IMPROVING THE UNDERSTANDING OF COGNITIVE-MOTOR FUNCTION AND LOWER-EXTREMITY BIOMECHANICS

by

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DEDICATION

I would like to dedicate this dissertation to the two people most involved with my successes in graduate school, Dr. Scott Monfort and Dr. Sarah Codd. It is not an understatement to say that the belief and support of these two phenomenal people played a fundamental role in me getting to where I am today.

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ABSTRACT

Anterior cruciate ligament injuries present a considerable problem for athletic populations, especially those that engage in sports with open-skill movement demands like rapid changes of direction. These injuries typically occur in a non-contact setting, that is, the forces generated by the athlete's own movement overburden the ligaments in the knee and cause partial or total rupture of the tissue. Considerable effort has been devoted to researching and, by extension, counteracting the physical contributions to injury risk; for example, athletes are encouraged to develop better balance and lower-extremity strength to counteract the adverse effects of poor movement performance. However, anterior cruciate ligament injury risk is also tied to cognitive factors as well as physiological factors. This athlete-specific cognitive-motor relationship interacts with external distractions in the sporting environment to compromise an athlete's ability to move safely and effectively. The purpose of this research was to investigate contributions of different cognitive domains to movement performance in distracted, sport-relevant scenarios, to develop a better understanding of the cognitive-motor relationships that underpin injury rates in these athletic populations. A series of studies involving biomechanical and cognitive outcome measures demonstrated that cognitive function has an important, if not fully understood, role to play in mitigating an athlete's susceptibility to distractions during open-skill movement performance. This research adds to a critically underdeveloped body of work explaining the subject-specificity of dual-task movement performance in a lab setting and provides a foundation for developing new injury risk assessment and mitigation efforts for clinicians and coaches.

AN INTRODUCTION TO THE NON-CONTACT ACL INJURY

In the last minutes of the final game of the regular season, a collegiate soccer athlete receives a pass and sprints down the sideline with the ball. As she weaves through defenders, she struggles to tune out the roar of the crowd, the sunbaked turf, and the nagging thought that the score is knotted at 0-0. A sharp pain in the back of her left thigh reminds her that, between some lingering hamstring tightness and the concussion she likely got in practice a few weeks ago, she should have sat these last few minutes out. The added pressure of punching her team's ticket to the playoffs brought her back onto the field, however, and she powers towards the net with only one defender to beat. As she sets herself up for a quick sidestep around her opponent, she gives a feint with her torso and left leg to trick the defender into committing too soon. With her left foot planted, leg nearly fully extended, she suddenly pushes off to her right at a sharp angle and POP. Her season is over, her left knee's anterior cruciate ligament (ACL) completely torn.

ACL injury incidence surpasses 100,000 injuries in the United States each year, affects athletes of every skill level, and comes with an associated yearly cost exceeding $2 billion [4-7]. Rehabilitation following an ACL injury is both expensive and time-intensive, lasting, on average, between six and twelve months with an associated cost exceeding $30,000. ACL reconstruction is a common treatment for those who intend to return to sport, however the return to a similar level of competition following this invasive procedure is inconclusive [8, 9]. Upon return to sport, an athlete that has suffered an ACL injury is predisposed to lasting strength deficits and elevated risks of osteoarthritis progression in the knee, obesity, ACL reinjury, and subsequent contralateral and ipsilateral musculoskeletal injuries [10-12]. This combination of persistent comorbidities motivates the need to develop a robust understanding of what all contributes to an ACL injury, so future researchers might pursue targeted prevention efforts and improved rehabilitation outcomes.

In addition to pervasive musculoskeletal damage, lesions to the ACL compromise neuromotor pathways vital to the normal function of the affected limb [13-15]. Adaptations to the central nervous system are noted following ACL injury and reconstruction, with appreciable changes seen in neural activation associated with visuomotor information processing, the brain's pathway to integrating visual stimuli with desired neuromuscular outputs. These adaptations persist long after traditional return-to-sport metrics clear the athlete for athletic participation. Loss of the native ACL is also associated with decreased proprioceptive ability in the affected limb, likely due to the native ACL being innervated via posterior branches of the tibial nerve that control an involuntary stabilization of the knee joint, the "ACL reflex" [16]. This loss of innervation at the knee is associated with a transition from reliance on subconscious to conscious postural control, compromising the affected athlete's ability to manage simultaneous motor and cognitive tasks [17]. That ACL injuries are innately coupled to neurological comorbidities motivates the need to revisit how clinicians assess an athlete's readiness for competition. However, existing ACL injury prevention efforts have yet to bridge this gap, due to a lack of detailed understanding of how cognitive-motor function influences athletic performance in sport-relevant scenarios.

Figure 1.1: Out-of-plane loading at the knee dramatically increases strain on the ACL (ACL location indicated with the red arrow). Sufficiently high loads generated by sport-specific movements induce ligament tears requiring surgical repair to return to pre-injury activity levels. Image adapted from [2] (left) and [3] (right)

The ACL is a small band (~3 cm) of fibrous tissue that stabilizes the knee joint by restricting anterior translation of the tibia relative to the femur (**Figure 1.1**) [18]. The restriction of this front-to-back movement provided by the passive restraint of the ACL contributes to the hinge-like performance of the joint [19]. Injuries to the ACL in a sport setting occur one of two ways: by contact mechanisms (a direct impact with the knee joint by an external object) or by non-contact mechanisms (catastrophic loading stemming from poor neuromuscular control) [20]. In athletic populations, non-contact ACL injuries typically occur during out-of-plane movement tasks like sidestepping, pivoting, decelerating, or landing from a jump [1, 21]. For the purposes of this dissertation, focus will be exclusively on understanding the non-contact ACL injury moving forward, for two reasons. First, non-contact ACL injuries are the more common of the two injury mechanisms (approximately 70% of ACL injuries are non-contact in nature) [21]. Second, the strategies to combat non-contact ACL injuries fundamentally differ from those needed to combat contact ACL injuries. Strategies to limit external contact to the knee may be limited to sport-specific rule changes [22], while non-contact ACL injury prevention strategies include addressing different facets of the affected athlete's training scheme, as will be discussed below.

Non-contact ACL injuries are inherently multifaceted, with contributing factors ranging from environmental (ground conditions, equipment usage) considerations to modifiable and non-modifiable physiological, biomechanical, and cognitive contributors [11, 23-29]. Modifiable contributors include fatigue levels, quadriceps-hamstring co-activation during movement, hip-knee-ankle coupling, skill level, and familiarization with the desired movement. Fatigued athletes typically perform with poorer neuromuscular control, though the exact relationship between fatigue, conditioning, and ACL injury risk is currently unclear [30-34]. Hamstring co-activation counteracts the anterior translation of the tibia, especially as the knee travels deeper into flexion [35, 36]. Better joint coordination at the hip and ankle contribute meaningfully to reducing loads developed at the knee [37]. Skill level helps to counteract the detrimental effects of sport-specific attentional demands present during ACL injury scenarios (though this relationship is underdeveloped) [38]. Preliminary data suggest that an injury-relevant movement training program can lead to better performance of that movement, reducing the risk of an athlete compromising safe neuromuscular control for a competitive advantage [39]. Non-modifiable contributors include sex differences and subject-specific tibiofemoral anatomy differences: females are consistently found to be at an increased risk of ACL injury compared to males due to contributions from pelvis width, different hormonal cycles affecting joint laxity, and differences in muscular strength, and posterior tibial slope contributes to load transmission in the ACL [40-44]. While not much may be done to address non-modifiable contributors to ACL injury risk, considerable efforts to mitigate the effects of modifiable contributors have been explored.

Existing ACL injury prevention efforts may be divided into two broad camps, injury risk assessments and risk mitigation retraining. Injury risk assessments seek to provide clinicians and coaches with rapidly deployable characterizations of an athlete's relative risk for a subsequent injury, based on how the athlete's movement mechanics during a standard task compare against an established cohort [45-55]. Risk mitigation retraining, meanwhile, focuses on modifying neuromuscular contributors to injury risk, such as quadriceps/hamstring strength imbalances and joint laxity. Current retraining protocols focus primarily on proprioceptive training, core strength stability, plyometrics, isometric strengthening of relevant muscle groups, and flexibility training [50, 56-61]. The efficacy of such programs, however, leaves room for improvement [62]. Recent meta-analyses of the most popular injury risk assessments found them to have poor predictive power in subsequent athletic populations [61]. The most successful risk mitigation retraining programs, meanwhile, have reported a top success rate of 53% [63]. A retraining program that works for over half of considered athletes is noteworthy, but the existence of the other 47% of athletes that went unassisted by the program begs the question of what these injury prevention efforts are missing. Critiques of existing injury prevention efforts cite the unpredictability of competitive sport and the difficulty of capturing environmental validity in the clinic [64, 65]. To that end, much research has been devoted to recreating sport-specific environmental demands while performing injury-relevant movements like jump-landings and running changes of direction.

The environmental demands of competitive sport extend past those of some primary movement to include secondary tasks that researchers wish to emulate in the lab. Secondary task paradigms vary from sport-specific (e.g., reacting to a directional cue, fixating on a visual target) and general (e.g., sustained backwards counting, memory span) cognitive tasks to motor-based (e.g., dribbling a soccer ball) secondary tasks [31, 66-73]. The introduction of secondary tasks, by and large, leads to compromised neuromuscular control in open-skill (i.e., occurring in a dynamic, changing environment) movements. These compromises are manifested as increased medial knee collapse, decreased knee flexion, elevated ground reaction forces, and adverse changes in postural control like increased postural sway. These compromises in neuromuscular control are thought to be attributed to interference in the athlete's central nervous system, stemming from the limitations of an individual's ability to switch conscious attention between two or more tasks [74].

The individual's capacity for attending to simultaneous tasks may best be understood as the rapid, continual switching of attention between two or more task demands [75]. An everyday example of this would be walking while text messaging with a cell phone [76]. Because the concurrent demand of two or more tasks requires the individual to shift focus between performing each one, task inefficiencies arise in one or both tasks [77]. In the walking-while-texting example above, task inefficiencies may be a decreased walking speed, slower or inaccurate messaging, or a combination of the two. Task inefficiencies while multitasking in a competitive sporting environment, meanwhile, have been demonstrated to include compromised lower-extremity control and overall movement quality, as discussed above. Quantifying these task inefficiencies in the laboratory is the central premise of dual-task research in the biomechanics community. However, a key facet of how these inefficiencies arise, an individual's cognitive function, has been overlooked in the context of ACL injury risk until very recently.

