechanical alterations characterized by reduced peak hip and knee flexion angles, accompanied by increased vertical ground reaction forces, knee abduction, and tibial internal rotation [33]. These findings collectively support the growing evidence that increased cognitive load impairs neuromuscular control, resulting in softer landing, more protective landing mechanics for this variable [7, 31, 34, 35]. The current data extend this literature by examining single-leg jump-landing, demonstrating that decision-making demands resembling athletic scenarios can elicit mechanical patterns associated with elevated ACL loading even in healthy individuals. Such results highlight that the capacity to process sport-relevant information and execute movement safely under cognitive stress is a critical determinant of injury risk. Accordingly, training and prevention programs should incorporate cognitively demanding, and time-pressured tasks to enhance decision-making efficiency and dynamic control. Future studies should evaluate whether integrating these challenges into neuromuscular training paradigms can mitigate risky biomechanics and reduce the incidence of non-contact ACL injuries in athletic populations.

A unique aspect of this study was the explicit quantification of participants' ATR-Target, which revealed that once individuals' ATR-Target was included in the model, and given that the cognitive conditions differed in their prescribed ATRs (450 ms for Simple and 582 ms for Complex), only significant Success and Condition effects were observed for pKAbA. This finding along with the significant relationship for the ATR-Target factor for pKAbA and pKAbM suggest that biomechanical changes often linked to cognitive load may be partly driven by the limited time available for movement preparation and motor planning, highlighting ATR-Target as a potentially important confounder rather than attributing these effects to cognitive processing alone. Interestingly, participants in the present study exhibited shorter ATR during unbalanced trials than during successful ones (Figure 8), indicating that reducing the ATR may become insufficient for reliable perceptual processing and motor planning, leading to a higher probability of unsuccessful landings. Conversely, a slightly longer preparation time appeared to support more coordinated movement control; however, such deliberate delays are not possible in real-world sport situations, where athletes must make instantaneous decisions under pressure. Accordingly, shorter ATR, while behaviorally faster, may increase ACL loading risk by constraining feedforward control and forcing reliance on reactive stabilization strategies. In sport environments, where athletes face both cognitive and time pressures, the trade-off between reacting quickly and maintaining stable movement control may be a key factor contributing to ACL injury risk. Future research on decision-making should concurrently evaluate the effects of reaction-time constraints on movement safety to better inform prevention strategies that integrate cognitive and mechanical aspects of ACL injury risk.

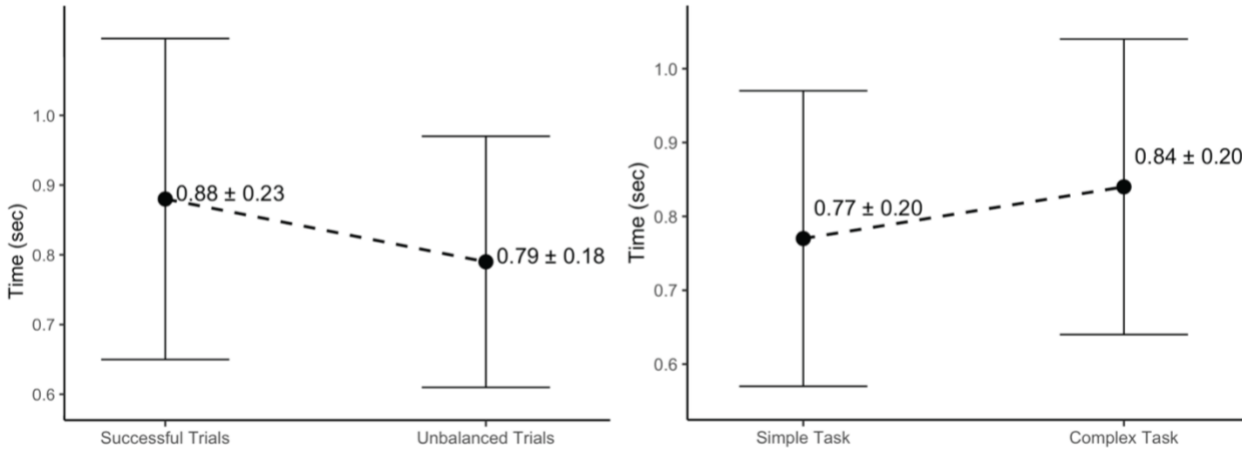


Figure 8: Average reaction time (seconds) for the participants in different conditions (right panel) and successful and unbalanced trials (left panel).

The results of this study underscore the need for integrated cognitive–motor approaches to ACL injury prevention. Traditional pre-screening and training programs typically assess movement mechanics in controlled and predictable settings, overlooking the cognitive and temporal complexities that characterize real sport environments [36]. Decision-making failures during reactive jump or cutting maneuvers likely replicate the conditions under which ACL injuries occur, making them critical to understanding primary injury mechanisms. However, our findings also suggest that individuals generally maintain similar patterns of knee mechanics across Simple, and Complex conditions, even as risk magnitude increases with cognitive challenge (high correlation between successful and unbalanced trials: pKFA: $r = 0.85$, $p < 0.001$; pKAbA: $r = 0.88$, $p < 0.001$; pKAbM: $r = 0.685$, $p < 0.001$). This implies that athletes might maintain relative performance across unanticipated challenging jump-landing tasks. Consequently, instead of removing unbalanced trials, including them can give a more complete picture of movement quality and when injury risk is highest. Longitudinal studies tracking athletes across training cycles could

establish whether baseline reaction-time and condition interactions predict actual ACL injury incidence. From an applied perspective, injury-prevention programs should include decision-making and time-pressured dual-task training to enhance attentional control, perceptual speed, and movement efficiency. Monitoring failed or unbalanced performances throughout these interventions may serve as a sensitive indicator of developing cognitive–motor resilience. Collectively, these directions advance a neurocognitive–temporal model of ACL injury, recognizing that perceptual decision-making and available time to react jointly shape mechanical risk.

It is essential to acknowledge the limitations of this study. First, the present laboratory-based jump-landing paradigm cannot fully replicate the complexity of real-world sport environments, where factors such as fatigue, opponent movement, and multitarget decision demands may further influence outcomes. Second, no corrections for multiple comparisons were made for this initial investigation, and therefore the risk of Type I error may be elevated, and borderline significant findings should be interpreted with caution. Third, ATR was evaluated post hoc; future studies should manipulate and control this variable experimentally to clarify causality. Fourth, our sample comprised healthy participants with basketball experience, which may limit generalization to athletes with prior injuries or different competitive levels. Fifth, the study focused on lower-limb biomechanics; future work integrating neural and visual-perceptual measures (such as eye-tracking) could illuminate underlying mechanisms of decision-making and attention control. Despite these limitations, the present results provide novel evidence that studying unbalanced trials during cognitive challenging movements are essential to understanding, and ultimately preventing, primary ACL injuries.

Conclusion

This study demonstrates that unbalanced jump-landing trials may provide important insight for ACL injury research, as they may represent situations in which athletes fail to maintain postural control under cognitive demands. Unbalanced trials showed riskier knee mechanics than successful trials, particularly in knee abduction loading, suggesting their inclusion may improve the identification of movement patterns associated with primary ACL injury risk. Cognitive-challenging conditions also influenced knee biomechanics compared with baseline jumping, highlighting the relevance of incorporating decision-making elements into biomechanical screening and injury-prevention training.

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CHAPTER FIVE

DO MEASURES OF ATTENTION CONTROL PREDICT DECISION-MAKING PERFORMANCE ON A REACTIVE JUMP LANDING TASK?

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Manuscript Information

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Abstract

Background:

Noncontact ACL injuries often occur during rapid, unanticipated movements that involve both cognition and motor control. In these moments, deficits in attention or decision-making can directly influence landing mechanics. Although unanticipated jump-landing paradigms capture these demands, failed or incorrect responses ("Failed%") are frequently discarded, potentially obscuring links between cognition and movement errors.

Purpose:

To determine whether individual differences in cognitive performance, attention control (AC) and choice reaction time (RT), are associated with decision-making failures during cognitively challenging, unanticipated jump-landing tasks in healthy athletes.

Methods:

Forty-one recreationally active adults (17F/24M; 23.7 ± 3.7 y) completed baseline cognitive testing (Reaction Time (RT); Attention Control (AC) via Stroop-Squared, Flanker-Squared, Simon-Squared) and performed drop jump-landings under anticipated (Baseline) and unanticipated conditions (Simple, Complex). Failed landings were trials with incorrect cue responses, such as landing on the wrong limb, or put the other foot down in less than 0.25 seconds. Cognitive variables were standardized; RT z-scores were sign-reversed and averaged with AC to form a Composite Z-score. Spearman correlations tested associations between cognitive measures (AC, RT, Composite) and Failed% for Simple and Complex conditions.

Results:

Across all 41 participants, no significant associations were observed between Failed% and AC or RT ($p > 0.05$). The Composite Z-score correlated modestly with Complex Failed% ($r = -0.319$, $p = 0.042$); Simple Failed% showed no associations. After excluding four participants, the Composite–Complex relation persisted ($r = -0.35$, $p = 0.034$), and AC showed a significant negative correlation with Complex Failed% ($r = -0.34$, $p = 0.042$). Descriptively, Simple and Complex failure rates were correlated, but only the higher-demand Complex condition exposed cognition–performance links.

Conclusions:

In healthy athletes, better composite cognitive performance, driven by attention control, was weakly associated with decision-making errors during high-demand unanticipated landings. However, attention control and RT alone did not fully explain variability in failures, underscoring that cognition–movement coupling is multifactorial and task-dependent. Future work should assess attention control within movement-embedded and examine whether targeted cognitive-motor training reduces landing errors and ACL-relevant risk mechanics under time pressure.

Introduction

Anterior cruciate ligament (ACL) injuries are among the most common and devastating injuries in sport, often leading to long rehabilitation timelines, decreased performance, and elevated risk of reinjury [1, 2]. Approximately 70% of ACL injuries occur in non-contact situations, typically during sudden cutting, pivoting, or landing maneuvers [3-5]. These injuries often arise within 100 milliseconds after contact with the ground, leaving athletes little time to make corrective adjustments to misplaced steps or potentially injurious movements [6]. A growing body of evidence suggests that such injuries cannot be explained solely by the biomechanics surrounding the event but rather are multifactorial in nature.

Increasing cognitive demands during movement appear to challenge neuromuscular control, highlighting cognition as a key factor contributing to ACL injury risk [7, 8]. Two neurocognitive components, attention control and reaction time, play central roles in how athletes perceive, process, and respond to environmental cues under time pressure. Attention control is a core executive function that allows individuals to selectively focus on relevant cues while suppressing distractions and competing responses [9]. This function has been proposed as the mechanism linking working memory and fluid intelligence and may play a pivotal role in multitasking and dual-task performance [9-11]. In sport, athletes are constantly required to attend to rapidly changing stimuli, such as the position of opponents or the trajectory of a ball, while maintaining precise motor strategies [12]. When visual attention is diverted or constrained, athletes may struggle to react effectively, resulting in altered landing mechanics during challenging jump-landing tasks [13].

Reaction time, often measured through simple or choice response tasks, reflects the speed of cognitive processing from stimulus detection to action selection. Shorter reaction times indicate greater processing efficiency, whereas slower reaction times may signal difficulty integrating perceptual information and selecting the correct motor response [14, 15]. Thus, understanding how processing speed and decision-making interact is essential for modeling how cognitive load influences athletic movement.

Unanticipated jump landing tasks have been widely adopted as an experimental paradigm to simulate the conditions under which non-contact ACL injuries occur [13, 16]. In these tasks, athletes are required to process reaction cues and adjust their movements within milliseconds, placing simultaneous demands on cognitive processing and motor control. Variability in performance during these tasks reflects differences in individuals' ability to process visual information and coordinate landing mechanics. The trials that participants failed to react correctly usually removed from biomechanics study, however, these failed trials have been proposed as markers of impaired neuromuscular control and greater injury risk [10, 17, 18]. Therefore, unanticipated jump-landing paradigms provide a valuable framework for examining how cognitive decision-making and motor execution interact under time pressure, helping to reveal the cognitive contributors to movement errors that may elevate ACL injury risk.

Therefore, the purpose of this study was to investigate the relationship between attention control and landing performance in cognitively demanding, unanticipated jump landing tasks. We hypothesized that individuals with worse attention control would commit a greater number of landing errors, reflecting reduced ability to allocate cognitive resources under dual-task conditions and potentially higher risk to ACL injury.

Methods

Participants

Forty-one healthy athletes (17F/24M, 23.7±3.7 yrs; 1.74±0.10 m; 72.56±12.12 kg; Tegner: 6.8±1.3; Marx: 10.3±3.5) completed cognitive tasks and a drop jump task under anticipated and unanticipated conditions. To be eligible for participation, individuals had to be physically active by running, cutting and pivoting at least twice a week [19], and have a Tegner score of greater than 5 [20], indicating that they were recreational athletes. Additionally, individuals could not have undergone any lower-extremity surgeries, had any ligament tears, had lower-extremity injuries within the past three months, or had a concussion within the past six months.

Cognitive Tasks

Upon obtaining informed consent and verifying participant eligibility, the participants completed four cognitive tests including to choice reaction time (Figure 9) [21] and attention control tasks (AC) to determine baseline cognitive performance related to decision making (Figure 10) [22]. The tasks were instructed using E-Prime (Psychology Software Tools, Pittsburgh, PA, 2020). In the choice visual reaction time test (RT), participants press “F” on a computer keyboard as soon as they saw a square, or “J” as soon as they saw a circle for 25 sec of practice following with one trial with duration of 180 seconds (Figure 9). The RT scored calculated based on the average of time to react to the cue that appeared during that 180-second trial. Attentional control tasks required participants to focus attention while suppressing distraction. We used three efficient, reliable and valid tests related to attention control which are recently introduced as strongly defining an attention control latent factor: Stroop Squared, Flanker Squared, and Simon Squared

tasks [11]. These tests are scientifically rigorous, with high test-retest reliability (average of reliability of component scores, r = 0.67 [11]). In the Stroop Squared task, participants identified the printed color of a word while ignoring its semantic meaning. The Flanker Squared task required reporting the direction of a central arrow while ignoring surrounding distractors. The Simon Squared task required responding to arrow direction irrespective of screen location. Each test lasted 90 seconds, with participants completing a practice round and 30 seconds seated baseline prior to testing (Figure 10). Performance scores for the AC tests were calculated as the number of correct responses minus incorrect responses. Scores were weighted according to published factor loadings (Stroop = 0.58, Flanker = 0.64, Simon = 0.82) [11] and summed to yield a composite attention control score, with higher values reflecting better performance.

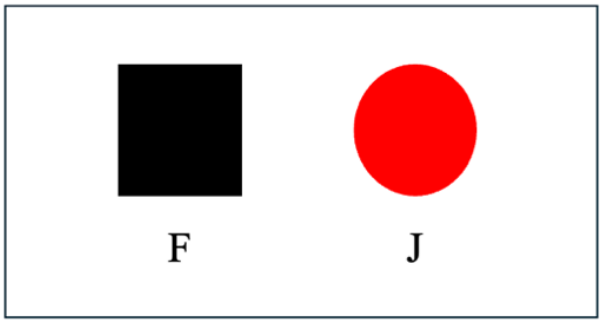


Figure 9: Choice reaction time task as a secondary parameter, pressing the “F” keyboard key for square cue, and the “J” key for circle cue



Figure 10: Attention control tasks: Stroop Squared, Flanker Squared, and Simon Squared tasks.