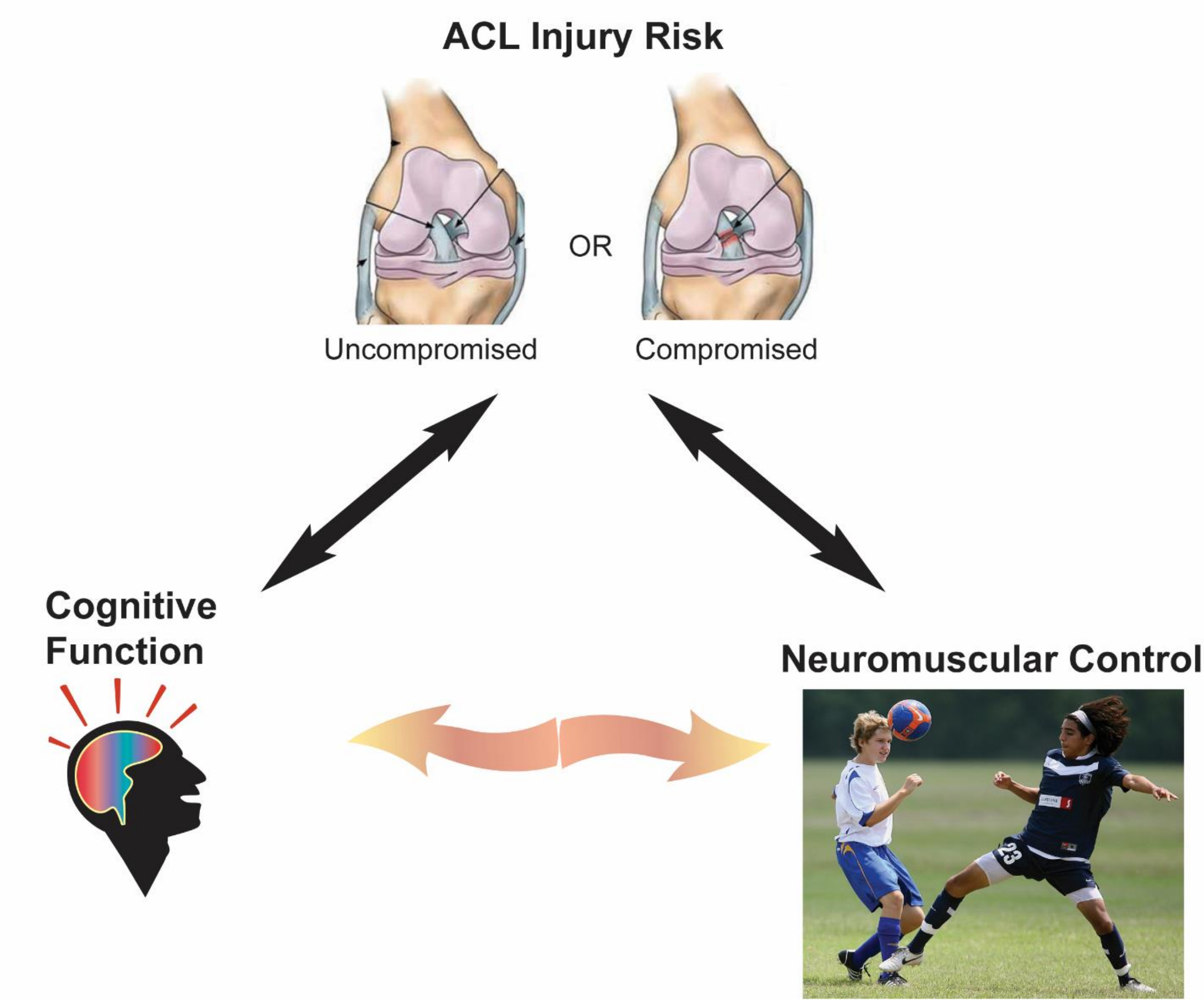

Figure 1.2: Researchers have established the link between cognitive function and injurious (compromised) neuromuscular control, and it is well-understood that dual-task demands in athletic environments pose a threat to safe open-skill movement performance. What has yet to be fully developed is the connection between dual-task demands and cognitive function, a potential key to more effective injury prevention. Image adapted from [78] (top) and [2] (right).

Baseline cognitive function plays an appreciable role in determining overall ACL injury risk, with slower reaction times and processing speeds and worse visuospatial memory being tied to elevated ACL injury risk in a cohort of competitive athletes [79]. Injurious movement patterns are tied to an athlete's cognitive-motor function, the two-way relationship between an athlete's movement performance and their brain-based skills allowing for learning and information manipulation (**Figure 1.2**) [27, 80-82]. This relationship is underdeveloped, however, as little research exists characterizing how dual-task effects change from athlete to athlete during open-skill movement. Dual-task effects have recently been identified as a research area of interest, due to an emergence of literature that implicates individual differences in cognitive function as a missing component to ACL injury risk assessment [83]. A more comprehensive picture of ACL injury mechanics necessitates the understanding of how dual-task demands influence movement performance because athletic performance often requires dynamic movements in the presence of simultaneous cognitive challenges [84].

It stands to reason that the secondary demands of competitive sport (managing a concurrent motor task, recalling the positions of teammates and game strategies, reacting to fluctuating opponent formations, etc.) challenge athletes in a manner that depends on their individual ability to effectively engage with each secondary task while maintaining high-performance movement [27, 28]. To address this question, researchers have investigated how different domains of cognitive performance relate to individual differences in dual-task movement performance. These preliminary efforts associate poorer baseline cognitive function with higher susceptibility to dual-task demands, meaning athletes with less capacity to effectively engage with secondary task demands more greatly compromise their movement quality in an attempt to manage all task demands simultaneously [85-87]. The existing literature on this topic of cognitive-motor function is, however, critically underdeveloped. Additional targeted work is needed to bolster the current understanding of individualized responses to secondary task demands in the athletic environment.

The central purpose of the research conducted for this dissertation was to develop a more comprehensive understanding of cognitive-motor relationships and their contribution to ACL injury risk factors. By characterizing the group and subject-specific differences in neuromuscular control arising from the introduction of various motor-based, working memory, and anticipatory dual-task paradigms, future efforts to understanding the complexities of ACL injuries may have a better-informed picture of how athletes negotiate their environment during competitive sport. The central hypothesis guiding this work was that poorer cognitive function would be associated with greater neuromuscular control deficits. The outcomes of this research are intended to lay the foundation for future exploration into cognitive-motor function in athletic populations as it pertains to non-contact ACL injury mechanics.

A LITERATURE REVIEW ON THE RELEVANCE OF COGNITIVE-MOTOR FUNCTION DURING SPORT MOVEMENTS

The whole of this research has been motivated by a growing understanding that ACL injury occurrence is tied to a risk profile appreciably more complex than an individual's physiological makeup and physical abilities [83]. The following literature review will begin with a brief discussion pertaining to the mechanics of the knee joint and how it is stabilized through passive (i.e., ligamentous) and active (i.e., muscular) components. With this foundation, the review will shift focus to an overview of the role of cognitive function in competitive sport. A thorough investigation of sport-relevant movement research methodologies and relevant findings will follow, with the literature review concluding in a brief discussion on the identified gaps in knowledge in the existing research.

C2.1 The Mechanics and Control of the Knee Joint

The knee joint is a system of active and passive elements that guide the hinge-like actuation of the tibia, femur, and patella while restricting out-of-plane translations and rotations [16, 19]. This stabilization makes basic locomotion (e.g., walking, running, jumping) possible. The primary actuation of the knee joint is flexion-extension, however a complex "screw-home" articulation (transverse rotation of the joint as the knee extends to terminal extension) is noted, with limited frontal rotation present as well (**Figure 2.1a**) [88]. Muscles crossing the joint drive knee articulation and provide active stabilization when the joint is loaded, while ligaments and cartilage act as passive restraints to transmit forces across the segments and functionally limit joint motion to the desired hinge-like behavior noted above. The ACL is one such passive restraint and is made up of a pair of innervated bundles of collagen fibers suspended within an extracellular matrix [18]. Innervation of the ACL is provided via the tibial nerve and contributes to lower-body proprioception [19, 89, 90]. The ACL attaches at the posterior aspect of the femoral head and the anterior aspect of the tibial plateau (**Figure 2.1b**) and stabilizes the knee by restricting anterior translation of the tibia relative to the femur and providing rotational stability to the knee joint [16, 19]. Like other connective tissue, the ACL exhibits a viscoelastic load response [91, 92]. This viscoelastic property is particularly important when considering the nature of ACL injury onset, which typically occurs within a narrow time frame (approximately 100 ms) following initial contact with the ground [21, 93-96]. This rapid development of loading transferred up through the kinetic chain corresponds to a "stiff" material response from the ligament [97]. The lack of compliance in the ligament in these loading scenarios can, in turn, contribute to a partial or total transverse tear of the ligament.

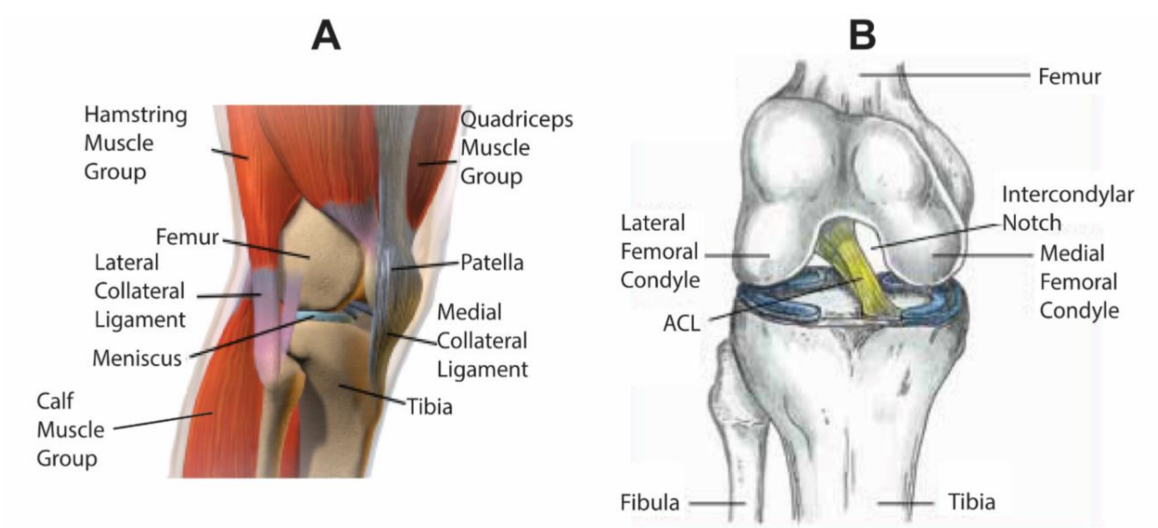

Figure 2.1: A) Restraint of the knee joint is accomplished via a combination of active (muscular) and passive (ligamentous/tendonous) elements crossing the joint space between the tibia and femur. B) The ACL provides passive restraint by drawing the anterior aspect of the tibia to the posterior aspect of the femur through the knee joint's range of motion. Image adapted from [98] (left) and [99] (right)

Knee joint mechanics are unique to the individual athlete's body measurements, also known as anthropometrics. Static alignment of the knee joint (how the thigh and shank segments are oriented in a resting position) associates with differences in ballistic movement mechanics, implicating body measurements as potential predictors of ACL injury [100]. Knee abduction angle, a component of static knee joint alignment, is predictive of future ACL injury in a high-risk athletic population [52, 101]. However, a non-contact ACL injury is dependent on the coupled motion of the ankle, knee, and hip joints of the affected limb to manage the forces developed in the knee joint [102].