For a more comprehensive perspective of participants' cognitive performance, a composite Z score for individual's reaction time and attention control was computed. A composite cognitive performance score was first converted into standardized Z scores using sample mean and standard deviation of each variable of choice reaction time and attention control ($z = (x - \mu)/\sigma$), where x represents the individual participant's raw score, μ is the sample mean for that variable, and σ is the corresponding standard deviation [23]. The z-score for reaction time was negated to code better performance (i.e., shorter reaction times) to more positive z-scores. A composite Z score was then derived by averaging the two standardized values [23], giving a single index representing main cognitive–motor processing efficiency (i.e., relatively better at both AC and RT tasks corresponded to higher composite z-scores).

Unanticipated Challenging Jump-Landing Protocol

During the movement task, participants performed a jump landing from a 30 cm box, located 1/3 of their height from the edge of the force plate, followed by landing on their left or right leg (with a subsequent 2 second hold), or bilateral landing followed immediately with a vertical jump as high as possible. Unanticipated conditions included two conditions of Simple and Complex tasks. A simple cognitive task (Simple, Figure 11) of landing on the limb towards a basketball image on one side of the screen or double-leg landing following jumping up when seeing a basketball hoop. A complex cognitive task (Complex, Figure 11) of landing on the limb

towards the picture of the basketball or away from a picture of a simulated opponent, or double-leg landing with jumping straight up when seeing a basketball hoop. The cues were programmed for unanticipated conditions by using E-Prime (Psychology Software Tools, Pittsburgh, PA, 2020). Failed trials were defined as trials where participants reacted incorrectly to the cue and landed on the wrong leg(s). The percentage of failed trials (Failed%) was calculated for both simple and complex jump-landing tasks in unanticipated conditions. The order of the drop jump tasks was randomized for each participant.

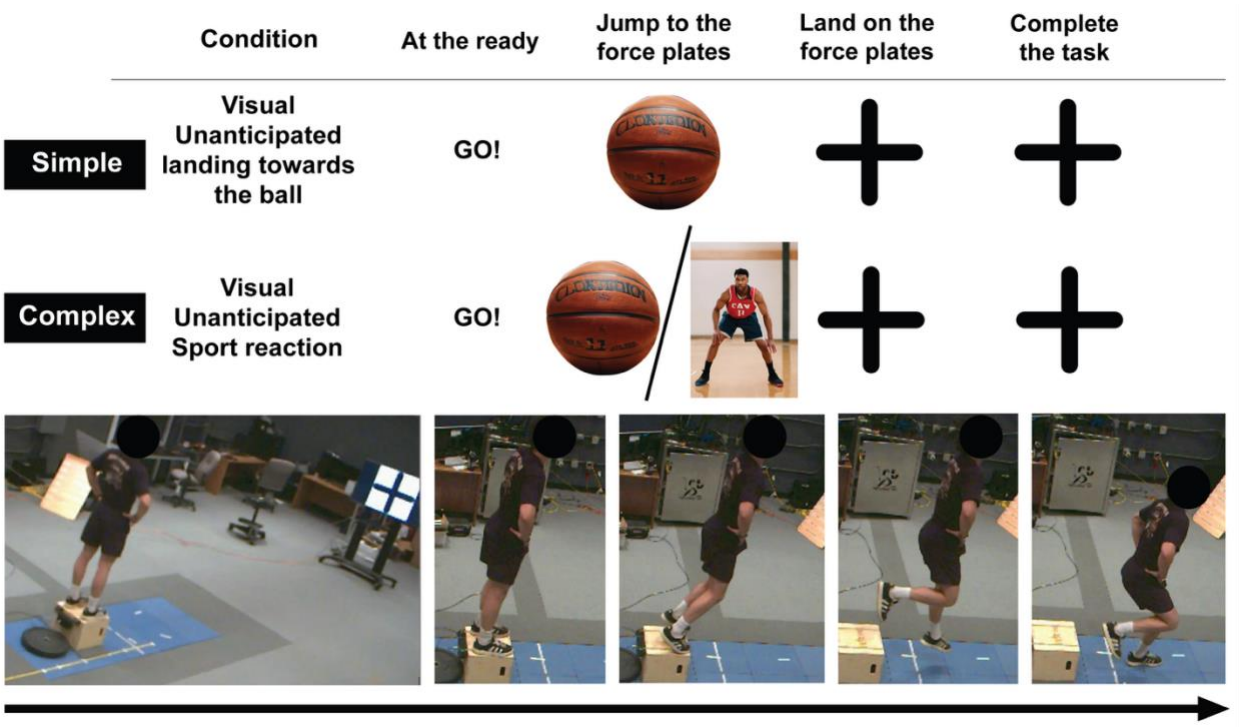


Figure 11: Jump-landing conditions of Simple challenge and Complex challenge

Power Analysis

A priori power analyses were conducted in G*Power (v3.1) for two-tailed bivariate correlations with $\alpha = 0.05$ and $1-\beta = 0.80$. Prior research [11, 24] suggests that attention control often correlates strongly with cognitive and multitasking measures ($r = 0.5$), we assumed medium effect size of interest ($r = 0.46$). For comparing cognitive tasks and Failed%, a sample size of $n = 32$ provides more than 80% power at $\alpha = 0.05$.

Statistical Analysis

After running a normality test of Anderson-Darling, cognitive tasks variables were not normally distributed, therefore the Spearman correlations were used to test the relationship between the baseline cognitive performance and Failed% calculated from two "Simple" and "Complex" drop landing conditions. Failed% served as the primary outcome, and its correlations with cognitive task measures (AC, RT, and composite z-score) were analyzed to evaluate the study hypothesis.

For post-hoc analysis, we aimed to guard against biased outcomes due to the potential for participants guessing or delaying their reactions rather than unaffected task performance. Participants who exhibited more than 60% failed trials in the complex condition were excluded, as such high failure rates could result from random guessing rather than purposeful responses (given the three possible landing options, consistently choosing the same limb could yield approximately 66% failed trials by chance). In addition, participants who showed long reaction times (waiting to see the visual cue before initiating movement) were also removed. E-Prime program showed the cue based on the designed task, and the time that the cue showed up was recorded in the motion capture software during data collection. Reaction time was determined

using E-Prime event markers for the cue and force plate data, allowing precise detection of landing onset relative to cue presentation.

Results

The results are based on 41 participants and post-hoc analysis with 37 participants after removing potential outliers based on high Failed% (guessing) or showing delay to react to the cue with low Failed% (Table 8). There were no significant correlations between Failed% for either condition with cognitive tasks performance during attention control and choice reaction time ($p > 0.05$, Figure 12). However, the correlation between Composite Z-score and Complex Failed% was significant ($r = -0.319$, $p = 0.042$, Figure 13), indicating that lower cognitive performance was associated with more failed landings. Additionally, the correlation between AC and Complex Failed% was trending to a negative correlation ($r = -0.29$, $p = 0.07$, Figure 13).

Table 8: Average of interested variables

	Score (Average ± Standard deviation) for complete dataset (n = 41)	Score (Average ± Standard deviation) with removing the questionable participants (n = 37)
Attention Control (AC)	108.70 ± 16.39	109.94 ± 16.13
Stroop Squared Task	40.12 ± 12.32	41.02 ± 12.05
Flanker Squared Task	42.36 ± 11.62	42.73 ± 11.82
Simon Squared Task	71.12 ± 8.46	71.70 ± 8.60
Choice Reaction Time (RT, seconds)	0.42 ± 0.06	0.41 ± 0.06
Simple – Failed%	25.11 ± 16.69	24.18 ± 15.86
Complex – Failed%	35.11 ± 17.27	33.92 ± 16.25
Composite Z-score	0.016 ± 0.86	0.09 ± 0.84

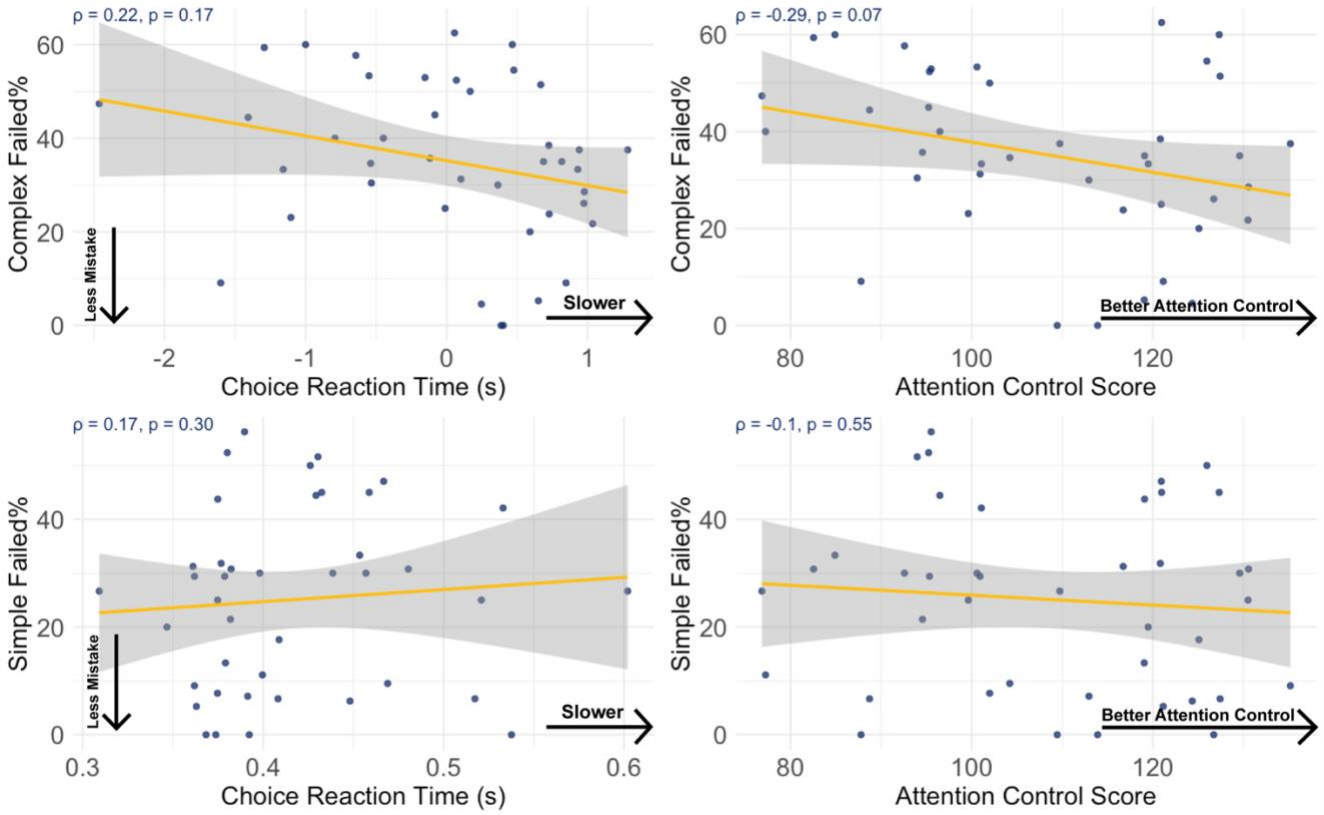


Figure 12: Scatterplots of cognitive function scores and failed percentages

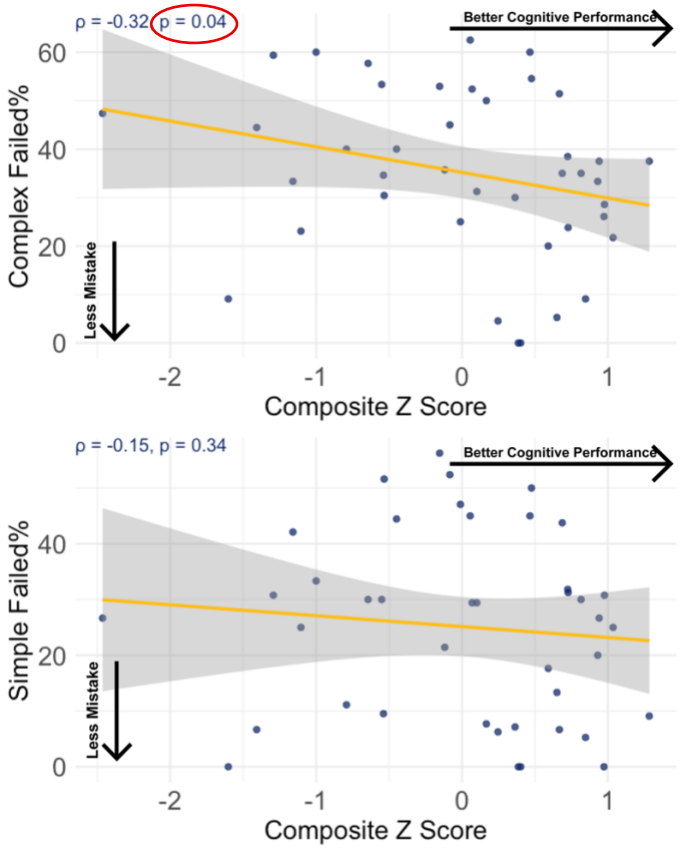


Figure 13: Scatterplots of Composite Z score of cognitive function scores and failed percentages

For the post-hoc analysis, after removing 4 participants, the correlation between composite Z-score and Complex Failed% remained significant ($r = –0.35$, $p = 0.034$, Figure 14). Additionally, a significant negative correlation occurred between AC and Complex Failed% ($r = –0.34$, $p = 0.042$, Figure 15).