Field-based studies provide key insight into the nature of sport-specific injury mechanics at the moment of injury (**Figure 2.2**). A large majority of ACL injuries are observed to occur when the affected limb is at or near full extension and positioned with exaggerated internal rotation and medial collapse (dynamic knee valgus) [1, 21, 93, 94, 96]. Video analysis of injury occurrence also notes that, at the point of injury, an opponent is typically in the

Figure 2.2: Video progression of a non-contact ACL injury (yellow jersey) from initial contact (B) to approximate injury onset (D). Figure adapted from Della Villa *et al.* [1].

near vicinity (within an estimated 1 m), and the injured athlete is occasionally tasked with maintaining control of a ball or other sport equipment; the presence of an opponent and secondary motor task demands both represent attentional demands the athlete must manage while moving [103]. Video analysis also implicates compromised trunk positioning (orienting the body away from the intended path of travel), suggesting that ACL injury is a whole-body affair. Finally, these field-based studies provide evidence for the rapid onset of ACL injuries: most ACL injuries occur within a short time frame following initial ground contact of the affected limb (40-100 ms) [94, 104]. Such a short time frame renders corrective action from sensory feedback ineffective; haptic reflex-based responses occur, on average, at approximately 150 ms [105]. This discrepancy in timing between the fastest available corrective actions and the onset of an ACL injury motivate effective preparatory strategies as a viable intervention target for ACL injury risk mitigation protocols. Field-based video analysis research has proposed a primary mechanism for ACL injury (exaggerated medial knee collapse coupled with internal rotation and terminal extension during single-limb stance) within a narrow time frame, with the presence of additional attentional demands. This has left other research groups the task of investigating how neuromuscular and cognitive factors contribute to the potential incidence of an ACL injury in competitive sport.

These field-based studies have been widely corroborated with mechanistic studies using *in vivo* and *in silico* methodologies. To characterize the primary mechanism of ACL injury (coupled knee extension, internal rotation, and medial collapse), extensive work done with cadaveric testing has characterized the susceptibility of the ACL to different load transmission patterns, based on the relative positions of the lower and upper leg segments. Cadaveric testing is advantageous for two reasons. First, cadaveric testing allows researchers the ability to tightly control the relative positions of the tibia and femur and examine the strain developed in instrumented ACLs [106, 107]. Second, cadaveric testing can simulate forces imparted on the limb that approximate the performance of some open-skill movement like a deceleration or pivot [108, 109]. This methodology has demonstrated that strain in the ACL is increased when any of the following conditions are met: the tibia is externally rotated relative to the femur, the knee joint is at or near full extension, and the knee joint demonstrates exaggerated medial collapse [110-122]. These joint positions demand that the ACL absorb a greater portion of the internal loading at the knee joint. Cadaveric studies, like those described above, corroborate field-based observations of exaggerated medial knee collapse, internal tibial rotation, and full extension as the recurring components of the ACL injury [20, 23, 94, 123].

Cadaveric studies have shown a relative lack of contribution from other ligaments to offload the out-of-plane loads noted above [114, 118, 119]. The noted discrepancy in load development between the ACL and other ligaments means the ACL plays the primary role in passively restraining the knee joint during instances of medial collapse at full extension and so must be bolstered by active contributions from lower-extremity muscles [113]. Active knee joint stabilization is a continuous process of lower-extremity muscular contractions initiated by the nervous system to counteract the loads developed during movement. This continuous neuromuscular contribution must be considered for a more complete understanding of how non-contact ACL injuries arise.

Musculoskeletal modeling provides insight into the active contribution of muscle activation patterns and the resulting loads that are developed in the ACL that may better inform the complex mechanics surrounding an ACL injury [124]. Musculoskeletal modeling is predominantly performed in an open-source software package that allows for the examination of approximated muscle and ligament contributions to simulated movement. By optimizing recorded motion trials and, when available, muscle activation data to validated musculoskeletal models, OpenSim simulates forces developed in muscles and derives strains in ligaments of interest to shed more light on the active stabilization of the knee joint during open-skill movements [125, 126]. Musculoskeletal modeling has highlighted the importance of muscle co-activation immediately following initial weight acceptance in the early part of some dynamic movement to stabilize the knee. The effective coordination of biarticular and uniarticular muscle groups that provide knee joint stabilization implicates three key active contributors to the problem of non-contact ACL injuries: 1) the contractile forces generated at the quadriceps increase ACL strain when not sufficiently counteracted by the hamstrings muscle groups [127-129], 2) knee joint stabilization is achieved through a coordination of all lower-extremity muscle groups [130-133], and 3) the muscles surrounding the knee joint present a performance-stability inverse relationship (what is best for the health of the ACL negatively impacts sports performance) [134, 135]. The agonist and antagonist muscle groups driving knee motion provide key stabilization of the joint but, in certain joint positions, can contribute to increased strain in the ACL and subsequently elevated risk of injury. Through musculoskeletal modeling studies, biomechanics researchers have developed a detailed understanding of how the knee is stabilized during movement, as well as how that stabilization might fail under certain loading conditions.

The combined methods of field-based and mechanistic research implicate an interaction of environmental factors with physiological contributors, both modifiable (e.g., adverse knee joint positioning and poor co-activation between the agonist and antagonist muscle groups) and non-modifiable (e.g., ligament thickness and posterior tibial slope), that contribute to ACL injuries [20, 123]. However, risk factors for ACL injuries extend past an individual's musculoskeletal makeup and the environmental demands of competitive sport. Although the research methodologies mentioned earlier provide key insight into the physical nature of ACL injuries, they are unable to account for another key component of movement performance: an athlete's cognitive function.

C2.2 Cognitive Function and Competitive Sport

Recent examinations of injury rates in athletic populations have shown that athletes who go on to suffer an ACL or other lower extremity injury display poorer measures of cognitive function than their uninjured counterparts [27, 80, 81]. Specific domains of cognitive function that have been implicated thus far include visual and verbal memory, processing speed (the rate at which an individual can take in information), and reaction time. Swanik *et al.* (2007) identified medium-to-large discrepancies in memory, processing speed, and reaction time (|Cohen's d|: 0.46-0.77) between athletes that went on to suffer a non-contact ACL injury and matched control subjects [27]. Wilkerson *et al*. similarly identified a greater rate of lower-extremity injuries in athletes associated with slower reaction time measures from the ImPACT assessment (reaction times > 0.545 s - Odds Ratio: 2.94; Relative Risk: 2.17; p = .038) [81]. Athletes with poorer processing speed and slower reaction time are likely at a disadvantage when responding to the rapidly-changing environment of competitive sport, and it is reasonable to interpret this temporal disadvantage as translating to more adverse compromises in movement quality, resulting in a higher rate of injury incidence. Deficits in memory performance, meanwhile, may be linked to the higher-order demands of competitive sport; athletes with a reduced capacity to manage the cerebral aspects of competing likely find themselves devoting more attention to secondary task demands and compromising their ability to move effectively as a consequence.

It is also well established in the literature that suffering a mild traumatic brain injury (mTBI), colloquially referred to as a concussion, is attributed to an elevated risk of subsequent ACL and other non-contact lower extremity injuries [82, 136]. It is estimated that 3.8 million sports-related mTBIs occur in the United States each year across all skill levels. An mTBI is associated with deficiencies in the athlete's attentional control and memory, but these injuries are also associated with lasting deficits in postural control and multitasking ability between a cognitive and a motor task. Due to its prevalence in competitive sport, the sex differences noted in concussion symptoms, and the understanding that not all mTBI are identified [137-140], the negative cognitive and neuromuscular impacts of mTBI serve as another motivator for why cognitive-motor function in injury-relevant movements should be more fully developed. Recall that effectively managing the various aspects of active knee stabilization plays a large role in determining how much strain the ACL must absorb during sport-specific movements. In the context of an injury that typically occurs within an imperceptibly short time frame, effective movement execution is especially reliant on an individual's ability to process and respond to incoming stimuli. Any deficits in cognitive function, in turn, pose a threat to an athlete's efficient neuromuscular control.

An athlete's cognitive function underpins their management of the complex demands of competitive sport. The cognitive domains that make up an individual's capacity to prioritize and manage task performance in competitive sport, however, are not well understood within the context of sports biomechanics literature. An individual's cognitive capacity for understanding and responding to their surroundings can be broadly divided into two camps: fluid intelligence and crystallized intelligence. Fluid intelligence deals with the individual's capacity to creatively problem-solve and benefit from novel experiences, while crystallized intelligence deals with ingrained behaviors and well-established patterns [141]. Because the nature of competitive sport demands will always retain some semblance of novelty to the athlete [142], the present discussion will focus on how aspects of fluid intelligence factor into the discussion of athletic performance.

An individual's fluid intelligence depends on several cognitive functions to effectively respond to novel situations: primary memory capacity and attentional control to name a few [75, 143, 144]. Primary memory capacity represents the extent to which an athlete can retain task-relevant information over a short period of time [144]. Primary memory demands in competitive sport are akin to recalling the spatial positions of an athlete's teammates and opponents. Attentional control is an athlete's ability to initiate responses based on task-relevant information and is linked to the neurocognitive "arousal" of the athlete [145]. One example of the role attentional control serves the athlete is by allowing them to tune out the noise of the crowd while responding to the coach on the sidelines. The domains of fluid intelligence noted above represent an important, but insofar undeveloped, facet of cognitive-motor research that has the potential to aid in explaining the subject-specificity of ACL injury risk profiles. Because of cognition's inherent ties to sports performance and injury risk, a thorough investigation into how these domains of cognition interact with neuromuscular control and the resulting lower extremity mechanics is warranted.

C2.3: The State of Sport-Relevant Motion Capture Research

A central limitation of the field-based studies discussed in C2.1 is that precise measurements of the joint positions and developed loads at the time of injury are unavailable to the observing researcher [21]. This unavailability of a detailed view into how the athlete performs sport-specific movements translates to an incomplete picture of how secondary tasks (e.g., responding to defenders, ball control, etc.) influence an athlete's movement. To investigate the cognitive-motor relationships discussed in C2.2, biomechanics researchers require a measurement methodology that allows for a comprehensive examination of the athlete's movement mechanics in a controlled setting, with the ability to introduce sport-specific demands. Passive optical motion capture of sport-specific movement is one commonly-used methodology that allows biomechanics researchers the ability to quantify movement mechanics during injury-relevant movements of interest [146].

The desired outcome from collected marker trajectory data is the pose estimation of a biomechanical model. Pose estimation describes the orientation of the different segments of the body in relation to each other. This estimation, in turn, allows for the calculation of variables like segment velocities and accelerations for kinetic analysis. This pose estimation is quantified by the rotation matrix from the global (lab-based) to the local (segment-based) coordinate system *R* and translation vector between global and local origins $\vec{O}$ found in **Eq. 2.1** [147].

$$\vec{P}_i = R'\vec{p}_i + \vec{O} \qquad \textbf{(Eq 2.1)}$$

Here, $\vec{P}_i$ represents the three-dimensional position *P* of each segment marker *i*, defined by the marker trajectories, with respect to the global coordinate system. This is what is collected during motion capture trials. $\vec{p}_i$ represents the position of each segment marker with respect to its corresponding local coordinate system. Local coordinate systems for each segment are defined in a static calibration trial using anatomically-relevant marker placements [148]. Pose estimation is typically accomplished using one of three methodologies: direct pose estimation, segment optimization (six degree-of-freedom method), and global optimization (constrained inverse kinematics method) [147, 148].