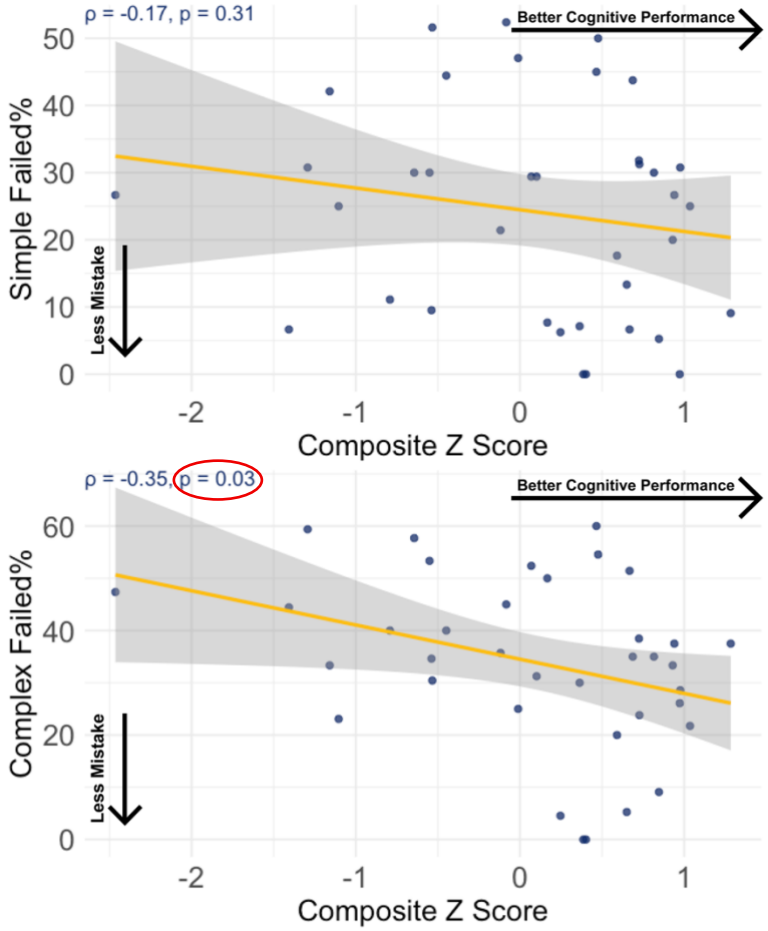


Figure 14: Scatterplots of cognitive function scores and failed percentages after removing the four participants

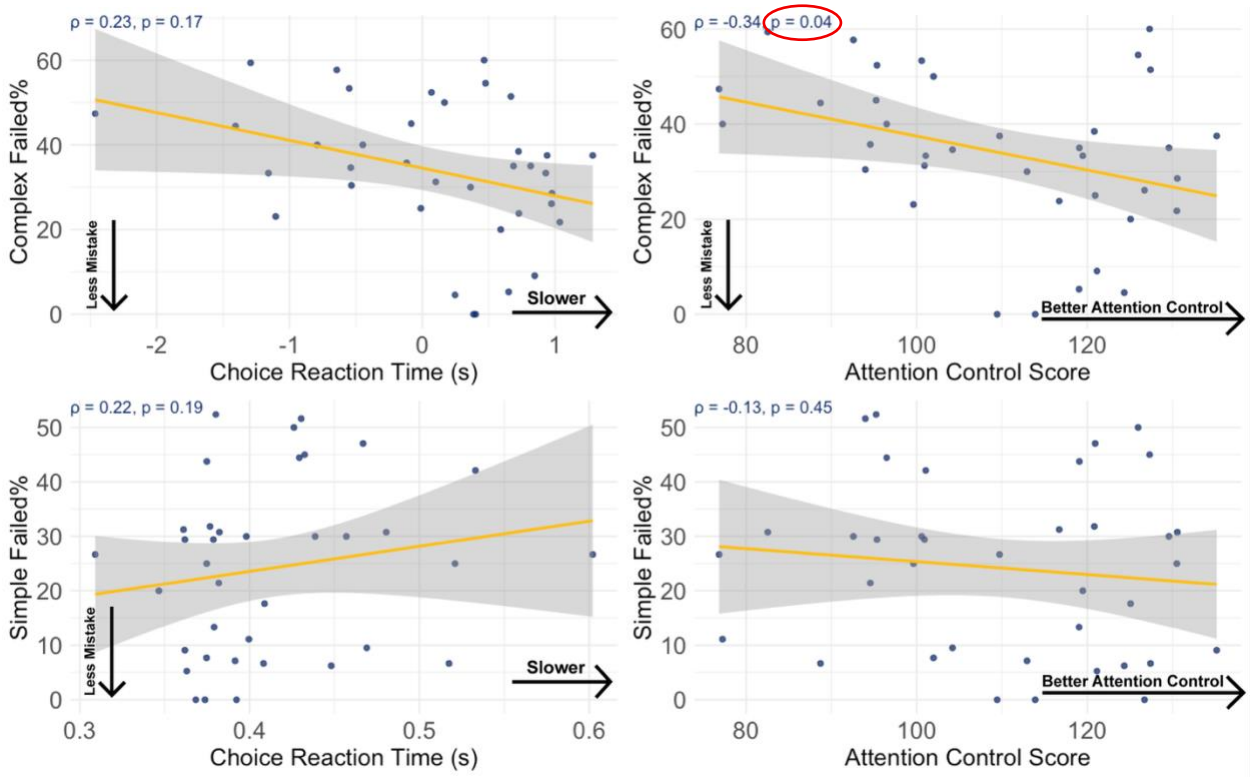


Figure 15: Scatterplots of Composite Z score of cognitive function scores and failed percentages after removing the four participants

Discussion

The purpose of this study was to examine whether individual differences in cognitive performance, specifically attention control and reaction time, were associated with decision-making success during a dynamic jump-landing task in healthy athletes. Contrary to our expectations, only select, moderate correlations (ρ = -0.35, ρ = -0.32) were observed between Composite Z-score of cognitive performance and Complex Failed%, suggesting that substantial variance in decision-making performance on a challenging jump landing task remained unexplained by attention control. With removing potential guessing or delay in the reaction,

besides the mild correlation between Composite Z score and Complex Failed%, a mild negative correlation between AC and Composite Z-score was observed. Although both results indicated that participants with fewer failed trials in the complex condition tended to perform better on cognitive tasks, this relationship may not fully capture the complexity of cognitive–motor interactions. Understanding these multidimensional interactions will be critical for developing integrated training approaches that enhance both cognitive and neuromuscular performance and, ultimately, reduce primary ACL-injury risk.

Attention control is a fundamental component of cognitive processing and multitasking ability [25, 26], yet it does not necessarily translate directly into improved performance during cognitive-motor challenges such as unanticipated landings. These tasks demand rapid integration of sensory information, decision-making, and motor execution. Collectively, these findings suggest that the connection between cognition and neuromuscular performance is multifactorial. Attention control contributes to overall cognitive performance, but complex, real-world movement tasks likely rely on a combination of cognitive domains that enable efficient perception–action coupling. The relatively weak correlation between AC and Complex task performance is likely influenced by 1) limits on the reliability of the Failed% metric itself (thereby providing a ceiling for the correlation with cognitive metrics) and 2) limitations in how attention control was assessed rather than its relevance to movement control. Moreover, previous research showed that neurocognitive assessments may not fully capture the demands of cognitive–motor coordination relevant to dynamic movements [27-29]. Prior work in ACLR populations has demonstrated that computerized tools such as ImPACT [30] often fail to differentiate between individuals with ACLR and uninjured controls or to predict single-limb landing biomechanics [28]. Similarly, Rush et al.

[27] emphasized that current cognitive testing approaches lack ecological validity and may overlook the neurocognitive and attentional compensations athletes employ to maintain knee stability and neuromuscular control. Supporting this interpretation, Giesche et al. [10] demonstrated that athletes who committed more landing errors during unplanned single-leg tasks (~22%, 7.6 trials out of 35) exhibited poorer working memory, cognitive flexibility, and short-term memory, indicating that such failures reflect cognitive–motor instability rather than random variability. The present results in healthy athletes reinforce this perspective, underscoring the need to examine cognitive performance as it operates during active, movement-based contexts rather than in isolation.

Given our findings in healthy athletes, several future directions merit attention. First, although both Simple and Complex task failure rates were highly correlated (Figure 16), only the Complex condition showed moderate significant associations with cognitive and composite Z-score. This pattern suggests that both tasks likely engage overlapping decision-making mechanisms, but the higher cognitive load demands of the Complex task may amplify performance variability to a degree that reveals underlying cognitive differences [10, 31]. In other words, rather than representing distinct processes, the Complex condition may simply exceed a threshold of attentional demand necessary to expose the limits of cognitive–motor integration during rapid movement decisions. Reporting the relative differences in failure rate across these conditions in future work could help confirm whether performance deficits reflect genuine difficulty or cognitive overload rather than task design effects.

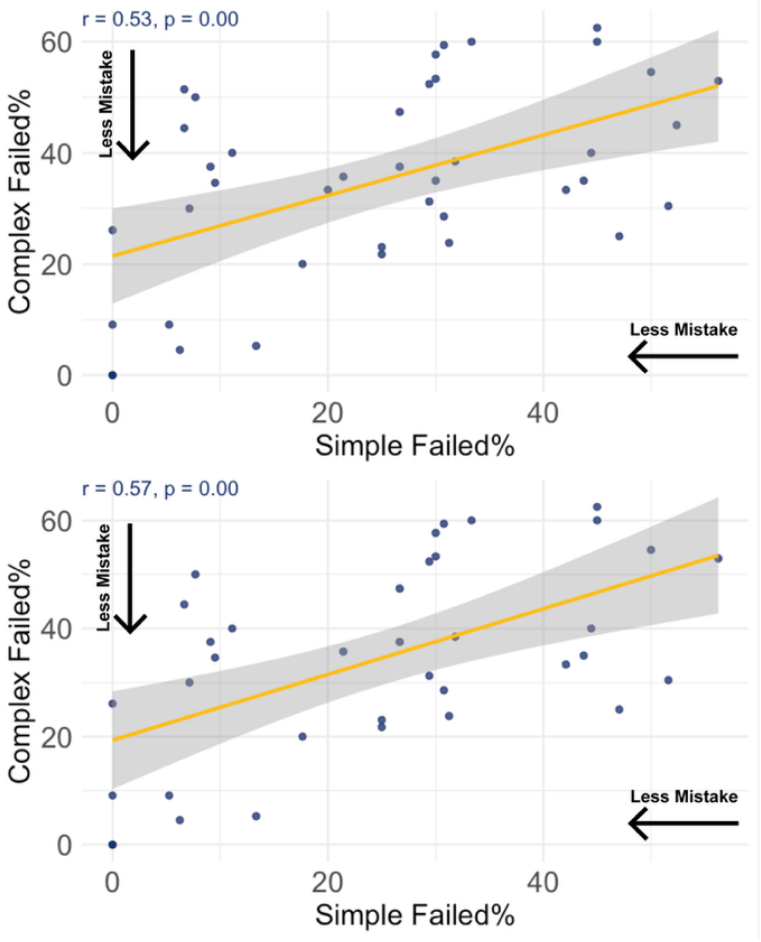


Figure 16: Scatterplots of correlations between failed percentages of Simple and Complex tasks without removing the outliers (Up) and after removing the outliers (Down)

Although the present study involved healthy participants, the observed variability in cognitive and behavioral performance underscores the potential value of integrating cognitive–motor assessments into athlete screening frameworks. Evaluating athletes under decision-based or time-constrained conditions may help identify individuals who are more susceptible to attentional overload or delayed reactions during high-risk movements. Building on these findings, future research should employ controlled interventions to determine whether cognitive–motor training can reduce landing errors and improve biomechanics during unanticipated movements [32].

Interventions such as dual-task drills, rapid decision-making exercises, and inhibition-control training (e.g. drills that train athletes to stop or redirect movements in response to changing cues) have been shown to enhance reaction time, attention shifting, and perceptual–motor coordination, all of which are directly implicated in ACL injury mechanisms [8, 33]. Incorporating such evidence-based cognitive–motor training strategies into prevention and performance programs may improve athletes' ability to maintain stable motor control when cognitive demands and temporal constraints are elevated.

While our study offers novel insights, several limitations must be acknowledged. Our cross-sectional design precludes causal inference; we cannot determine whether lower cognitive scores cause higher failure rates, or whether another factor drives both. The sample size, although sufficient for detecting moderate correlations, may not capture smaller effect sizes or subgroup effects (e.g., sex, sport type). The jump-landing task, while decision-demanding, remains a laboratory simulation and may not perfectly mimic chaotic sport environments. Finally, because our sample was comprised of healthy athletes, the generalizability to injured or clinical populations (or to actual injury risk) is unknown. Nonetheless, these data provide a foundational step toward integrating cognitive–motor screening into sport-performance and injury-prevention paradigms.

Conclusion

This study examines the relationship between cognitive performance and movement errors in unanticipated jump-landing tasks, considering failed trials as potential indicators of neuromuscular control deficits. The lack of strong significant correlations suggests that attention control alone may not predict an athlete's decision-making accuracy during dynamic movements. Future research should prioritize developing and integrating real-world, movement-based attention

control assessments to more accurately characterize how cognitive demands contribute to motor instability under time-critical conditions.

Acknowledgement

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CHAPTER SIX

DO MEASURES OF NEURAL ACTIVATION PREDICT DECISION-MAKING PERFORMANCE ON A REACTIVE JUMP LANDING TASK?

Contribution of Authors and Co-Authors

Manuscript in Chapter 6

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Contributions: Conceptualization, Testing, Data collection, Formal analysis, Investigation, Visualization, Methodology, Manuscript preparation

Co-Author: Alexandra C. Lynch

Contributions: Data processing, Data interpretation, Manuscript preparation

Co-Author: James N. Becker

Contributions: Study design, Data interpretation, Manuscript preparation

Co-Author: Keith A. Hutchison

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Contributions: Study design, Data collection, Data processing, Data analysis, Data interpretation, Manuscript preparation

Manuscript Information

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Status of Manuscript:
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☐ Officially submitted to a peer-reviewed journal
☐ Accepted by a peer-reviewed journal
☐ Published in a peer-reviewed journal

Abstract

Background:

Anterior cruciate ligament (ACL) injuries often occur when athletes must make rapid, unanticipated movement decisions that overload cognitive–motor control. Although altered cortical activation has been observed in athletes following ACL reconstruction, the link between neural activation during cognitive tasks and real-time decision-making performance during sport-like movements remains unclear.

Purpose:

To examine whether prefrontal cortical activation during attention-control tasks predicts decision-making failures during cognitively demanding, unanticipated jump-landing tasks in healthy athletes.

Methods:

Forty-one healthy athletes (17F/24M, 23.7±3.7 yrs) completed an attention-control battery while fNIRS measured activation in the left dorsolateral prefrontal cortex (Brodmann areas 46 and 9 (BA46, BA9)). Participants then performed unanticipated single- and double-leg jump landings under Simple and Complex cue-based conditions requiring rapid visuomotor decisions. Cortical activation (t-statistics for oxygenated and deoxygenated hemoglobin) and the proportion of failed landings (Failed%) were analyzed using Pearson correlations.

Results:

Data from 31 participants were analyzed following quality control actions of the data, such as checking for cap movement, poor optode–scalp contact, or calibration issues checking for cap

movement, poor optode–scalp contact, and calibration issues related to hair type. No significant correlations were observed between cortical activation (BA46 or BA9) and Failed% in either the Simple or Complex conditions (all $p > 0.05$), although small to moderate effect sizes ($|r| \approx 0.3$) suggested a nonsignificant trend toward fewer failed landings with greater prefrontal activation.

Conclusions:

Cortical activation during stationary attention control tasks did not predict decision-making success during unanticipated jump-landing movements. These findings suggest that neural efficiency measured at rest or during seated cognitive testing may not translate directly to performance under dynamic, time-pressured conditions; however, additional data is needed to more definitively determine the presence and clinical relevance of potential lower strength relationships. Stronger relationship may be elucidated when more directly assessing neural activation related to transient overload in cognitive-motor integration. Future research using real-time neuroimaging (fNIRS or EEG) during movement may identify neural mechanisms underlying brief lapses in control that contribute to ACL-relevant risk.