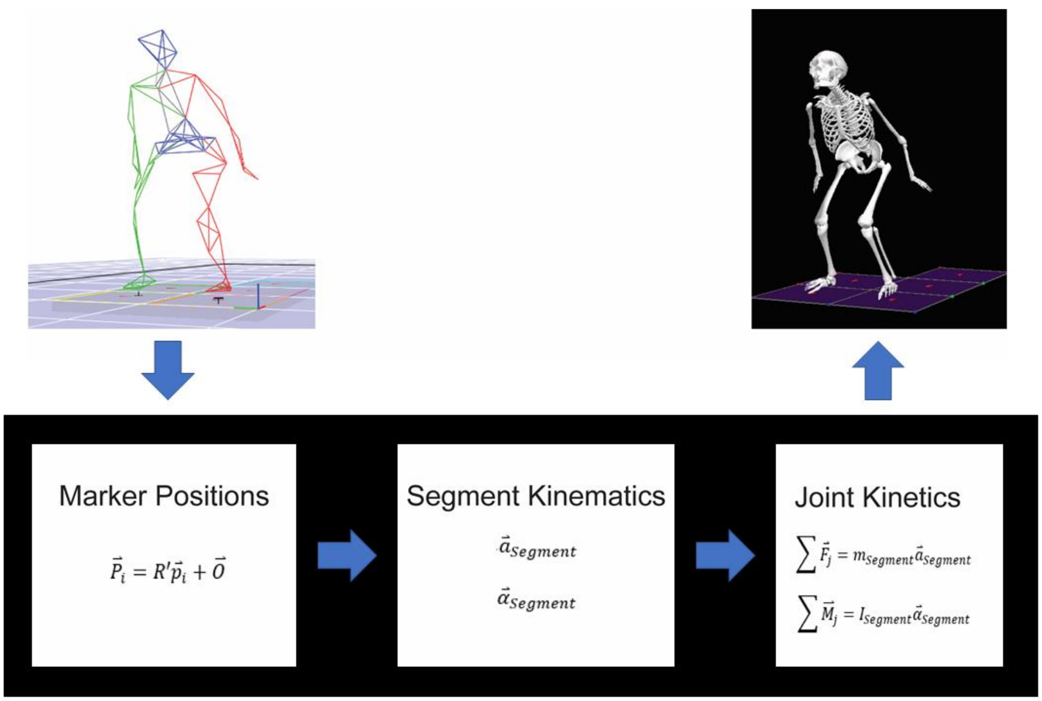

Figure 2.3: General workflow for kinematic and kinetic analyses(Counter-clockwise, from top left) Collected motion capture data are used to calculate segment positions in three-dimensional space. Second derivatives of segment trajectories provide translational and rotational velocities and accelerations. These kinematics, in conjunction with ground reaction force data, are then used to determine net joint forces and moments.

Direct pose estimation leverages the same anatomical markers that are used in static calibration trials to directly solve for R and $\vec{O}$. The primary limitations of the direct pose estimation approach are error propagation from distal to proximal segments (i.e., an error in tracking a proximal marker compounds down the segment, because distal and proximal segments share a joint center), susceptibility to soft tissue movement artifact, and sensitivity to marker occlusion (missing data) [147].

Segment optimization (6DOF) pose estimation is based around the premise of tracking each segment of interest independently. 6DOF pose estimation is informed by **Eq. 2.1** and collapses to a set of equations (**Eq 2.2.-2.4**) [147].

$$f\left(R_{Segment}, \vec{O}_{Segment}\right) = \sum_{i=1}^{m}[(\vec{P}_i - R'_{Segment}\vec{p}_i) - \vec{O}_{Segment}]^2 \qquad \textbf{(\textit{Eq. 2.2})}$$

$$g\left(R_{Segment}\right) = R'_{Segment}R_{Segment} - I = 0 \qquad \textbf{(\textit{Eq. 2.3})}$$

$$\nabla f\left(R_{Segment}, \vec{O}_{Segment}\right) - \lambda \nabla g\left(R_{Segment}\right) = 0 \qquad \textbf{(\textit{Eq. 2.4})}$$

Eq. 2.2 defines the sum of squares error between the collected motion capture data and the estimated positional data based on R and $\vec{O}$. In the 6DOF methodology, the sum of squares error is minimized subject to the following constraint: the estimated rotation matrix *R* multiplied by its transverse *R'* is to be equal to the identity matrix *I* (i.e., orthonormal) (**Eq. 2.3**). **Eq. 2.4** states that the gradient ∇ of the sum of squares error will be equal to a set of Lagrangian multipliers λ times the gradient of the orthonormal boundary condition. The 6DOF approach may be solved analytically (i.e., there is a unique solution that describes the model's movement) as long as the number of tracking markers *m* for each segment is greater than 2 [147]. The positions of each segment are informed by these additional tracking markers that may be separate from the anatomical markers used in static calibration.

6DOF pose estimation allows for the determination of both joint translations and rotations, because each segment is tracked independently. Quantifying joint translations in addition to joint rotations is particularly useful when examining clinical pathologies relating to joint injuries (e.g., anterior translation of the tibia in ACL-reconstructed subjects) [149-151]. This methodology is, however, dependent on the robustness of the marker data collected [152]. A central limitation of the 6DOF method is the presence of soft tissue movement artifact, which can manifest as unrealistic joint translations in dynamic trials [153]. Redundant tracking markers and proper smoothing techniques may minimize this limitation of soft tissue movement [154, 155]. However, adding in tracking markers presents its own limitation of added study participation time that may not be suitable for all applications.

The global optimization (IK) methodology assumes that the various segments of the body are affixed in a kinematic chain that respects typical joint ranges of motion, thereby forcing the resultant pose estimation to behave according to expected human movement. The result of these user-defined constraints is that the resulting solution of *R'* and *O* takes the form of **Eq. 2.5,** with associated cost function **Eq 2.6** [147, 156]:

$$\vec{P}_i = R'(\vec{q})\vec{p}_i + \vec{O}(\vec{q}) \qquad \textbf{(\textit{Eq. 2.5})}$$

$$E(\vec{q}) = \sum_{i=1}^{m}[\vec{P}_i - R'(\vec{q})\vec{p}_i - \vec{O}(\vec{q})]^2 \qquad \textbf{(\textit{Eq. 2.6})}$$

Eq. 2.5 is an extension of **Eq. 2.1**. In this case, however, R and $\vec{O}$ are given with respect to generalized coordinates $\vec{q}$. User-defined constraints (e.g., zero translation between the distal end of the thigh segment and proximal end of the shank segment) are subsequently defined through these generalized coordinates. **Eq. 2.6** defines the sum of squares error between the collected motion capture data and the estimated positional data based on R and $\vec{O}$, subject to kinematic constraints. The primary benefit of the IK approach is the user's ability to eliminate nonphysiological movement. Defining kinematic constraints at the joints mitigates the problem of soft tissue movement artifact, which, in turn, allows for data collection with relatively sparse marker sets. The tradeoff for this added convenience and time saved is that the IK method limits the ability to examine clinically-relevant joint translations (e.g., if a constraint is imposed to not allow joint translation) [157].

Analytic solutions to pose estimation using the IK methodology do not exist, so numerical solutions to R and $\vec{O}$ that solve for the minimum of **Eq 2.6** must be explored [158]. Optimization of the desired pose estimation is commonly achieved using one of three techniques: the Levenberg-Marquardt, the Quasi-Newton, and the Simulated Annealing optimization methods [159]. The Levenberg-Marquardt optimization is the least computationally expensive [160]. Its major limitation, however, is its potential to arrive at a local maximum or minimum solution, rather than the global solution, if the initial guess is sufficiently close to that local extreme [161]. What this means in the context of computing joint kinematics, is that this optimization method will periodically find "solutions" that do not resemble anatomically-feasible behavior (e.g., an athlete performing a jump-landing with perfectly neutral frontal-plane orientation from beginning to end). More computationally demanding, but still in the realm of usable for large data sets, is the Quasi-Newton optimization method [162]. The Quasi-Newton method is markedly slower in its computation time but is less susceptible to erroneously finding local extrema rather than the global extreme [163]. Most computationally demanding is the Simulated Annealing solution method [164]. At the cost of drastically increased computation times, the Simulated Annealing method demonstrates near-perfect identification of a global solution, particularly when systems of data demonstrate a high degree of disorder [165]. However, while the Simulated Annealing method is the most robust of the three in terms of determining the global solution, its computational demands outweigh the benefits of using this approach in most biomechanical applications [165].

When choosing a pose estimation approach for the studies of this dissertation, the methodological choice was made to use the IK methodology with a Quasi-Newton optimization method rather than a 6DOF approach. The primary benefit of the IK methodology in this context was the use of fewer tracking markers, thereby allowing for the examination of more dual-task paradigms without making the time commitment overly burdensome for participants. This methodological choice comes with a tradeoff, however, as joint translations like anterior tibial shear cannot be examined and may be of potential benefit in examining ACL injury-relevant mechanics.

Pose estimation yields kinematic data in three dimensions, constituting segment orientations and positions across the trial. Linear and angular accelerations ($\vec{a}_{Segment}$, $\vec{\alpha}_{Segment}$) are obtained for each segment through time differentiation of these signals. These data can then be coupled to ground reaction force data to calculate net joint reaction forces and moments (**Figure 2.4**).

$$\sum \vec{F} = m_{Segment}\vec{a}_{Segment} \quad \textbf{(\textit{Eq. 2.7})}$$

$$\sum \vec{M} = \bar{I}_{Segment}\vec{\alpha}_{Segment} \quad \textbf{(\textit{Eq. 2.8})}$$

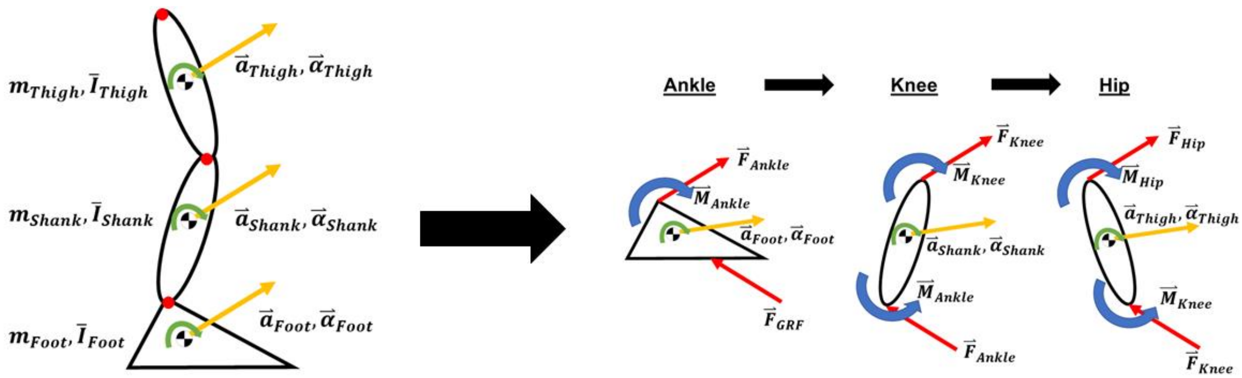

Figure 2.4: Two-dimensional simplification of determining net joint reaction forces and moments, beginning with ground reaction force data ($\vec{F}_{GRF}$). Not pictured: head, arm and trunk segments

$m_{Segment}$ and $\bar{I}_{Segment}$ constitute each segment's mass and mass moment of inertia tensor, respectively, which may be calculated based on subject-specific anthropometric measures and established standards [166]. $\sum \vec{F}$ and $\sum \vec{M}$ represent the sum of forces and moments, respectively, acting on a given segment, which are used to solve for net reaction forces and moments. These net forces and moments represent the net effect of all joint structures required to be consistent with observed kinematics [167]. This net effect constitutes the contributions of all the joint structures at that point (e.g., muscle forces, ligament restraints, joint contact forces) [168]. Granular analysis of these individual contributions, however, requires additional analysis through musculoskeletal modeling programs. This additional analysis is required because regions of interest like the knee are overdetermined systems [169-172].

Motion capture-based assessments have considered a range of different basic movements (continuous walking and running, jumping, landing, and jump-cutting to name a few) in a variety of populations (generally active populations, recreational and competitive sport-specific athletes, a mix of both), reflecting the heterogeneity of sports performance assessment. Due to the disproportionate number of non-contact ACL injuries in open-skill sports like soccer and basketball compared to sports like cross-country running, this discussion will be focused only on motion capture research focused on dynamic movements commonly found or replicating those found in open-skill sports. The state of the literature currently presents a host of opportunities to investigate, in real time, how athletes move and respond to the demands of competitive sport.

Open-skill movement assessments, where an athlete is required to complete a discrete set of movement demands (typically of a ballistic nature), are commonly used in motion capture studies to approximate the movement demands observed in sports where non-contact ACL injuries are most common (**Figure 2.5**). These movement assessments are typically directed at simulating a change-of-direction demand and may require unilateral (single-limb) or bilateral (double-limb) involvement. Multiplanar movements provide some immediate insight into the demands of open-skill sport, however they are not without critique. Two main critiques surrounding open-skill methodologies are the repeatability of lab-based versus sport-relevant movement demands and the disparity between lab-based and sport-relevant environmental demands. The first critique represents a central limitation of lab-based assessments in general; a host of different movement demands may all result in a non-contact ACL injury. Researchers may address this limitation by striking a balance between what is repeatable in the lab with what is environmentally relevant for the sport in question and examining to what extent athletes adopt similar movement strategies across different movements. The second critique is addressed by introducing dual-task demands to the movement assessment.

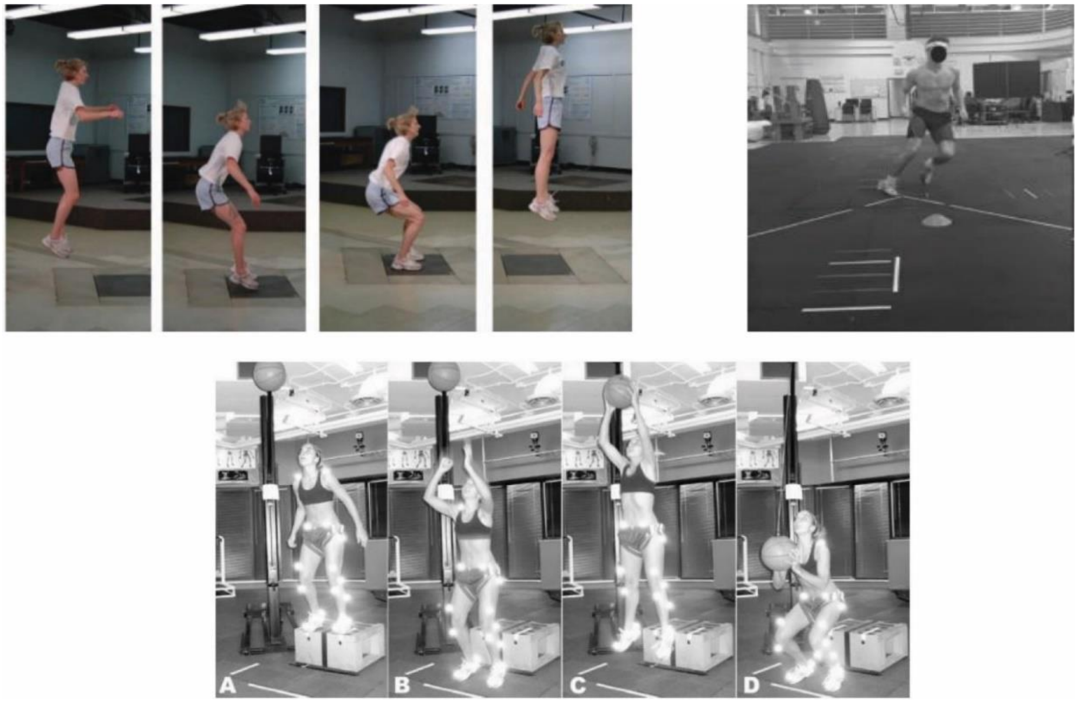

Figure 2.5: A variety of open-skill movements have previously been used to investigate the role of different considerations in regard to non-contact ACL injuries, with the common intention of simulating the scenario within which these injuries commonly occur (Clockwise, from top left: jump-landing (adapted from Herman and Barth), running sidestep (adapted from Monfort *et al.*), and drop-jump tasks (adapted from Ford *et al.*))

The dual-task in movement assessments is, broadly speaking, the requirement that a study volunteer complete a secondary task while performing the desired movement. It can be movement-related (e.g., dribbling a soccer ball while performing a running sidestep) or movement-unrelated (e.g., counting down by sevens while performing a drop-jump). The dual-task method may also be motor-based (i.e., requiring the simultaneous coordination of some movement to manipulate a physical object) or cognitive-based (i.e., requiring the attention of some mental exercise not tied to physical manipulation of an object) (**Table 2.1**). The aim of the dual-task paradigm, whether movement-related or unrelated, motor-based or cognitive-based, is to direct the athlete's attention away from their movement, thereby simulating the distracting environment of competitive sport and inducing additional attentional demands on the individual [103]. There are several different accepted dual-task methodologies that induce the desired attentional demands. However, these established paradigms represent only a starting point from which more complex dual-task methods may be explored.

Table 2.1: An overview of established dual-task paradigms used in sports biomechanics studies. Depending on the nature of the research protocol, combinations of these dual-task paradigms may be explored to investigate the compounding effects of attentional overload in a sports setting.

	Cognitive-Based	**Motor-Based**
Movement-Related	Unanticipated Overhead Target	Ball-handling Lacrosse stick manipulation
Movement-Unrelated	Serial 7’s Stroop	-----

The most commonly-used dual-task paradigm in a sports setting is a movement-related, cognitive-based task: the unanticipated condition. Unanticipated dual-tasks are meant to simulate the in-game demands of a rapidly changing field of play [66, 173]. In this paradigm, the athlete performing the task is given a number of different directions they may be asked to go and provided with the instruction to move in the requested direction as soon as it is presented. This approach limits the athlete’s ability to pre-plan their intended movement. Unanticipated movement paradigms are commonly used in sports biomechanics research for two key reasons: these paradigms are well-established in terms of their translation to real-world competitive sport demands, and they have relatively low demands as far as additional equipment is concerned. The unanticipated paradigm has been investigated using both general and sport-specific directional cues, with systems consisting of colored lights, shapes, or simulated “opponents” serving to indicate the desired path of travel [30, 31, 33, 66, 67, 71, 72, 87, 174-184]. The unanticipated movement paradigm has a demonstrably negative impact on neuromuscular control across a range of different athletic populations, though not all unanticipated effects are consistent. The most consistent effect the unanticipated movement has on neuromuscular control is an elevated degree of knee frontal plane motion and loading [67, 175], while various changes in knee extension and muscle activation patterns of muscles surrounding the knee joint are also noted [174]. Taken together, this means that the ability of an athlete to pre-plan their movement is associated with more optimal knee mechanics. By “mapping” the desired trajectory before starting the movement, the athlete would be afforded ample opportunity to activate the required muscles to orient the lower extremity segments in the most appropriate manner [185-188]. In the context of sport-specific movements, the unanticipated paradigm translates to compromising the athlete’s ability to lean on this motor control strategy of targeted muscle pre-activation and leaving the athlete unable to minimize the load transferred to the ACL and other passive restraints of the knee.

Another commonly-used dual-task paradigm that has similar motivations relating back to simulating in-game demands are the various motor-based movement-related dual-task paradigms, specifically ball-handling (dribbling and fielding), simulated rebounding, and static possession of sporting equipment while performing a sport-relevant movement. Previous work by multiple research groups has identified the presence of an overhead goal (simulated rebound) leads to compromised lower-limb biomechanics and greater ground reaction forces, resulting in greater forces transmitted to the knee joint [67, 73, 189]. Additional work examining the effects of ball-handling as a dual-task paradigm suggests that the added attentional demands of negotiating a movement while maintaining control of a ball are sufficient to induce compromises in neuromuscular control [190, 191]. The demands of passively securing and maintaining possession of sporting equipment (e.g., a field hockey stick or ball) is also associated with compromised postural control and neuromuscular adaptations (more upright trunk position, increased vertical ground reaction forces) [72]. Motor-based dual-task paradigms represent another potential hazard inherent in competitive sport that is inseparable from the sport itself.

Restricting athletes visual gaze represents a key gap in knowledge that warrants further development in the literature. Unanticipated paradigms (and, to a lesser extent, motor-based tasks like ball-handling and simulated rebounds) in the literature are hindered by a central potentially-confounding factor: the requirement that athletes direct their visual gaze away from the intended path of travel to complete the secondary task. This visual constraint may contribute as a confounding factor to the results seen in previous studies [67, 73, 189]. A recent study by de Sire *et al.* provides further context by examining an extreme version of visual constraint, blindfolding participants and examining their muscle activation patterns during a single-limb drop-landing [192]. Key findings relevant to the current discussion center around a 33% increase in muscle co-activation during the blindfolded conditions compared to the visually unconstrained conditions. This may be interpreted as a precautionary measure taken by the athlete to protect against injury in the absence of visual feedback during movement. However, the use of neutral visual constraints (visual constraints that are not tied to other dual-task demands) is critically underdeveloped in the literature and does not currently allow for a thorough discussion of how visual constraint factors into neuromuscular control.

There are several cognitive tasks that have been developed in the psychology literature that may be useful in implementing dual-task conditions that are designed to probe certain cognitive processes of interest. Domain-specific cognitive secondary tasks are less representative of in-game task demands but have rather been developed to challenge a specific domain of cognitive function. Because of the paucity of their use, cognitive dual-task effects are not widely developed in the sports biomechanics literature. A few studies have, however, demonstrated that including general cognitive tasks in open-skill movements have been associated with ACL injury-relevant changes in neuromuscular control (increased vertical ground reaction force, decreased peak knee flexion, increased knee abduction) [32, 69, 193]. This initial foray into general cognitive demands and how they influence movement performance lends credence to more efforts to study the effects of cognitive tasks developed for challenging specific cognitive domains more cleanly [143]. This allows biomechanical researchers to tap into the methods developed by the cognitive psychology field and provides new opportunities for investigating the various domains that might contribute to effective movement performance.