Introduction

Anterior cruciate ligament (ACL) injuries are among the most common non-contact injuries in sport and are frequently attributed to failures in cognitive–motor control during unanticipated movements [1]. Athletes must rapidly process environmental cues, allocate attention, and coordinate neuromuscular control within milliseconds to plan their next movement to react. Although biomechanical risk factors have been extensively studied [1-7], growing evidence also implicates disruptions in neural processes that support visuomotor coordination and movement planning during dynamic tasks, specifically for ACL injury [8-10]. Despite this emerging evidence, the relationship between neural processing and real-time decision-making failures during sport-like tasks remains poorly characterized.

During challenging jump-landing tasks, athletes may make decision-making errors, such as moving in an inefficient or hazardous manner, that are typically excluded from research analyses to minimize variability. However, these failed decision-making outcomes may better represent the instances when cognitive–motor resources are overloaded and ACL injury–related biomechanics emerge [11, 12]. Therefore, evaluating such failures instead of discarding them may provide a more realistic view of when athletes become vulnerable to injury during sport.

Attention control defined as the ability to allocate and shift attention under competing task demands [13]. It is increasingly recognized as a neurocognitive factor related to lower limb movement because sport requires continuous allocation of attention under multitask demands [12, 14, 15]. A recent study showed that there is a strong correlation between single-leg dynamic balances based on center of pressure movement and attention control, measured by the Eriksen’s

Flanker test, as neurocognitive evaluations [16]. This highlights that certain neurocognitive processes may contribute to maintaining movement stability under athletic demands. Decision-making demands and divided attention shift landing and cutting movements toward ACL-risk patterns such as reduced knee flexion at initial contact and greater knee valgus and extension moments [12]. Baseline neurocognitive performance in activities that require high processing speed and attention control, shows independent associations with ACL-relevant knee mechanics. Specifically, lower attention control is linked to greater frontal-plane knee loading (elevated valgus angle and abduction moment) under heightened task complexity or dual-task demands [1]. These findings support integrating dual-task challenges to reveal attention control deficits associated with elevated ACL injury risk.

Neuroimaging studies further indicate that visuomotor control and rapid movement decisions rely on activation of the prefrontal cortex (PFC), including during movement preparation and response selection [8, 17]. Alterations in cortical activation and sensorimotor integration has been documented in athletes with ACL injury history during balance and landing tasks, suggesting compensatory higher-order cognitive control to maintain stability [18-20]. Thus, neural activation during attention control tasks may help understand neural activation patterns that relate to athletes' ability to successfully execute an unanticipated jump landing.

Functional near-infrared spectroscopy (fNIRS) offers a promising approach to investigate the neural mechanisms that underlie attention control during movement. This portable, non-invasive neuroimaging method enables measurement of cortical activation during dynamic, ecologically relevant tasks [21-25]. Although fNIRS has been applied to motor activities such as

walking and balance [26-30], its use in examining attention-related neural activation during complex, sport-like movements remain limited.

Accordingly, the purpose of this study is to examine the relationship between PFC activation during cognitive tasks and decision-making during challenging unanticipated jump landing conditions. This work seeks to provide new insights into the cognitive–motor functions related to ACL injury risk. We hypothesized that higher failed decision-making during unanticipated jump landing tasks would be associated with decrease PFC activation.

Methods

Participants

A cohort of 41 healthy athletes (17F/24M, 23.6±3.6 yrs; 1.74±0.10 m; 72.65±12.25 kg; Tegner: 6.8±1.3; Marx: 10.3±3.5) participated in the study after providing informed consent per Montana State University's Institutional Review. All participants were right leg dominant, as determined by the leg they would use to kick a ball as far as possible. Exclusion criteria included a history of concussion in the 6 months prior to their study visit, a history of any attention deficit disorders, or any lower limb injuries requiring surgery. Moreover, all participants were physically active by running, cutting and pivoting at least twice a week [31], and had a Tegner scale more than 5 [32].

Attention Control Test Battery

Attention control was evaluated using a computerized battery consisting of the Stroop squared, Flanker squared, and Simon squared tasks (Figure 17) [33]. In the Stroop squared task, participants identified the printed color of a word while ignoring its semantic meaning. The Flanker

squared task required reporting the direction of a central arrow while ignoring surrounding distractors. The Simon squared task required responding to arrow direction irrespective of screen location. Each test lasted 90 s, with participants completing a practice round and a 30 s seated baseline prior to testing.

Performance scores were calculated as the number of correct responses minus incorrect responses. Scores were weighted according to published factor loadings (Stroop = 0.58, Flanker = 0.64, Simon = 0.82) [33] and summed to yield a composite attention control score, with higher values reflecting better performance, it has been defined as an efficient and robust assessment of AC that has linked to multitasking another cognitive process [33].

To assess the neural basis of attention control, cortical activation was recorded using fNIRS while participants performed these tasks, allowing evaluation of prefrontal activity related to attention control task execution (Figure 17).

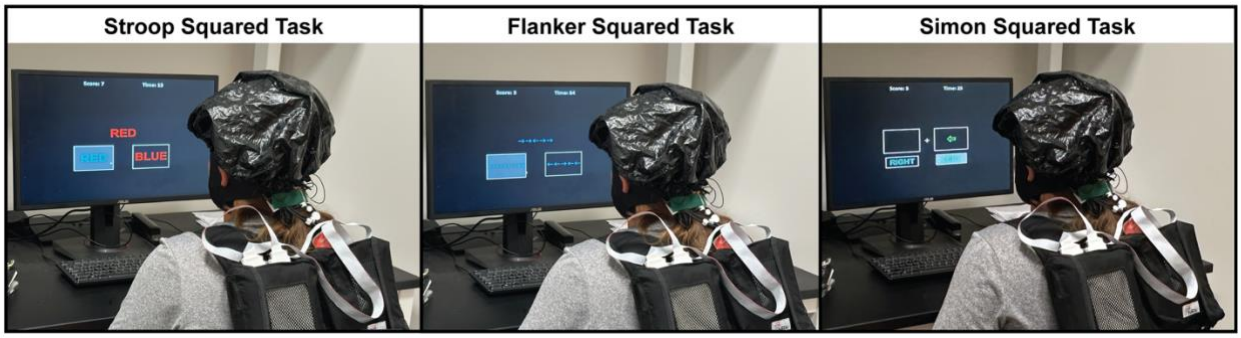


Figure 17: Attention Control Tasks; Participant performed Stroop Squared, Flanker Squared, and Simon Squared tasks while wearing the fNIRS cap.

Unanticipated Challenging Jump-Landing Protocol

An unanticipated challenging sport-relevant movement was chosen to emphasize rapid decision making during demanding sport movements [1, 34]. In the jump-landing protocol, participants initiated each trial by jumping off a 30 cm box. They were instructed to perform either a single-leg landing on the left or right leg while maintaining balance for two seconds, or a double-leg landing followed immediately by a maximal vertical jump. Participants were asked to keep their hands on their hips the entirety of the trials. Unanticipated conditions incorporated two levels of cognitive challenge. In the simple condition (Figure 18), participants were required to land on the limb corresponding to the side of the screen displaying a basketball image, or to perform a double-leg landing with a subsequent vertical jump when a basketball hoop appeared. In the complex condition (Figure 18), participants were instructed to land either toward the basketball image or away from an image of a simulated opponent, or to complete a double-leg landing following a vertical jump when cued by the basketball hoop. Each participant completed at least three practice trials to become familiar with the task. For the Simple condition, 15–20 trials were collected, and for the Complex condition, 20–25 trials were targeted to ensure sufficient variability across successful and failed trials. The order of drop-landing tasks was randomized for each participant. Trials were classified as failed when participants responded incorrectly to the visual cue, such as landing on the right limb but the correct response was to land on the left limb or tried to land on the correct limb but touched the ground with the other limb in less than 0.25 seconds in single-leg landings. The proportion of failed attempts (Failed%) was calculated separately for simple and complex unanticipated jump-landing conditions. To minimize potential sequencing effects, the order of all drop-landing tasks was randomized for each participant.

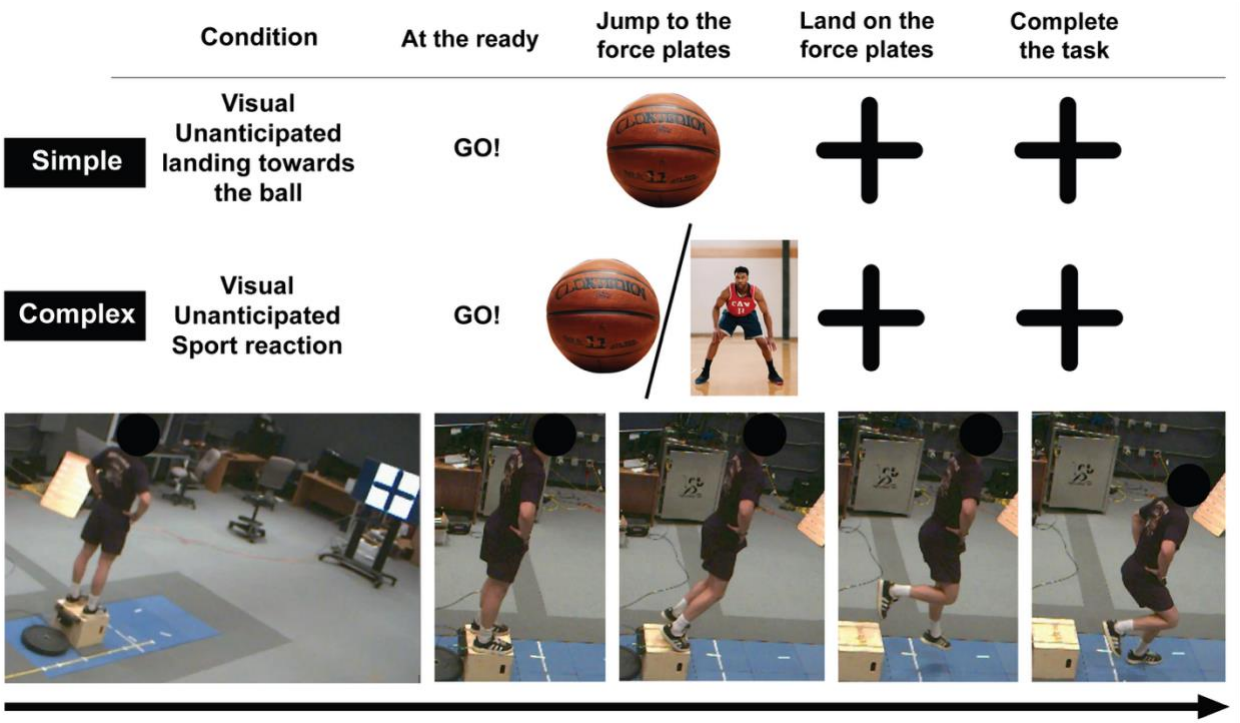


Figure 18: Unanticipated jump landing conditions

fNIRS Data Acquisition

Cortical activation was recorded using a NIRSport 2 system (NIRx Medical Technologies LLC). Cap placement was determined from nasion–inion and preauricular distances, with Cz as the central reference (10–20 system). The montage consisted of 8 sources and 8 detectors, producing 15 channels, plus 8 short-separation channels via a breakout detector. One of the detectors was used for all short-separation channels from all sources. Sources emitted light at 690 and 830 nm and sampled at 10.17 Hz. The focus for this study involved the three sources and three detectors (Sources 1, 2, 3 and 7, and detectors 1, 2, and 3, Figure 19) that were positioned over the

Brodmann areas 46 and 9 as defined by the Talairach Daemon atlas [35], corresponding to the left dorsolateral prefrontal cortex (DLPFC; BA46) and prefrontal cortex (PFC; BA09). A black over-cap minimized ambient light contamination.

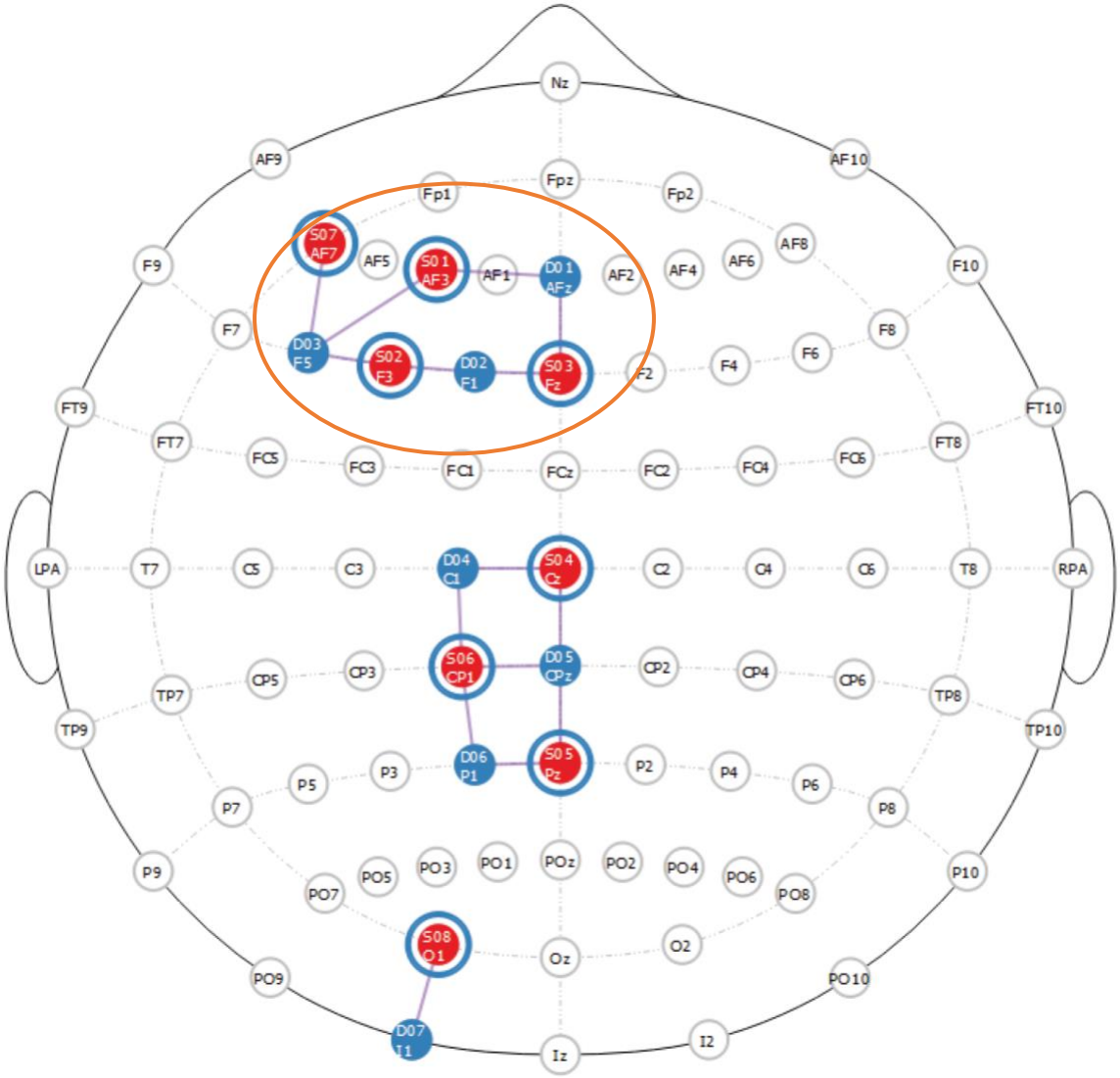


Figure 19: fNIRS montage focusing on left brain cortex; Red circles: sources, Blue Circles: detectors, Circles around red circles: short-separation channels

fNIRS Data processing

Data were processed in MATLAB R2025a using the NIRS Brain AnalyzIR Toolbox [36]. The raw signals were initially inspected to verify data quality and confirm the absence of large spikes or abrupt signal shifts. Data were resampled to 4 Hz. Optical density was calculated, and motion artifacts were corrected using the temporal derivative distribution repair (TDDR) method [37]. A fourth-order Butterworth lowpass filter (0.5 Hz) was then applied to attenuate physiological noise (e.g., heartbeat) and low-frequency drift. Concentrations of oxygenated (HbO) and deoxygenated (HbR) hemoglobin were derived using the modified Beer–Lambert law with a partial pathlength factor of 0.1 [38]. Data were then processed using a general linear model (GLM)-based approach with short-separation regression to reduce extracerebral and motion-related artifacts [26-30]. Neural activation was estimated through a GLM implemented via an autoregressive iterative least-squares (AR-IRLS) approach [39], which incorporated short-separation channels as regressors to reduce superficial physiological interference. The AR-IRLS algorithm down-weights motion-related outliers using bisquare weighting and corrects for serial autocorrelation in fNIRS time series, enhancing model robustness and controlling false positives. This GLM approach has demonstrated superior artifact correction compared to conventional preprocessing methods [40]. For each channel, β-coefficients (and T-statistics) were estimated from the AR-IRLS, representing task-related neural activation. The t-values provided normalized measures of cortical activation (Figure 20) [39]. Regions of interest (ROIs) corresponding to BA46 and BA09. Channels overlapping or adjacent to these ROIs were assigned tapered spatial weights based on their proximity to the target region, increasing sensitivity to localized activation while minimizing noise from unrelated areas [35]. ROI T-stat values were used as the primary neural

outcome variables for statistical analysis, with higher t-statistics reflecting stronger task-evoked activation in BA46 and BA9.

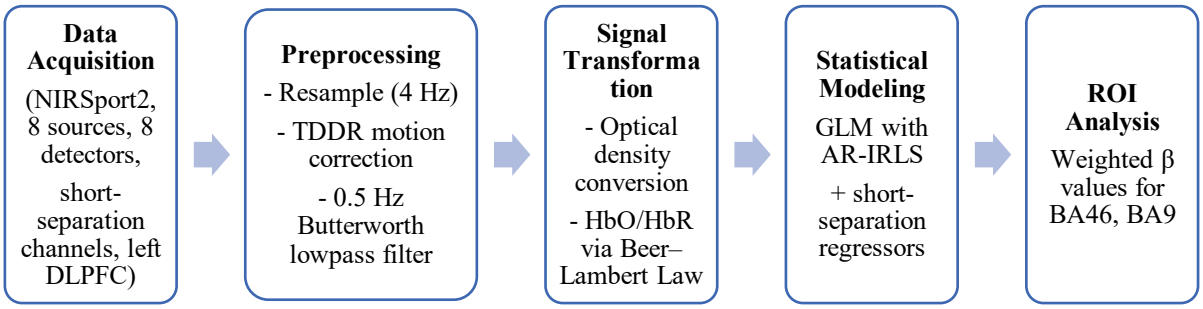


Figure 20: fNIRS processing pipeline

Power Analysis

G*Power (v3.1) was used for power analysis for two-tailed correlation analyses with significance threshold of $\alpha = 0.05$ and desired power of $1-\beta = 0.80$. Prior research has reported moderate to strong relationships between cortical activity and performance measures (approximately $r = 0.5$) [41, 42]. On this basis, a medium effect size was selected as the smallest effect of interest ($r = 0.5$). The analysis indicated that a total sample of 26 participants would be sufficient to achieve the targeted power for examining the association between fNIRS T-Stats and the proportion of failed trials (Failed%).

Statistical Analysis

Normality of all variables was assessed by using the Shapiro-Wilk test. Pearson correlations were used to test the relationship between neural activations and Failed% calculated

from two “Simple” and “Complex” drop landing conditions. The dependent variables were Failed% and the T-Stats for BA46 and BA09 regions from the subject-level analysis of fNIRS data.

Results

Data Quality Summary

After visually checking the raw signals, eight participants were removed due to data quality issues (i.e., movement of the cap during the tasks, poor calibration due to the hair thickness and type). A total of 34 participants remained. Additionally, three participants were excluded from the jump landing analyses due to excessive failure rates (>60%, approaching random chance) in the Complex condition or delayed jumping (i.e., increasing the time to react). These exclusions were made because excessive failure rate may reflect guessing rather than true task engagement, while delayed reactions reduced the cognitive–motor challenge by allowing additional time to respond. Therefore, 31 participants (15 females, 16 males; age = 23.1 ± 2.6 years; height = 1.73 ± 0.10 m; mass = 71.3 ± 12.6 kg; Tegner score = 6.8 ± 1.3; Marx activity score = 10.3 ± 3.8) included in the final analysis.

Neural Activation and Task Performance

Pearson correlations revealed no significant associations between cortical activation (T-Stats) in either BA46 or BA9 and the Failed% during the simple or complex unanticipated jump-landing conditions (all $p > 0.05$; Table 8, Figure 21, Figure 22). Although several correlations showed small to moderate effect sizes ($|r| \approx 0.3$ Figure 21, Figure 22), none approached statistical significance (all $p > 0.05$).

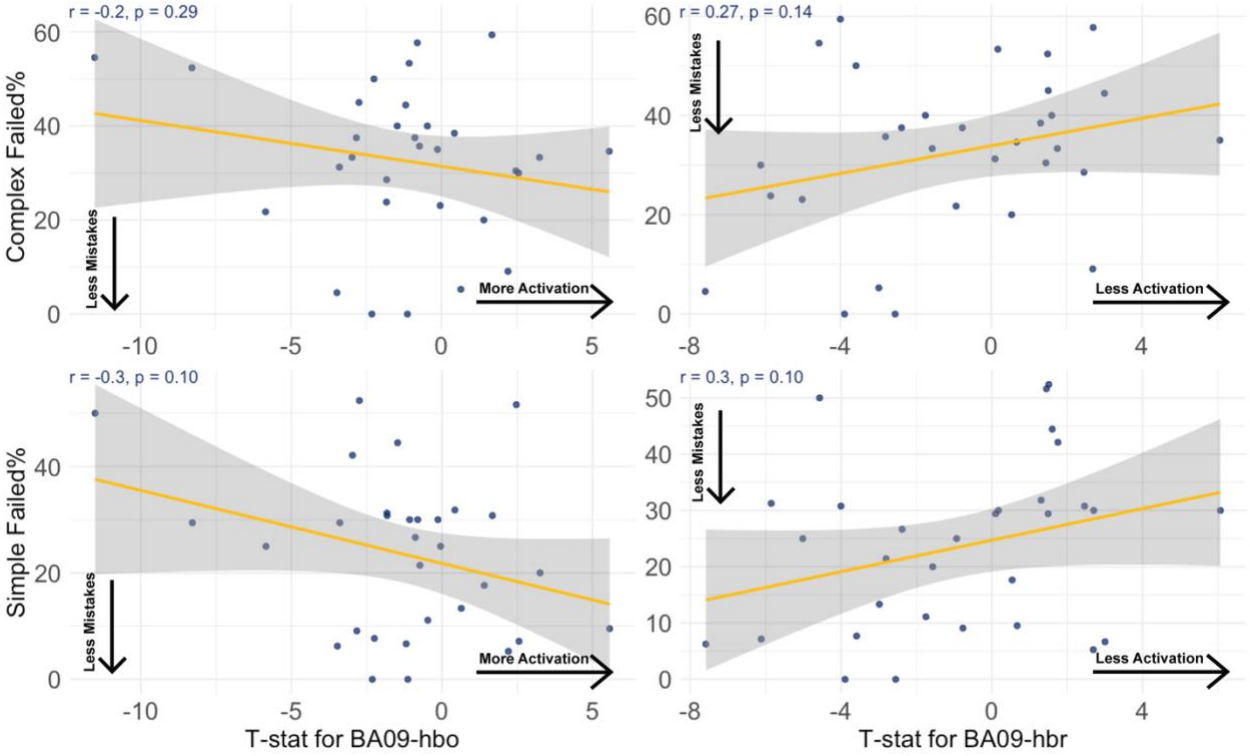


Figure 21: Scatterplots of T-stats for BA09 and Failed% of simple and complex jump-landing conditions

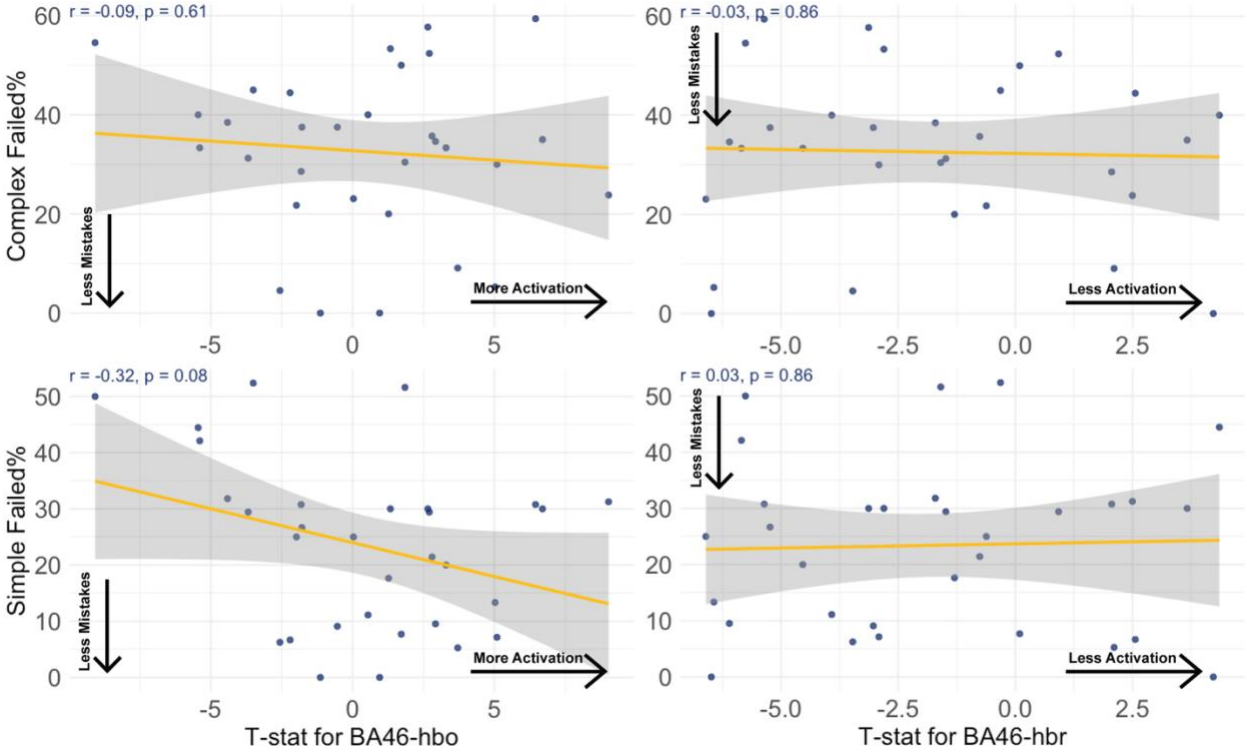


Figure 22: Scatterplots of T-stats for BA46 and Failed% of simple and complex jump-landing conditions

Table 9: Descriptive statistics (Mean ± SD) for behavioral and neural measures

Measure	Mean ± SD
Failed% – Simple Condition	23.4 ± 15.0
Failed% – Complex Condition	32.6 ± 16.5
T-Stats (BA46-hbr)	-1.8 ± 3.4
T-Stats (BA46-hbo)	0.5 ± 4.0
T-Stats (BA9-hbr)	-0.9 ± 3.2
T-Stats (BA9-hbo)	-1.2 ± 3.3

Abbreviations: Failed%: Failed percentage of the trials; T-Stats: associations between cortical activation (T-Stats) in either BA46 or BA9

Discussion

This study examined whether cortical activation during an attention control task is related to behavioral performance during unanticipated, challenging jump-landing movements. Overall, prefrontal activation within the dorsolateral prefrontal cortex (BA46, BA09) during cognitive testing was not significantly related to the athletes' decision-making accuracy or failure rates during unanticipated jump-landing tasks. These findings suggest that, within this cohort of healthy athletes, individual differences in cortical activation measured during cognitive tasks during an attention control task did not strongly predict motor-cognitive performance outcomes during movement challenges. Future work should examine neural activation during actual movement execution and integrate precise measures (e.g., EEG or time-synchronized fNIRS) to better capture how rapid cognitive–motor interactions contribute to performance variability and injury risk.

A key objective of this study was to link cognitive performance to movement outcomes by examining how neural activation during an attention-control task relates to decision-making failure in challenging jump-landing performance. The absence of significant correlations does not negate this link but highlights its complexity. The cognitive task used here captured how efficiently individuals engage attention control during isolated cognitive tasks, whereas the unanticipated jump landing tasks required fast perception and decision-making to coordinate a dynamic neuromuscular response under limited time. Performance differences may reflect brief disruptions in neural processing that affect how decisions are carried out in movement. Such short-term reductions in cortical engagement have been shown to alter visuomotor coordination, motor planning, and joint stabilization in athletes' performance [9, 43, 44]. Evidence from neuroimaging and neurophysiological studies further indicates that athletes with ACL injury or reconstruction

demonstrate delayed cortical activation and altered connectivity within prefrontal and sensorimotor regions, reflecting compensatory or inefficient neural strategies during movement and the complexity of ACL injuries [15, 45]. Collectively, these findings support the view that brief disruptions in neural processing can compromise decision accuracy and motor execution during high-demand tasks, thereby increasing vulnerability to the neuromechanical patterns associated with ACL injury risk.

Although neural alterations in visuomotor and decision-making networks have been found in athletes who sustain ACL injuries [8, 17], the present results in healthy athletes suggest that attention control and cognitive task performance alone may not strongly predict failures during complex jump-landing tasks. The absence of significant correlations may indicate that, in a healthy population, individuals are generally able to maintain effective cognitive–motor regulation during dynamic actions, even when challenged. However, in this study, failed landings may reflect brief moments when the jump task becomes too demanding to process quickly, resulting in small mismatches between the decision and the movement. Even in healthy athletes, these brief mistakes can reveal conditions where movement control is more at risk, similar to the split-second situations in which ACL injuries occur in sport [46]. This interpretation aligns with evidence that ACL injuries typically occur during brief failures of neuromechanical coordination, not during routine movement [12]. Thus, even in healthy athletes, failed trials may provide valuable insight into conditions where cognitive–motor demands temporarily overwhelm available control, resulting in mechanics linked to increased injury risk. Future studies integrating EEG with fNIRS could help characterize these transient neural disruptions more precisely. EEG provides millisecond-level temporal resolution, allowing detection of rapid neural events, such as delays in stimulus

evaluation or response preparation, that may precede decision-making failures. Combined with the spatial specificity of fNIRS, this multimodal approach could clarify how and when neural control lapses contribute to at-risk movements.