The dual-task effects mentioned above have been, until recently, treated in the literature as a binary matter: either a dual-task effect is or is not present. Recall, however, the earlier discussion on individual differences in cognitive function and how that has given rise to a better understanding of ACL injury risk. With this richer understanding of the subject-specificity of ACL injuries, several groups have begun to investigate interactions between dual-task demands, individual baseline cognitive function, and neuromuscular control in sport-specific movement assessments. Recent findings point to individual cognitive domains being associated with subject-specific differences in several different types of dual-task paradigms [79, 85-87, 184]. Specifically, worse measures of reaction time, processing speed, attentional control, and visuospatial memory have been associated with worse lower-extremity mechanics during open-skill movements like running sidesteps and jump-landings. However, the dual-task paradigms that have been investigated do not represent the full level of complexity present in competitive sport, nor do the cognitive domains examined represent the full spectrum of individual cognition. More work is needed to develop a more comprehensive understanding of cognitive-motor function as it relates to ACL injury mechanics and dual-task susceptibility.

C2.4 Identified Gaps in Knowledge

We observed a large gap in the body of research pertaining to the link between athletes' baseline cognitive function, the secondary task demands of competitive sport, and the biomechanics associated with their performance of open-skill movements like sidestep cutting and jump-landing [79]. This gap in knowledge has subsequently led to a blind spot in efforts to meaningfully improve injury prevention and risk assessment protocols, as the requirements of competitive sport are likewise dependent on a subject-specific interaction of neuromotor and musculoskeletal factors [65].

The three gaps in knowledge posed in this section are to be addressed in the next three chapters, with a general summary of the findings and conclusions following thereafter. The first gap in knowledge that will be investigated through this dissertation research is a *lack of understanding of how higher-order cognitive domains, like attentional control and primary memory, contribute to negotiating dual-task demands during open-skill movement*. Neuromuscular control is a complex interaction of conscious and subconscious neuromechanical processes. Prior literature has identified select cognitive processes that associate with knee mechanics, but the spectrum of cognitive processes that have been considered remains sparse. Findings related to this knowledge gap are discussed in ***Chapter 3.*** The second gap in knowledge that will be investigated is a *lack of understanding of how dual-task demands generalize across unique open-skill* *movement*. Dual-task research has investigated the effects of a wide range of secondary task demands, but it is unclear if these effects are similar across different movement paradigms. Findings related to this knowledge gap are discussed in ***Chapter 4.*** The third gap in knowledge that will be investigated is to *separate visual constraint from rapid decision-making dual-task effects*. Dual-task research most commonly relies on a visual modality to induce secondary task demands, but visual constraint has not been identified or ruled out as a confounding factor. Findings related to this knowledge gap are discussed in ***Chapter 5***. Addressing the identified gaps in knowledge will shed new light on the complex nature of cognitive-motor function as it pertains to ACL injuries in athletic populations. This improved understanding of cognitive-motor function in a sport-relevant setting may, in turn, pave the way to developing new injury risk assessment and training paradigms with the hope of lowering ACL injury incidence in athletic populations.

EVALUATING THE SPECTRUM OF COGNITIVE-MOTOR RELATIONSHIPS DURING DUAL-TASK JUMP LANDING

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

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C3.1 Introduction

Anterior cruciate ligament (ACL) injuries account for an annual cost exceeding $2 billion [5] and carry a range of comorbidities [10-12]. During sport, these injuries often occur when athletes pivot, change direction, or land from jumping [20, 94, 96]. Considering sport is a cognitively-demanding, temporally-constrained environment where athletes must quickly process task-critical information, the interplay between task demands, innate cognitive function, and neuromuscular control may contribute to more comprehensively understanding ACL injury risk.

Several studies have established cognitive function as an integral ACL injury risk consideration. Athletes who sustained non-contact ACL injuries demonstrated lower cognitive function compared to matched, uninjured controls [27], and ACL injury rates increase for athletes following concussions [194], supporting the premise that impairments from mild brain trauma influence ACL injury risk factors [82, 136, 139, 195-197]. Additionally, research linking slower reaction time to lower-extremity injuries [81, 82] further supports the relevance of cognitive-motor function, and the ACL Research Retreat identified cognitive-motor function as a research area of interest to aid in improving primary prevention efforts [83]. Cognition is vital to ACL injury research efforts because of the connection between attentional capacity (a key aspect of cognitive function), its limits, and the consequences of overburdening it with secondary task demands. When attention is divided, cognitive interference arises, causing task performance to suffer [103]. Cognitive interference manifests during multitasking requirements inherent in sports where these injuries occur; athletes must perform movements such as a jump-landing or changing direction while simultaneously attending to secondary task demands inherent in any sport [67, 69, 184, 198].

Cognitive-motor research suggests performing a secondary task during dynamic movement leads to adverse changes in knee mechanics [67, 69, 174-176, 184, 198, 199].

While the importance of lower extremity biomechanics during cognitive-motor tasks and cognitive function to ACL injury risk is clear, the link between athlete-specific cognitive function and neuromuscular control during cognitive-motor tasks is underdeveloped. Prior research reports that processing speed and reaction time were related to the knee mechanics of an unanticipated jump-landing [184], while visual-spatial memory was associated with knee abduction changes during a sport-specific sidestep movement [85]. Muscle activation differences between high- and low-cognitive performers during an unanticipated drop-sidestep have been demonstrated [86], and participants with lower attentional control demonstrated decreased postural stability during an unplanned single-leg landing [87]. While prior studies provide support for differences in cognitive-motor function, they have investigated cognitive-motor relationships with isolated consideration for cognitive challenges being introduced. As a result, the understanding of the spectrum of cognitive-motor relationships that are relevant to sport remains limited. This limited understanding motivates the need for a more systematic and targeted approach to elucidating the spectrum of cognitive-motor relationships in at-risk athletes during sport-specific, injury-relevant movements performed in a lab setting.

Given this knowledge gap, this study aimed to implement a systematic approach to more broadly elucidate cognitive-motor relationships that influence injury-relevant knee mechanics. Specifically, the study’s purpose was twofold: 1) identify the effects of various cognitive demands on landing mechanics, and 2) investigate associations between cognitive functions and landing mechanics. We hypothesized that 1) increasing cognitive challenge complexity will be associated with increased pKAbA and pKAbM and decreased pKFA, and 2) athletes with lower cognitive performance will exhibit greater changes in peak knee abduction angle (pKAbA) and moment (pKAbM) and peak knee flexion angle (pKFA).

C3.2 Methods

Participants were eligible if they were between age 18 and 30 years old, female, recreationally or competitively active in either basketball or soccer (played one of the sports at least three times a week or participated in either of those sports at least once a month and had prior high school varsity, college club, or equivalent competitive experience), free from lower-extremity surgeries, and had not suffered a concussion or lower-extremity injury within six months of study participation.

The study protocol involved two lab visits, each lasting approximately 2.5 hours. During the first visit, participants completed baseline cognitive tests. During the second visit, participants completed jump-land-jump movements. To identify factors that may influence differences in cognitive performance between the visits (approximately a week apart), participants were asked to self-report their sleep from the night before, perceived mental and physical fatigue and stress, and if they had suffered a concussion or acute head trauma since the initial visit (jump-landing session only).

The following cognitive tests were used to assess processing speed, primary memory, attentional control, and multitasking.

Processing Speed: Letter and pattern comparison tests were used, in written format, which involved indicating whether letter- or pattern-pairs were the same [200]. The objective of these tests was to complete the test quickly and accurately. Measured variables were completion time and number of correct responses. These tests' outcome variable was normalized as: score = (#correct - #incorrect)/Time to complete [200].

Primary Memory: Letter and digit span tests assessed primary memory [143, 201], where sets of six to ten letters or numbers were presented aurally (digit) or visually (letter), one at a time, to the participant using E-Prime 3.0 (Psychology Software Tools). After each set, participants were required to recall the most recent three to seven numbers or letters they had been given. Participants were given feedback on their performance, followed by another item set. These tests' outcome variable was the total number of letters or numbers the participant could correctly recall [143, 201].

Attentional Control: The anti-saccade and Stroop tests assessed attentional control [202, 203], administered through E-Prime 3.0. In the anti-saccade test, participants were instructed to look to the opposite side of the computer screen from a flashed cue (*) in order to detect a quickly presented target item (O or Q) before it disappeared and was replaced by a pattern mask (#). This task requires suppressing the urge to look towards peripheral distractors and to instead use these cues to direct eye movements in the opposite direction to catch the target. In the Stroop test, color-words were shown to participants in font colors that were congruent with the word itself (e.g., the word "green" in green font) or incongruent with the word itself (e.g., the word "green" in red font). Participants were instructed to vocally respond to the font color, rather than read the word on the screen. These tests' primary outcome variables were response accuracy (both) and reaction time (Stroop only) [202, 203].

Multitasking: One test assessed participants' multitasking ability [75]. The Control Tower test consists of three primary tasks (number matching, symbol matching, letter finding) and four secondary tasks (radar monitoring, arithmetic puzzles, color flash response, auditory decision making). Participants completed as many primary and secondary tasks as they could for ten minutes. The primary outcome variable was the number of primary tasks completed [75].

During the second research visit, reflective markers were attached to participants using double-sided tape according to a modified plug-in-gait marker set [198]. Additional tracking markers were placed bilaterally on the shoes over the head of the first metatarsal and the lateral aspect of the calcaneus. For consistency, the same researcher placed all calibration markers on each participant. Upon recording a standing calibration trial, the markers at the medial femoral epicondyles and malleoli were removed. Participants then completed a standard warm-up of two sets each of eight bodyweight squats and five countermovement jumps [204].

Participants performed jump-land-jumps following an established protocol [184] under a baseline (single task) and four multitasking conditions (**Figure 3.1**). Participants were asked to jump in three secondary directions (**Figure 3.2**). Three good trials in each direction were recorded for each condition. Secondary tasks were administered using E-Prime 3.0 and a 62-inch high-definition television screen placed approximately 5 m away from the primary landing zone. Conditions were performed one at a time. To mitigate the risk of preferentially focusing on one task, researchers instructed participants to "not focus on any one task in particular" and to "do their best on all tasks". Participants were allowed as many practice trials as needed to feel comfortable prior to recording data. One to three trials were typically needed, depending on the condition. Conditions were block-randomized to mitigate systemic fatigue and learning effects. A trial was "good" if each foot landed within the boundary of separate force plates and the participant jumped in the correct secondary direction immediately after landing. Kinematic data were recorded at 250 Hz using a 10-camera motion capture system (Motion Analysis Corp.; Rohnert Park, CA, USA).

Ground reaction force data were recorded at 1000 Hz using two force plates (OPT464508-2K; Advanced Mechanical Technology, Inc.; Watertown, MA, USA).