The absence of significant correlations between neural activation during the isolated attention control task and decision-making failure during jump landing task indicates that baseline cognitive neural efficiency has limited transfer to movement success under complex jump-landing conditions. In the athletic sample performing a highly complex, decision-based landing task, as in the current study, neural efficiency effects may therefore be minimized or masked by the high processing demands placed on all participants [47, 48]. These findings suggest that the demands of the task, rather than general cognitive ability, have a greater influence on whether a failed landing occurs. However, the significant correlation between failure rates in the Complex and Simple conditions indicates that some individuals consistently struggled across both levels of task demand, suggesting an underlying trait-like component of attentional or cognitive–motor efficiency that influences performance across contexts. From a practical standpoint, training that includes reactive and unpredictable cues may help athletes maintain control and avoid decision-making errors when attention is challenged. To more accurately characterize the neurocognitive mechanisms underlying these high-risk performance breakdowns, future work should explore methods capable of assessing neural processing during movement without compromising signal quality, as current neuroimaging tools are limited by motion artifacts during high-impact tasks such as jump landings.

Several limitations must be acknowledged. First, cortical activation was recorded during the attention control task only, not during jump landing, which limits inference about how neural

activation patterns during cognitive processing directly relate to the timing of motor responses. Second, the fNIRS optode montage was based on standardized scalp coordinates rather than individualized anatomical measurements, which may have introduced small spatial inaccuracies in mapping channels to cortical regions. Finally, laboratory-based landing tasks cannot fully replicate the sensory complexity of live sport scenarios. The challenging jump landing task and the Failed% outcome used in our analysis also introduces an upper limit to the correlations with neural activation. Further research is needed to determine the reliability of this outcome, increase the sample size to more definitively determine if lower strength relationships exist, and determine the clinical relevance of such relationships, if detected. Future studies combining motion capture, fNIRS, and electroencephalography (offers millisecond-level temporal resolution, allowing researchers to track rapid fluctuations in neural activity) during unanticipated movements can better characterize how neural activity evolves immediately before failed or unstable landings.

Conclusion

No significant relationships were detected between decision-making during challenging jump landing tasks and neural activation during attention control task, albeit lower strength relationship may be detectable with additional data. These results suggest that neural activation measured during isolated cognitive tasks may not strongly predict behavioral outcomes during challenging cognitive-motor jump-landing tasks. Instead, decision-making failures may emerge task-specific overload in cognitive–motor integration when attention and perceptual resources are challenged. Future studies should extend this work by capturing neural activity during dynamic, ecologically valid tasks and by exploring how fluctuations in cognitive engagement relate to performance stability.

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CHAPTER SEVEN

GENERAL DISCUSSION

The purposes of this dissertation were to (1) evaluate cognitive-motor impairments that persist after ACLR, (2) determine the correlation between clinical dual-task tests relative to laboratory-acquired second ACL injury risk biomechanics for cognitive-motor interference, (3) investigate the effects of unbalanced landings and cognitive challenge on outcomes related to primary ACL injury risk, and (4) examine whether individual differences in cognitive performance and neural activation were associated with decision-making success during unanticipated, challenging jump-landing tasks. These aims were accomplished through five studies (Table 9). Chapter 1 assessed whether cognitive challenge exacerbates residual biomechanics deficits following ACLR compared to healthy controls and demonstrated persistent altered knee biomechanics even after return-to-sport clearance. Chapter 2 evaluated whether clinically implementable dual-task hop tests reflect laboratory-based ACL injury risk biomechanics, revealing the potential clinical relevance of subjective experiences in the rehabilitation process. Chapter 3 investigated unbalanced landings and available time to react, showing that decision-making pressure and temporal constraints produce the highest-risk movement patterns and that failed movements should not be removed from biomechanical analysis. Chapter 4 explored whether individual differences in cognitive performance (attention control and reaction time) predict errors in unanticipated landings, highlighting that cognition contributes but is not singularly determinative of safe movement execution. Finally, Chapter 5 examined neural activation using fNIRS to determine whether cortical engagement during attention control predicts landing outcomes, suggesting that neural activation during stationary attention control is not correlated

with the decision-making during challenging jump-landing tasks. Collectively, these five studies advance the understanding of the role of cognitive-motor in ACL injury risk, emphasizing the need for a multifactorial approach. Effective prevention and rehabilitation should therefore address not only biomechanical factors and movement patterns but also the underlying cognitive–motor processes that influence neuromuscular control.

Table 10: Summary of chapters in this dissertation

Chapter	Purpose / Focus	Main Findings	Key Contribution	Recommendations
1 — ACLR Cognitive-Motor Biomechanics Study	Examine whether cognitive challenges expose persistent neuromechanical deficits after ACLR	ACLR group showed persistent KEM asymmetry risk → unaffected by cognitive task type; unanticipated demands reduced pKFA for both groups	Identifies **baseline vulnerability** after ACLR and shows cognitive-motor demands **add risk**, justifying cognitive-loaded RTS assessments	Include cognitive-motor assessments in post-ACLR evaluations; longitudinal studies are needed to link cognitive-motor function to ACLR outcomes.
2 — Clinical Dual-Task Tests vs. Lab Biomechanics	Determine whether clinical dual-task hop tests predict dual-task biomechanical risk	DTC was **not** predictive; **direct dual-task performance** showed fair correlations to risk biomechanics	Supports **clinical relevance of considering individual performance**; emphasizes performance under cognitive load is more informative than difference-score metrics	Consider all aspects of cognitive tasks in clinical aspect by looking at **single, dual, and dual-task change values** (Figure 24) and see the overall performance of patient, while recognizing limitations of relying solely on DTC metrics
3 — Healthy Athletes: Unbalanced vs. Successful	Evaluate influence of cognitive demands and unbalanced landings	Unbalanced trials = **highest-risk** knee mechanics; ATR explained deterioration under cognitive challenge	Demonstrates that **unsuccessful landings** and **temporal pressure** reveal risk of injury mechanisms → foundation for neurocognitive-temporal model	Include unbalanced trials when evaluating risky knee mechanics; Future study on unbalanced trials on **ACLR group**, and study in a **sport field** or add **VR** for cognitive task
4 — Cognition ↔ Decision-Making Errors	Test whether cognitive performance (attention, reaction time) predicts landing failures	Only **weak** associations; attention not sufficient to predict failures	Isolated cognitive tasks such as attention control **did not predict** performance during challenging cognitive–motor movements	Weak correlation ↔ could be meaningful in **smaller correlation coefficients** [168-170] → Add more participants + revisit the design of the study with focusing on AC during movement
5 — Neural Activation ↔ Decision-Making Errors	Link prefrontal activation (fNIRS Attention Control Task) to motor failures	No significant correlations: neural efficiency may mask variability in skilled athletes	Indicates that risk occurs **during** movement under cognitive load → supports need for **neural assessment during dynamic tasks**, not isolated cognition	Add **EEG** and study on neural activation during **movement** + more participants to have a smaller correlation coefficient [168-170]

Abbreviation: KEM: knee extensor moment; DTC: dual-task cost; pKFA: peak knee flexion angle; RTS: return to sports; ATR: available time to react; fNIRS: functional near-infrared spectroscopy. Neural activation during isolated cognitive tasks did not predict performance during challenging cognitive–motor movements.

Across all five studies, this dissertation established that cognitive–motor demands fundamentally shape neuromuscular control and ACL injury risk in both post-reconstruction and healthy athletes. The first two studies of this dissertation focused on the effect of cognitive–motor function on second ACL injury risk following ACLR. Collectively, these findings demonstrate that individuals with ACLR continue to exhibit altered neuromechanical control and persistent asymmetries during sport-like jump-landing tasks even after clinical return-to-sport clearance. The first study revealed that ACLR participants displayed greater knee extensor moment asymmetry across all cognitive conditions, indicating ongoing mechanical vulnerability. Although cognitive challenge did not exacerbate between-group differences, unanticipated landings universally reduced peak knee flexion angle and induced stiffer, risky movement patterns across all participants. From a multivariable perspective, these results suggest additive risk: baseline asymmetries in ACLR individuals may compound with the generalized stiffening observed under cognitive demand, highlighting how rapid decision-making can magnify neuromuscular inefficiency during real-world sport scenarios (Figure 23). These findings highlight that the interaction between cognition and motor functions can reveal underlying deficits that remain undetected during traditional, predictable assessments.

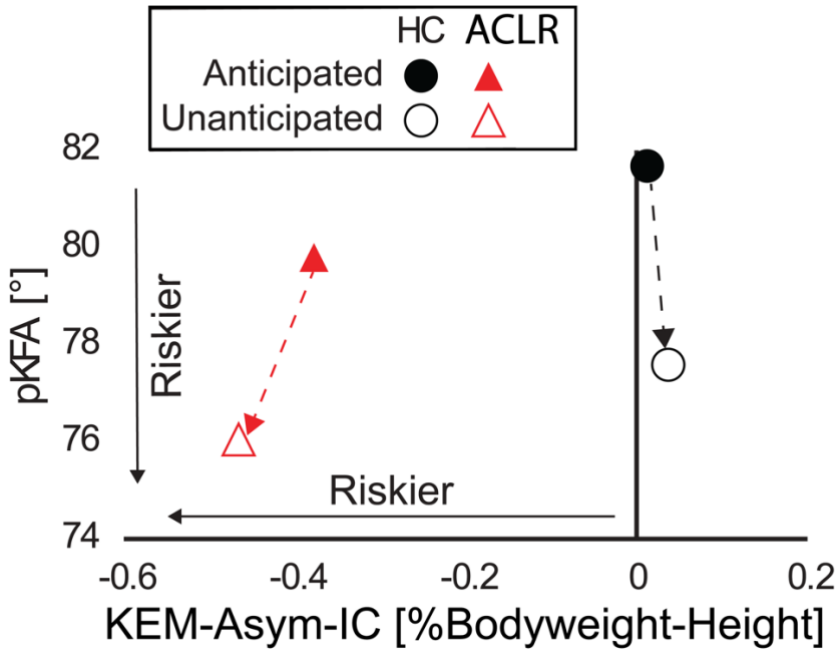


Figure 23: Multivariable perspective of injury risk of the current dataset. Peak knee flexion angle (pKFA) and asymmetry of knee extensor moment at initial contact (KEM-Asym-IC) during anticipated and unanticipated conditions (average of three unanticipated conditions) for the ACLR (ACLR) and matched healthy controls (HC) groups. Arrows indicate group-specific shifts in outcome variables between anticipated and unanticipated conditions.

Building on these observations, the second study explored whether clinical dual-task hop tests can capture cognitive-motor interference patterns observed in laboratory biomechanics. Contrary to the initial hypothesis, derived dual-task cost metrics demonstrated limited correspondence with laboratory measures of cognitive-motor performance, whereas absolute single- and dual-task outcomes showed stronger associations with key biomechanical indicators of second-injury risk. This suggests that absolute performance during cognitively demanding tasks, rather than change-based dual-task costs, may provide a more reliable reflection of underlying neuromuscular control (Figure 24). These results also revealed that task-specific cognitive demands can influence motor responses, although considerable overlap between single- and dual-

task performance suggests that well-trained athletes may maintain relatively stable neuromuscular control across conditions. This finding underscores that while cognitive load can alter motor execution in certain contexts, individual resilience or task familiarity may mitigate these effects. Together, these two studies highlight the importance of incorporating cognitive–motor elements into both assessment and rehabilitation frameworks after ACLR, while recognizing that task complexity and athlete skill level can influence the degree of observed cognitive–motor interference. A multidimensional approach, incorporating measures of motor capacity, task-specific performance under cognitive load, and individual variability in cognitive-motor interference, may offer a more valid and personalized framework for identifying athletes at elevated reinjury risk and optimizing their return-to-sport readiness.

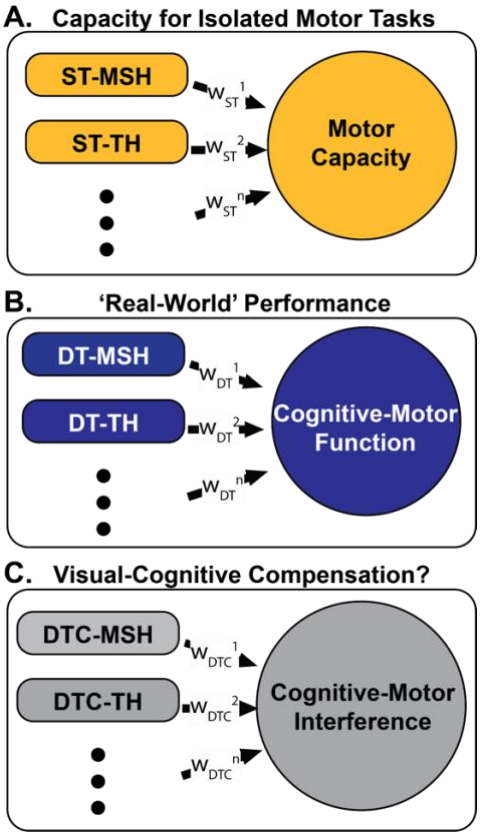


Figure 24: Prospective theoretical framework for comprehensive evaluation of patient cognitive-motor function. Complementary perspectives from single-task, dual-task, and dual-task cost outcomes, each defined by composite factors determined from performance on multiple clinically tests. **A.** Evaluate motor capacity using various hop and strength tests (e.g., ST-MSH: traditional single-task medial side hop; ST-TH: traditional single-task triple hop, isokinetic strength), with hypothetical weightings defined by w_{ST}^1, etc. **B.** Assess 'real-world' performance via a composite metric defined by performance on multiple cognitive-motor tests (e.g. DT-MSH: Dual-task Medial Side Hop weighted by w_{DT}^1; DT-TH: Dual Task Triple Hop weighted by w_{DT}^2; additional tests having respective weightings (w_{DT}^n)). The approach may circumvent reliability and test-specific pitfalls of relying on dual-task change/cost metrics from isolated clinical tests to ultimately be more robust in understand cognitive-motor function in rehabilitation programs. **C.** Probe for maladaptive visual-compensatory strategies using dual-task change outcomes across multiple cognitive-motor tests. Notably, insights afforded by **B** and **C** are likely enhanced by first ensuring adequate performance on **A**. Additionally, optimal sets of clinical tests and their relative weightings for each composite factor would need to be determined through future research.

The next three studies of this dissertation extended the cognitive–motor framework to examine how failures in decision-making, cognition, and neural engagement contribute to ACL injury mechanisms in healthy population. Chapter 4 demonstrated that unbalanced landings are not random outliers but rather represent meaningful performance breakdowns that expose elevated biomechanical risk. Across both balanced and unbalanced trials, cognitive challenge amplified frontal-plane knee loading (increased pKAbA and pKAbM), which elevates ACL risk, but also increased sagittal plane motion, suggesting a compensatory increase in knee flexion to maintain stability under decision-making pressure. In contrast, studies examining unanticipated run-to-cut tasks, which involve single-limb movement, have reported reduced knee flexion and greater stiffness, indicating that anticipatory limitations in unilateral movements may constrain sagittal-plane motion more severely [171, 172]. Importantly, when average time-to-react was modeled as a covariate, condition effects diminished, indicating that the limited time available for movement preparation, rather than cognitive load alone, drives much of the observed mechanical risk. This finding suggests that unbalanced landings offer valuable insight into the limits of perceptual–motor control. It also emphasizes that reaction time constraints interact with attention demands to shape neuromuscular control. From a practical standpoint, this interaction implies that interventions designed to reduce ACL injury risk should incorporate time-pressured decision-making movements that simultaneously challenge perceptual speed and motor planning. From a research perspective, future work should integrate neural and behavioral metrics under varying time constraints to quantify how reduced preparation windows alter cortical activation, motor coordination, and joint loading. In general, including these unsuccessful trials, rather than discarding them, yields a more representation of sport-specific behavior and highlights the need

for prevention programs that train athletes to maintain safe movement patterns under time-pressured and cognitively demanding conditions.

Chapters 5 and 6 advanced this model by linking behavioral and neural indices of cognitive performance to motor outcomes. Chapter 5 showed that although attention control scores modestly correlated with decision-making success in the complex jump-landing task, much of the variance in failure rates remained unexplained by static cognitive metrics alone. These results indicate that cognitive–motor integration during dynamic movement depends on multiple interdependent domains rather than isolated cognitive capacities. Chapter 6 further explored this relationship by comparing cortical activation during an attention-control task with behavioral performance in unanticipated landings. Although no significant correlations emerged, the direction of effects suggested that greater prefrontal engagement may support better motor decision-making. The absence of strong associations likely reflects both the high competence of the athletic cohort and the challenge of relating neural efficiency measured during seated tasks to behavior during explosive, full-body movements. Collectively, Chapters 4–6 advance a comprehensive neurocognitive–temporal model of ACL injury risk, positing that brief disruptions in attention or processing time during high-demand movements, not chronic deficits alone, precipitate the neuromechanical errors that increase ACL loading. This framework bridges biomechanics, cognitive neuroscience, and rehabilitation science, underscoring the importance of integrating cognitive-motor and neural measures into future injury-prevention, assessment, and return-to-sport protocols.

Together, these studies advance a neurocognitive–temporal model of ACL injury risk that integrates biomechanics, cognition, and neural function into a combined framework. By bridging

controlled laboratory biomechanics, clinical dual-task assessments, and neural activation approaches, this work highlights the importance of cognitive–motor function in understanding ACL injury as a multifactorial condition. In this model, risk is conceptualized not as a static trait but as a dynamic state of vulnerability, one that fluctuates with attentional resources, task complexity, and time pressure. Chapters 4 through 6 particularly underscore that failed or unbalanced performances, often discarded in traditional analyses, reveal critical moments when cognitive load exceeds available processing capacity, leading to maladaptive movement strategies. Meanwhile, Chapters 2 and 3 show that such breakdowns persist even after rehabilitation, emphasizing the insufficiency of return-to-sport testing focused solely on symmetry or strength restoration. Integrating these perspectives positions ACL injury as a problem of cognitive–motor adaptability: the athlete's ability to sustain efficient, flexible neuromuscular control when faced with competing cognitive and temporal demands. This synthesis not only reframes how injury mechanisms are conceptualized but also underscores the translational need to merge biomechanical and cognitive evaluations in both research and clinical practice.

Future Directions and Next Steps

The next phase of this research should pursue longitudinal and multimodal approaches to establish how neural, cognitive, and biomechanical markers jointly predict injury and recovery trajectories. Future studies should employ concurrent motion capture, electromyography, and neuroimaging (e.g., fNIRS or EEG) during more complex and ecologically valid movement tasks to directly characterize neural–motor coupling under heightened cognitive-motor challenge. This need is reinforced by behavioral evidence showing that attention control tasks (e.g., Flanker, Stroop, Simon) often yield only small-to-moderate associations with performance accuracy ($r \approx$

0.20–0.40) [168-170], highlighting the need for future studies to recruiting larger samples and revisiting task design to better capture meaningful variability in attention control tasks. The clinical relevance of such small-to-moderate magnitude correlations will also need to be evaluated in future studies. Incorporating virtual reality (VR) environments will allow researchers to simulate authentic sport scenarios that require rapid visual processing and decision-making, thereby improving the ecological validity of laboratory paradigms [173-176]. In addition, it is critical to extend incorporating VR to ACLR populations by examining failed and unbalanced movements, which may reveal subtle neuromechanical and neurocognitive deficits that remain undetected in traditional analyses. Developing portable, real-time systems capable of monitoring both neural activity and movement quality will enable continuous, in-field assessment of athletes during training and rehabilitation. From a translational perspective, intervention studies that combine VR-based decision-making, inhibition control, and perceptual-motor training should be implemented to determine whether enhancing cognitive-motor integration can reduce asymmetry, stiffness, and failure during cognitive-motor challenging tasks. Expanding this framework to diverse groups, including female athletes, youth participants, and more professional athletes, will further clarify the mechanisms of cognitive–motor resilience. Ultimately, the long-term goal is to develop rehabilitation models that not only restore joint function but also strengthen brain–body coordination, allowing athletes to perform safely and effectively when under cognitive and time demands.

General Conclusion

This dissertation provides converging evidence that ACL injury risk cannot be fully explained by mechanical factors alone, highlighting the critical role of cognitive–motor integration in understanding when and how high-risk movement patterns emerge. Taken together, the studies presented advance a neurocognitive–temporal framework that integrates biomechanics, cognitive science, and neuroscience to explain the temporal interplay between cognition and motor control during sport-related movement. Rather than proposing a wholly new model, this framework builds on existing neurocognitive theories that link attention or decision-making errors to altered movement mechanics [26, 34, 36, 121], extending them by using different cognitive challenges and looking at behavioral failure under task demands.

This work also aligns with dynamical systems perspectives, which view movement stability as the result of interactions between the brain, body, and environment [177, 178]. From this standpoint, ACL injury can be seen as a temporary loss of stability, where brief lapses in attention or timing lead to mechanical failure.

Translationally, these findings advocate for the integration of cognitive–motor and neurophysiological assessments into return-to-sport testing, injury-risk screening, and neuromuscular training. Future research should expand on this framework through longitudinal, multimodal designs that track how neural, cognitive, and mechanical markers evolve across recovery and training. Ultimately, this body of work contributes to a broader paradigm shift in sports biomechanics, from restoring movement form to optimizing the underlying brain–body processes that enable athletes to perform safely and effectively under cognitive and temporal constraints.

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APPENDICES

APPENDIX A

Supplemental Material of Chapter 2

Supplemental Table A1: Number of good and missed trials among all participants in each condition and each group

CONDITION	GROUP	NUMBER OF GOOD TRIALS (OUT OF 175 (35 PARTICIPANT X 5 TRIALS))	PERCENT MISSED TRIALS	AVERAGE OF ALL COLLECTED TRIALS AMONG ALL PARTICIPANTS	AVERAGE OF MISSED TRIALS AMONG ALL PARTICIPANTS
NAD	HC	175	1±5%	5.1±0.3	0.1±0.3
	ACLR	174	0.00±0.03%	5.0±0.2	0.03±0.17
NAF	HC	175	2±6%	5±0	0.1±0.4
	ACLR	175	2±6%	5.1±0.4	0.1±0.4
VAM	HC	175	6±11%	5.4±0.9	0.4±0.8
	ACLR	150	12±18%	5.0±1.3	0.6±0.8
VUF	HC	177	24±18%	7.0±1.8	2.0±1.9
	ACLR	156	22±17%	5.9±1.5	1.4±1.2
AUD	HC	175	12±17%	5.9±1.3	0.9±1.4
	ACLR	164	12±13%	5.4±1.3	0.7±0.9
AUF	HC	176	19±20%	6.7±2.1	1.6±2.1
	ACLR	172	12±16%	5.7±1.4	0.8±1.3

Note: For each condition, 5 good trials were collected; however, some trials were removed due to issues in post processing, and for a few participants extra trials were collected to make sure enough trials would be acceptable (HC: Healthy Control, AR: ACLR group).

Supplemental Table A2: Confirmatory analysis for available time to react to unanticipated directional cues and memory task

	Group	VUF	AUD	AUF	VAM
Available Time to React (msec)	HC	248 (51)	376 (81)	347 (75)	258 (76)
	ACLR	239 (58)	353 (77)	335 (76)	236 (57)

note: AUD and AUF times include ~100 msec audio file duration.

Supplemental Table A3: Average variables for each group and limb for Knee Extensor Moment at initial contact (KEM-IC), normalized to body weight and height in percentage (%BW-HT)

Condition	Group	Inv-KEM-IC (%BW-HT)	Uninv-KEM-IC (%BW-HT)
NAD	HC	0.75 ± 0.98	0.78 ± 0.86
	ACLR	0.71 ± 0.93	1.07 ± 1.08
NAF	HC	0.74 ± 0.89	0.74 ± 0.94
	ACLR	0.75 ± 1.09	1.15 ± 1.22
VAM	HC	0.76 ± 0.81	0.84 ± 0.82
	ACLR	0.80 ± 1.05	1.15 ± 1.28
VUF	HC	0.76 ± 1.09	0.79 ± 0.87
	ACLR	0.76 ± 0.93	1.12 ± 1.16
AUD	HC	0.80 ± 0.97	0.70 ± 0.89
	ACLR	0.73 ± 1.00	1.21 ± 1.25
AUF	HC	0.90 ± 1.08	0.88 ± 0.90
	ACLR	0.83 ± 1.00	1.30 ± 1.30

Abbreviations: HC: Healthy Control, ACLR: ACLR group, Inv: Involved limb, Uninv: Uninvolved limb, NAD: Baseline, no visual constraint, NAF: Baseline with visual constraint, VAM: Anticipated secondary direction with visual working memory task, VUF: Visual unanticipated, AUD: Auditory Unanticipated, AUF: Auditory unanticipated with visual constraint.

Supplemental Table A4: p-values for linear mixed effect models for second ACL injury predictors with different analysis approaches.

	Random Effect	Covariates	Group	Condition	Group*Condition	R^2_{adj}
Uni-HRot-Imp	Pair	Included	**0.005**	0.929	0.754	37%
KEM-Asym-IC	Pair	Included	**<0.001**	0.999	0.764	45%
Inv-KAbA-range	Pair	Included	0.149	0.777	0.744	53%
Uni-HRot-Imp	Individuals	Not included	0.147	0.647	0.267	72%
KEM-Asym-IC	Individuals	Not included	**0.012**	0.966	0.399	76%
Inv-KAbA-range	Individuals	Not included	0.493	0.084	0.034	91%
Uni-HRot-Imp	Individuals	Included	0.174	0.753	0.346	72%
KEM-Asym-IC	Individuals	Included	**0.005**	0.985	0.396	76%
Inv-KAbA-range	Individuals	Included	0.607	0.038	0.069	91%

Abbreviation: Uni-HRot-Imp: Uninvolved hip rotation net moment impulse; KEM-Asym-IC: Limb asymmetry in knee extensor moment at initial contact normalized to body weight and height; Inv-KAbA-range: Range of knee abduction angle for the involved limb ($p<0.05/3 = 0.0166$ considered as significant).

Supplemental Table A5: *p*-values for linear mixed effect model analysis for general ACL injury predictors with different analysis approaches.

	Random Effect	Covariates	Group	Condition	Group*Condition	R^2_{adj}
pKFA	Pair	Included	0.151	**<0.001**	0.999	52%
pKAbA	Pair	Included	0.069	0.956	0.986	54%
pKAbM	Pair	Included	0.225	0.929	0.940	49%
pKFA	Individuals	Not included	0.293	**<0.001**	0.967	91%
pKAbA	Individuals	Not included	0.35	0.61	0.512	96%
pKAbM	Individuals	Not included	0.985	0.127	0.514	90%
pKFA	Individuals	Included	0.486	**<0.001**	0.962	91%
pKAbA	Individuals	Included	0.400	0.665	0.499	96%
pKAbM	Individuals	Included	0.866	0.215	0.490	90%

Abbreviation: pKFA: peak knee flexion angle; pKAbA: peak knee abduction angle; pKAbM: peak knee abduction moment normalized to body weight and height ($p<0.05/3 = 0.0166$ considered as significant).

Supplemental Table A6: Average variables for each group and condition for contralateral ACL injury predictors variables.

Condition	Group	CL-KFA (°)	CL-HFA (°)	Contact Time (s)	Stiffness (N/[m*Kg])
NAD	HC	83.7 ± 11.4	86.7 ± 14.1	0.53 ± 0.13	62.3 ± 28.9
	ACLR	86.4 ± 8.5	93.5 ± 11.6	0.58 ± 0.12	62.0 ± 17.9
NAF	HC	82.4 ± 10.7	84.9 ± 14.4	0.52 ± 0.12	63.5 ± 27.8
	ACLR	87.2 ± 8.2	92.6 ± 12.5	0.62 ± 0.14	59.6 ± 16.9
VAM	HC	78.4 ± 11.7	78.5 ± 14.1	0.48 ± 0.12	70.4 ± 29.3
	ACLR	82.4 ± 8.3	87.3 ± 13.0	0.55 ± 0.12	69.9 ± 21.8
VUF	HC	77.7 ± 7.7	79.5 ± 11.4	0.54 ± 0.13	70.1 ± 26.1
	ACLR	81.0 ± 7.8	87.1 ± 13.9	0.58 ± 0.11	74.9 ± 21.3
AUD	HC	77.3 ± 9.1	81.3 ± 12.6	0.51 ± 0.12	71.4 ± 29.1
	ACLR	79.6 ± 8.4	87.0 ± 11.5	0.54 ± 0.12	77.0 ± 20.6
AUF	HC	77.2 ± 8.1	79.6 ± 11.5	0.52 ± 0.13	70.6 ± 26.4
	ACLR	80.5 ± 7.4	86.9 ± 12.4	0.56 ± 0.12	75.2 ± 19.7

Abbreviation: CL-KFA: contralateral limb knee flexion angle; CL-HFA: contralateral limb hip flexion angle.

Supplemental Table A7: Linear mixed effect model analysis for contralateral ACL injury predictors with different analysis approaches. Presented outcomes are *p*-values.

	Random Effect	Covariates	Group	Condition	Group*Condition	R^2_{adj}
CL-KFA	Pair	Included	**<0.001**	**<0.001**	0.948	38%
CL-HFA	Pair	Included	**<0.001**	**<0.001**	0.982	41%
Contact Time	Pair	Included	**<0.001**	**<0.001**	0.393	50%
Stiffness	Pair	Included	0.437	**<0.001**	0.598	39%
CL-KFA	Individuals	Not included	0.095	**<0.001**	0.462	87%
CL-HFA	Individuals	Not included	**0.014**	**<0.001**	0.656	90%
Contact Time	Individuals	Not included	0.039	**<0.001**	**0.007**	84%
Stiffness	Individuals	Not included	0.727	**<0.001**	0.052	85%
CL-KFA	Individuals	Included	0.050	**<0.001**	0.450	87%
CL-HFA	Individuals	Included	**0.011**	**<0.001**	0.638	90%
Contact Time	Individuals	Included	0.052	**<0.001**	**0.012**	84%
Stiffness	Individuals	Included	0.830	**<0.001**	0.032	85%

Abbreviation: CL-KFA: Contralateral knee flexion angle; CL-HFA: Contralateral hip flexion angle ($p<0.05/3 = 0.0166$ considered as significant).