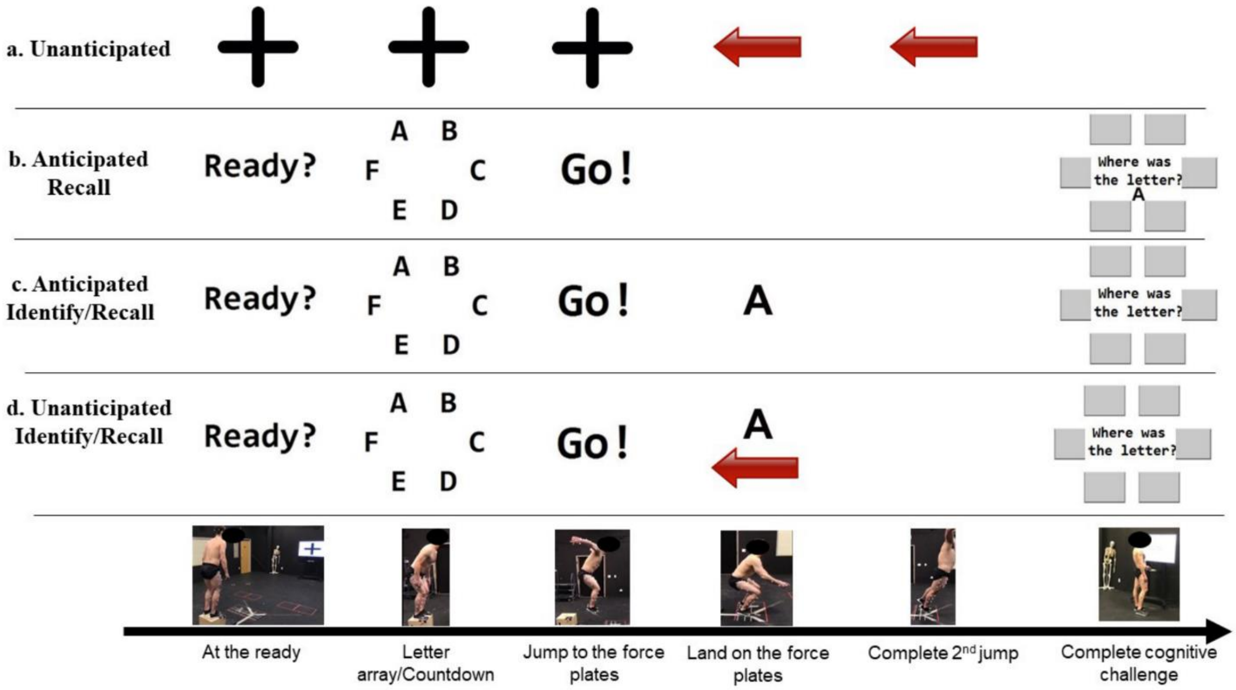

Figure 3.1: The trial progression for each dual-task jump landing condition. Each row corresponds to the series of images seen on the television screen from the beginning ("At the ready") to the end ("Complete second jump/cognitive challenge") of the trial. Each column corresponds to the image presented to participants during a specific point in the trial (e.g., the appearance of response letter "A" prior to landing on the force plates).

Baseline: Participants stood atop a 30-cm box placed a distance one-half their height away from the force plates. The researcher told participants which secondary direction to jump before beginning. Participants were instructed to jump to the force plates, and then to immediately jump "as high and as hard" as they could to one of the secondary landing zones (**Figure 3.2**). Secondary landing zones to the right and left of the force plates were outlined in red tape, one meter forward and 45° to the right or left of the force plates.

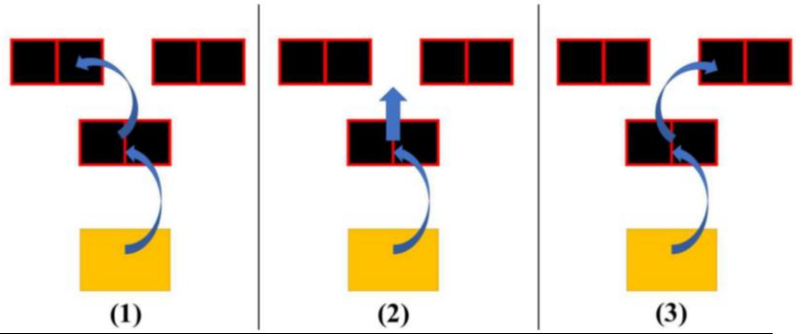

Figure 3.2: Overhead view (not to scale) of jump directions from the box to the primary landing zone, to the secondary landing zones (1) to the left, (2) straight up, or (3) to the right.

The *Unanticipated* condition (**Figure 3.1a**) challenged rapid decision-making. Participants did not know the secondary jump direction before beginning the trial. They fixated on a large cross presented on a television in front of them. Approximately 250 ms prior to landing on the force plates [71, 184], an arrow appeared on the screen, indicating the secondary jump direction. Directional cues were triggered with a pressure sensor underneath the participant's left foot. This sensor was used to tune to participant-specific flight times between the top of the box and initial ground contact, such that coming off the pressure sensor started a participant-specific delay time. The randomly chosen directional cue was presented after the delay time expired.

The *Anticipated Recall* condition (**Figure 3.1b**) challenged working memory. While standing on top of the box, participants were shown six dissimilar letters [143] on the monitor in front of them for 1000 ms. They then completed the jumping task. Afterward, they were asked to recall the position of one randomly-selected letter from the six presented at the trial's beginning. Using six on-screen buttons, they selected the position of the letter within the array. The test recorded the accuracy of the response (correct: 1, incorrect: 0) and reset itself for another trial. Participants were not given feedback whether each response was accurate.

The *Anticipated Identify/Recall* condition (**Figure 3.1c**) challenged working memory and attentional control. It followed the protocol of the anticipated recall test, with one alteration.

Instead of presenting the response letter after the jump, the letter was presented ~250 ms prior to initial contact with the force plates for 1000 ms. The letter's appearance was triggered by the pressure sensor in the same manner as the directional cue in the Unanticipated condition. Participants were instructed to identify the response letter while completing the jump. They recalled the position of this letter at the end of the trial, in the same manner as the anticipated recall test.

The *Unanticipated Identify/Recall* condition (**Figure 3.1d**) challenged working memory, attentional control, and decision-making. It followed a similar protocol to the anticipated identify/recall condition, with an added challenge that participants were presented their directional cue, in the form of an arrow pointing in the direction of their secondary jump, directly below the response letter. Both letter and arrow were presented ~250 ms prior to initial contact, for 1000 ms, and were triggered by the pressure sensor as described before.

Only straight-up trials were considered in this analysis. Motion capture and force plate data were filtered in Visual3D (C-Motion; Germantown, MD, USA) using 4^{th} order, zero-lag, lowpass Butterworth filters with cutoff frequencies of 15 Hz [205]. Kinematic and kinetic data were calculated using an inverse kinematics model with a Quasi-Newton optimization method [162]. An inverse kinematics model was used to eliminate unrealistic translations at the hip, knee, and ankle joints and restricted the hip and knee joints to three degrees of freedom (rotation: flexion/extension, abduction/adduction, internal/external rotation) and the ankle joint to two degrees of freedom (rotation: plantarflexion/dorsiflexion, inversion/eversion). Joint angles were calculated using a X-Y-Z Cardan rotation sequence, corresponding with flexion/extension, ab/adduction, and internal/external rotation. Joint moments were externally-defined in the proximal segment's coordinate system and normalized to participants' bodyweight and height. For each trial, the frame where the participant made initial contact with each force plate was defined as the first frame where the force plate reading exceeded 10 N. Custom MATLAB programs identified a 50 ms window, starting with the initial contact frame, for each trial and selected three ACL injury-relevant measures of knee mechanics, pKFA, pKAbA, and pKAbM [20], within that window. The first 50 ms following initial contact were chosen as the region of interest because prior video analysis has shown a majority of non-contact ACL injuries occur within this time frame [94].

Z-scores were calculated for participants' performance on each processing speed, attentional control, primary memory, and multitasking (MT) test. Z-scores were averaged between tests for a given cognitive process to obtain composite scores for processing speed (PS), attentional control (AC Accuracy, Reaction Time), and primary memory (PM). Composite measures were used instead of isolated test results (except for MT) to obtain a more robust estimate of the underlying cognitive domain [206].

Linear mixed models tested for a fixed effect of 'Condition' on pKFA, pKAbA, and pKAbM. 'Participant' was entered as a random effect, and composite Z-scores entered as covariates to the mixed effects models. Interactions between the composite Z-scores and 'Condition' were also included. If a significant fixed effect was found, follow-up Tukey pairwise tests were performed to assess pairwise differences. Effect sizes (Cohen's *d*) were calculated to gauge the impacts of the dual-task scenarios on neuromuscular control. A power analysis conducted using GLIMMPSE [207] determined that a sample size of n = 40 had at least 90% statistical power to detect differences between conditions of the same or larger magnitude that have previously been reported for unanticipated or cognitive challenges during jumping tasks for our selected dependent variables (4-5° average change in pKFA, 2-3° average change in pKAbA, 2-3%BW*Height average change in pKAbM) [67, 71].

Additional linear mixed models verified aspects of the protocol. Lead time, the time elapsed between stimulus presentation and initial contact, was considered as a dependent variable to determine if the amount of time to respond to the stimulus varied between visually-constrained conditions. Recall and identify/recall cognitive test performances were also considered as dependent variables to determine whether performance on these tests varied across conditions. Kruskal-Wallis tests were used to verify that self-reported measures (amount of sleep, physical and mental fatigue, stress) did not differ between days. Significance for all statistical tests was set at $\alpha = 0.05$.

C3.3 Results

Forty participants provided written informed consent to complete this IRB-approved study (**Table 3.1)**. No differences in self-reported sleep, mental fatigue, physical fatigue, or stress were observed between the two research visits (all $p > .05$; **Table 3.1**). Additionally, no concussions were reported between visits.

581 out of 600 jump-land-jump trials (40 participants × five conditions × three trials) were used for analysis. Missing/excluded trials were due to participants unable to successfully complete the movement, data collection issues, or improper foot strike. The distribution of the missing/excluded trials was: baseline (1), unanticipated (4), anticipated recall (0), anticipated identify/recall (2), unanticipated identify/recall (12). The missing trials resulted in some averages being calculated with fewer than three trials. Average estimates for the full 40 participants were

obtained for all conditions except the unanticipated identify/recall, which had estimates for 38 participants.