Supplemental Table A8: Average ± standard deviation variables for each group and condition for post-hoc multivariable (based on z scores)

Condition	Group	Composite Z-Score
NAD	HC	0.39 ± 0.83
	ACLR	0.02 ± 0.74
NAF	HC	0.28 ± 0.73
	ACLR	-0.08 ± 0.80
VUF	HC	0.06 ± 0.63
	ACLR	-0.25 ± 0.74
AUD	HC	0.17 ± 0.67
	ACLR	-0.32 ± 0.77
AUF	HC	0.10 ± 0.75
	ACLR	-0.33 ± 0.71

Abbreviations: HC: Healthy Control, ACLR: ACLR group, NAD: Baseline, no visual constraint, NAF: Baseline with visual constraint, VAM: Anticipated secondary direction with visual working memory task, VUF: Visual unanticipated, AUD: Auditory Unanticipated, AUF: Auditory unanticipated with visual constraint.

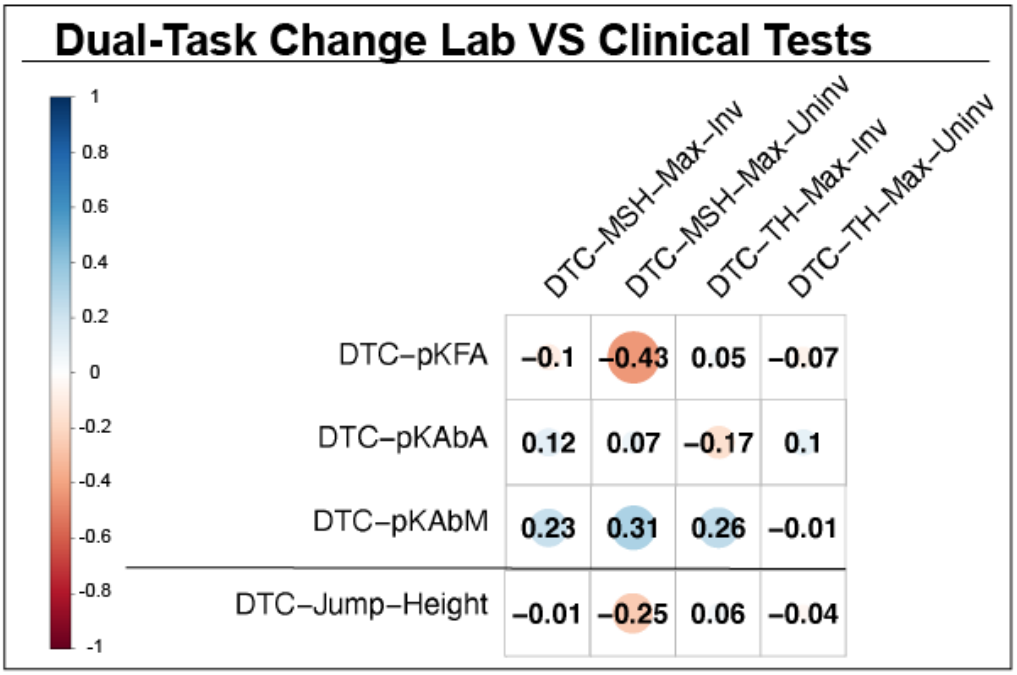
Supplemental Table A9: Linear mixed effect model analysis for multivariable perspective of injury risk with different analysis. Presented outcomes are *p*-values.

	Random Effect	**Covariates**	**Group**	**Condition**	**Group*Condition**	**R^2_{adj}**
Composite Z-Score	Pair	Included	**<0.001**	**0.013**	0.866	60%
Composite Z-Score	Individuals	Not included	**0.023**	**<0.001**	0.552	87%
Composite Z-Score	Individuals	Included	**0.022**	**<0.001**	0.505	86%

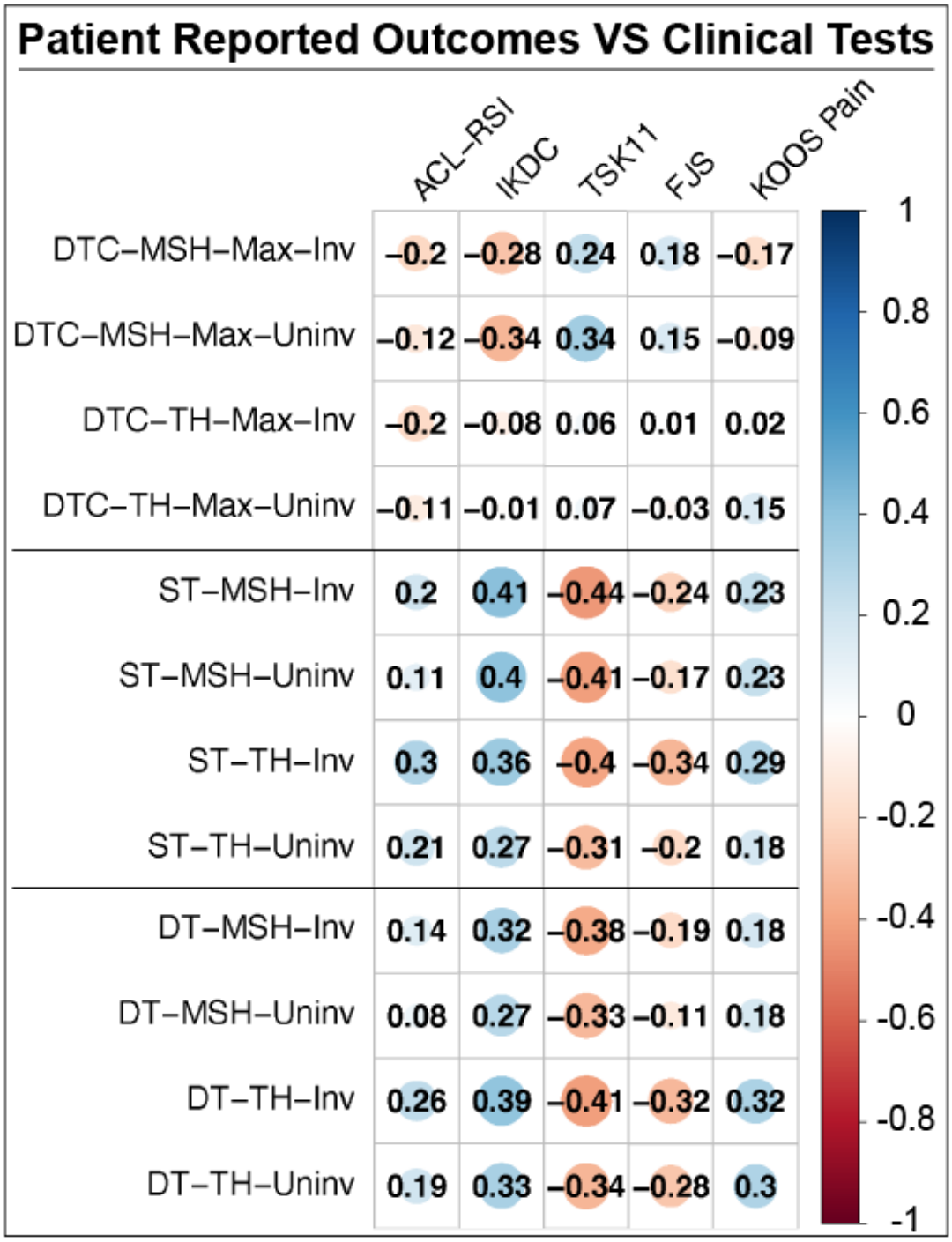
Abbreviation: CL-KFA: Contralateral knee flexion angle; CL-HFA: Contralateral hip flexion angle (p<0.05 considered as significant).

APPENDIX B

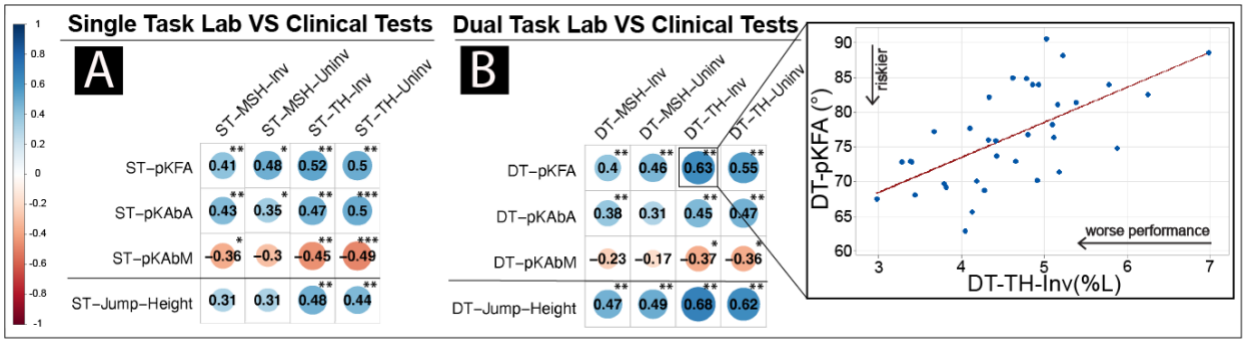
Supplemental Materials of Chapter 3



Supplemental Figure B1: Correlogram for dual-task change (DTC) for primary ACL injury predictors and overall performance in drop vertical jump, and clinical tests (TH: Triple Hop, MSH: Medial Side Hop).



Supplemental Figure B2: Correlogram of relationship between Patient Reported Outcomes (PROs) and clinical tests (TH: Triple Hop, MSH: Medial Side Hop, hop distances normalized to leg length, DTC: dual-task change, DT: dual task, ST: single task, Inv: Involved limb, Uninv: Uninvolved limb).



Supplemental Figure B3: (A) Correlogram for single-task variables (ST) for primary ACL injury predictors and overall performance in drop vertical jump in ST jump landing and clinical tests. (B) Correlogram for dual-task variables (DT) for primary ACL injury predictors and overall performance in drop vertical jump in DT jump landing and clinical tests (*: p-adj of correlation <0.05, **: p-adj of regression with gender as a covariate <0.05, ***: p-adj of regression with gender and jump height as covariates <0.05).

Supplemental Table B1: Average ± Standard deviation of clinical tests and lab drop vertical jump tests variables (*: Significant difference of p-value <0.05)

Clinical values	**ST**	**DT**	**DTC (DT – ST)**
MSH-Inv [%L]	1.08±0.3	1.07±0.3	-0.005±0.11
MSH-Uninv [%L]	1.12±0.33	1.1±0.31	-0.024±0.1
TH-Inv [%L]	4.91±0.99	4.55±0.89	-0.36±0.35*
TH-Uninv [%L]	5.03±1.03	4.73±0.86	-0.3±0.5*
Lab values			
pKFA [°]	80.2±7.5	76.5±7	-3.9±3*
pKAbA [°]	-13.5±6.6	-13.6±6.5	-0.3±2.1
pKAbM [%BW-HT]	3.4±1.3	3.6±1.4	0.2±0.6*
Jump height [m]	0.34±0.08	0.33±0.08	-0.008±0.02*

Supplemental Table B2: Number of good and missed trials among all participants

VALUES	PERCENT MISSED TRIALS	AVERAGE OF ALL COLLECTED TRIALS AMONG ALL PARTICIPANTS	AVERAGE OF MISSED TRIALS AMONG ALL PARTICIPANTS
ST-LAB	0±0%	5±0	0±0
DT-LAB	21±17%	5.9±1.4	1.3±1.2
ST-MSH-Inv	21±21%	4.2±2.0	1.2±2.0
ST-MSH-Uninv	21±19%	4.1±1.4	1.1±1.4
DT-MSH-Inv	18±19%	3.9±1.1	0.9±1.1
DT-MSH-Uninv	13±18%	3.7±1.0	0.7±1.0
ST-TH-Inv	16±17%	3.8±0.9	0.8±0.9
ST-TH-Uninv	15±17%	3.7±0.9	0.7±0.9
DT-TH-Inv	26±19%	4.3±1.1	1.3±1.1
DT-TH-Uninv	24±20%	4.3±1.3	1.3±1.3

Note: For the hop test 3 good trials were collected for each limb (total of 36 participants x 3 = 108 for each limb) and for dual-task lab test 5 good trials were collected, however some trials removed due to issues in post processing, therefore 160 trials were used out of 180 (36 participants x 5) trials. (TH: Triple Hop, MSH: Medial Side Hop, DT: dual task, ST: single task, Inv: Involved limb, Uninv: Uninvolved limb).

Supplemental Table B3: Correlations between single task (ST) and dual task (DT) of clinical tests and lab drop vertical jump tests variables (N: Newton, m: meters, s: second, BW: body weight, HT: height, %L: normalized to the leg length)

CLINICAL VALUES-ST	CLINICAL VALUES-DT	CORRELATION	P-VALUE
ST-MSH-Inv [%L]	**DT-MSH-Inv [%L]**	0.94	<0.001
ST-MSH-Uninv [%L]	**DT-MSH-Uninv [%L]**	0.955	<0.001
ST-TH-Inv [%L]	**DT-TH-Inv [%L]**	0.934	<0.001
ST-TH-Uninv [%L]	**DT-TH-Uninv [%L]**	0.897	<0.001
LAB VALUES-ST	**LAB VALUES-DT**		
ST-Uni-HRot-Imp [N.m.s/kg]	**DT-Uni-HRot-Imp [N.m.s/kg]**	0.712	<0.001
ST-KEM-Asym [%BW-HT]	**DT-KEM-Asym [%BW-HT]**	0.771	<0.001
ST-Inv-KAbA-range [°]	**DT-Inv-KAbA-range [°]**	0.906	<0.001

APPENDIX C

Supplemental Materials of Chapter 4

Supplemental Table C1: Average number of trials for each condition

Condition	Number of Trials (Average ± Standard Deviation)	Percentage from all Trials (Average ± Standard Deviation)
All - Simple	17.12±3.59	-
Failed - Simple	4.48±3.5	25.06 ± 16.81
Good Right limb- Simple	2.24±1.11	14.01 ± 8.06
Unbalanced Right limb - Simple	2.85±1.6	16.46 ± 8.34
All - Complex	22.02±4.37	-
Failed - Complex	7.97±4.72	34.26 ± 16.91
Good Right limb - Complex	2.97±1.33	14.27 ± 7.24
Unbalanced Right limb - Complex	3.63±2.01	16.51 ± 8.82
All - Baseline	11.71±1.95	-
Good Right limb - Baseline	3.00±0.39	26.37 ± 5.47
Unbalanced Right limb - Baseline	1.07±1.31	8.10 ± 8.82

Supplemental Table C2: Distribution of all successful, unbalanced and failed trials

Condition	Successful Trials (Average ± Standard Deviation (%))	Unbalanced Trials (Average ± Standard Deviation (%))	Failed Trials (Average ± Standard Deviation (%))
Baseline	78.58 ± 14.34	21.22 ± 14.47	0
Simple	42.31 ± 14.12	32.80 ± 11.97	25.06 ± 16.81
Complex	31.89 ± 12.08	33.24 ± 14.75	34.26 ± 16.91