Table 3.1: Cohort characteristics (Average ± SD)

Soccer/Basketball	31/9	
Age (years)	20.2 ± 2.57	
Height (m)	1.69 ± 0.07	
Mass (kg)	64.12 ± 8.29	
High School Experience (years)	3.15 ± 1.15	
College Experience (years)	0.44 ± 0.98	
Participation (days/week)	1.26 ± 0.99	
	Day 1	**Day 2**
# Hours Slept	7.4 ± 1.6	7.1 ± 1.2
Perceived Mental Fatigue (1-10)	2.9 ± 1.4	3.0 ± 1.7
Perceived Physical Fatigue (1-10)	2.3 ± 1.2	2.7 ± 1.3
Perceived Stress (1-10)	2.9 ± 1.6	2.8 ± 1.4

Table 3.2: Kinematic and kinetic raw values (Average ± SD) for all jump-landing conditions (*indicates $p < .05$ compared to Baseline, $^{+}$indicates $p < .05$ compared to Anticipated Recall)

	Baseline	**Unanticipated**	**Anticipated Recall**	**Anticipated Identify/ Recall**	**Unanticipated Identify/ Recall**
pKFA (°)	58.4 ± 4.8	**56.7 ± 4.2***	57.6 ± 4.1	**56.8 ± 4.6***	**56.7 ± 4.3***$^{,+}$
pKAbA (°)	10.4 ± 3.8	10.4 ± 3.8	10.0 ± 4.2	10.3 ± 3.8	10.2 ± 4.0
pKAbM (%BW*Height)	3.0 ± 1.3	3.2 ± 1.3	2.9 ± 1.5	3.1 ± 1.4	3.0 ± 1.4

Table 3.3: Cohen's *d* effect sizes for kinematic and kinetic results (*indicates $p < .05$). Visually constrained dual-task conditions displayed small-to-medium effects on pKFA compared to a visually unconstrained baseline jump-landing. (Conditions: Baseline (BL), Unanticipated (UA), Anticipated Recall (REC), Anticipated Identify/Recall (IR), Unanticipated Identify/Recall (UAIR)

	pKFA				**pKAbA**				**pKAbM**			
	BL	***UA***	***REC***	***IR***	***BL***	***UA***	***REC***	***IR***	***BL***	***UA***	***REC***	***IR***
UA	**0.36***	-	-	-	0.01	-	-	-	-0.15	-	-	-
REC	0.17	0.21	-	-	0.09	0.09	-	-	0.02	0.15	-	-
IR	**0.33***	-0.02	-0.18	-	0.03	0.03	0.06	-	-0.08	0.06	0.09	-
UAIR	**0.37***	0.01	**0.22***	0.03	0.05	0.04	-0.04	0.02	-0.06	0.08	-0.07	0.02

There was a significant 'Condition' effect for pKFA (**Table 3.2**; F = 7.72, $p < .001$). Post-hoc analysis found that, compared to the baseline condition, participants exhibited less pKFA during the anticipated identify/recall ($p = .001$, d = 0.33), unanticipated ($p = .001$, d = 0.36), and unanticipated identify/recall conditions ($p < .001$, d = 0.37) (**Figure 3.3**). Participants exhibited less pKFA during the unanticipated identify/recall condition compared to the anticipated recall condition ($p = .034$, d = 0.22). No other comparisons reached significance (**Table 3.3**; all $p > .200$). No cognitive covariates or interactions reached significance for pKFA (all $p > .200$).

Regarding pKAbA, there was no 'Condition' effect (**Table 3.2**; F = 0.25, $p = .911$). PM Z-score as a covariate in the mixed model trended towards significance (F = 3.00, $p = .093$), with better primary memory associated with higher pKAbA. No other covariates or interactions reached significance (all $p > .050$). Regarding pKAbM, there was no 'Condition' effect (**Table 3.2**; F = 1.10, $p = .360$). No Z-scores reached significance as covariates for pKAbM, and no significant interactions were observed (all $p > .050$).

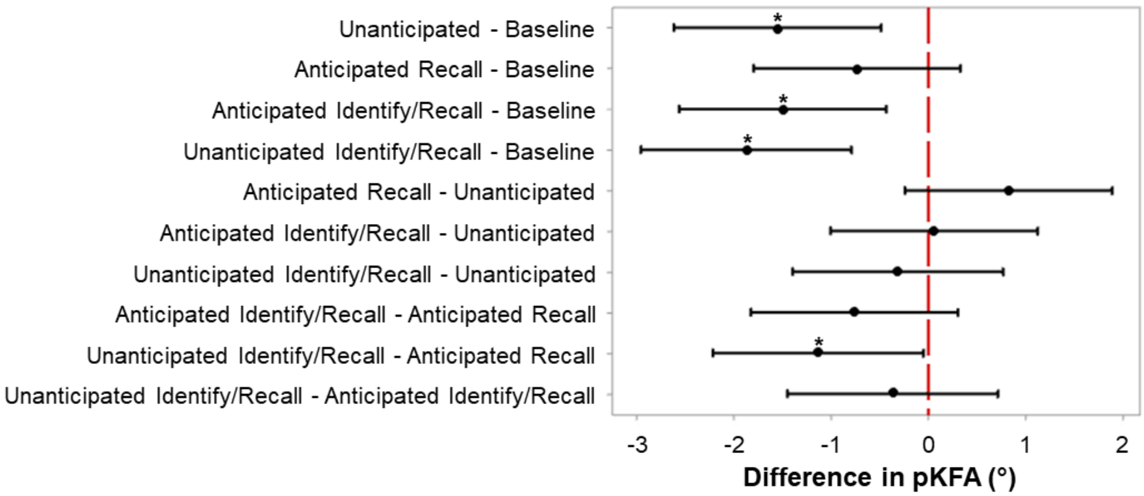

Figure 3.3: The 95% CI difference in mean pKFA between conditions. When compared with the baseline, dual-task conditions with divided visual attention led to decreased pKFA during early-stance landing. CI indicates confidence interval; pKFA, peak knee flexion angle. *$P < .05$.

Average lead times between visual stimulus presentation and initial force plate contact (**Table 3.4**; F = 0.90, p = .413) and Recall and Identify/Recall test scores (ability to accurately recall the position of the target letter) did not show a "Condition" effect (**Table 3.4**; F = 2.61, p = .080).

Table 3.4: Lead times (ms) and accuracy scores (%) for all dual-task conditions (Average ± SD)

	Unanticipated	**Anticipated Recall**	**Anticipated Identify/Recall**	**Unanticipated Identify/Recall**
Lead Time (ms)	279 ± 58	-	272 ± 83	267 ± 64
Accuracy (%)	-	59.16 ± 23.17	55.35 ± 24.34	51.51 ± 21.59

C3.4 Discussion

This study's purpose was to identify the effects of cognitively-challenging secondary tasks on landing mechanics and to quantify relationships between those secondary tasks, landing mechanics, and baseline cognitive performance measures. We hypothesized dual-task jump landings would be associated with adverse changes in neuromuscular control, with those changes in neuromuscular control dependent on individuals' cognitive performance. The current study's findings partially support the first hypothesis, but do not support the second hypothesis. Current results suggest athletes' responses to cognitively-challenging jump-landing tasks appears to be complex and context-specific.

We hypothesized cognitive challenges would be associated with adverse changes in neuromuscular control. This hypothesis was partially supported for pKFA, but not for pKAbA or pKAbM. Significant changes in pKFA from baseline were seen for all three visually-constrained dual-task conditions; notably, these effects were observed in pKFA across anticipated and unanticipated conditions (**Figure 3.1**). Rather than tracking their position throughout the jump, it became necessary to rely on indirect cues of position while jumping. Small- to- medium effects were observed in pKFA between the anticipated recall and unanticipated identify/recall (**Table 3.3**), lending limited support to the hypothesis that increased cognitive challenges would result in adverse changes in neuromuscular control. However, the presence of the dominant effect of visual constraint cannot be ignored. The anticipated recall condition placed no visual constraints on participants, and so it is possible these results are due, at least in part, to the same effects as detailed previously. Further investigation into different, visually-unconstrained cognitive challenges is warranted.

Visual constraints likely lead to a persistent deficit in sport-specific movements, an effect that has been previously suggested [67]. Almonroeder *et al.* considered the effects of an overhead goal, a visual directional cue, and a combination of the two on neuromuscular control during a drop-jump. They noted that, while both the presence of the overhead goal and the visual directional cue led to altered neuromuscular control compared to the baseline, there was not an appreciable difference between these conditions and the combined condition. That visual constraints influence neuromuscular control is further supported by several studies published recently [73, 189, 208]. Two studies found the introduction of an overhead goal led to decreases in pKFA and increases in peak vertical ground reaction forces [73, 189], while the third found that varying the difficulty of a visual search task during a countermovement jump was associated with changes in postural sway during the landing phase [87, 208]. While all previous studies found visual constraint effects on jump-landing performance using established paradigms, the current study expanded on previous findings by systematically introducing unique cognitive-motor tasks with different levels of complexity, finding similar effects associated with all visually-constrained challenges. Given the fact that these results and prior findings suggest divided visual attention plays an important role in altering landing mechanics, decoupling the contribution of divided visual attention from other cognitive challenges becomes important for more precise interpretations and understanding of cognitive-motor relationships.

In addition to the condition effects, we anticipated worse cognitive performance to be associated with more adverse landing mechanics (e.g., higher knee abduction and less knee flexion). In support of this hypothesis, Herman and Barth previously reported differences in unanticipated jump-landings between high- and low- cognitive performers, where participants were separated based on reaction time and processing speed [184]. However, no relationships specifically between processing speed ability and neuromuscular control were observed in the current study. Assessments of processing speed alone may not be sensitive enough to detect cognitive-motor relationships. Processing speed tests require several components of cognitive function including visual searching, symbol comprehension, and decision-making [200]. By combining processing speed and reaction time assessments, Herman and Barth demonstrated that adverse changes in neuromuscular control were dependent on overall cognitive performance. By contrast, the current study found that processing speed alone was not associated with individual differences in neuromuscular control. The current dataset contains 40 participants, which may be limited in its ability to fully reflect the spectrum of cognitive function that exists in the population. A dataset with larger spread of cognitive function may be better positioned to elucidate interactions between cognitive ability and cognitive-motor function.

Although previous literature observed changes in frontal plane knee mechanics arising with the introduction of unanticipated scenarios when compared to the baseline [67], the current study observed no such effects. Two suggestions for this outcome are offered here. First, prior literature reports both the presence [67] and absence [71, 198] of differences in early-stance knee abduction angle and moment between unanticipated and anticipated conditions for jumping and cutting movements. Therefore, the lack of differences identified in this study may further motivate the value in investigating the generalizability of cognitive-motor function across sport-relevant movements. Second, all conditions that were associated with altered landing mechanics involved a visual constraint that limited participants' ability to track their landing. The current results are consistent with participants adopting a stiffer landing strategy and potentially compensating for the reduced visual feedback. It is plausible that increased knee musculature co-contraction, driven by this compensatory landing strategy, would more greatly impact knee flexion relative to abduction. Future studies that measure muscle activation patterns would be needed to confirm this theory.

There are limitations to consider when interpreting these results. One methodological concession made was the omission of an unanticipated recall condition, to allow for other sub-protocols within the larger study to be completed. The kinematic and kinetic variables chosen for this manuscript represent a limitation. Non-contact ACL injuries are influenced by many different biomechanical variables at the ankle, knee, hip, and trunk. However, the authors chose *a priori* to restrict analysis to a select few ACL injury-relevant biomechanical variables to mitigate Type I statistical error. This study's inclusion criteria limit how these findings may be extended. Biomechanical differences between males and females [198, 209] and between healthy and pathological populations [210] mean caution must be taken in extrapolating these results. Including only uninjured athletes in this study may have limited the results pertaining to attentional control and reaction times, as those cognitive processes have previously been implicated as differing between injured athletes and healthy, matched controls [27, 81]. Soccer and basketball players exhibit different jump mechanics [211]; the low number of basketball players that completed the study does not allow for between-sport comparisons. The working memory secondary tasks used in this study deviate from multitasking in competitive environments. However, they serve as a novel attempt to isolate cognitive processes involved in the underlying cognitive-motor relationship.

DO DUAL-TASK DEMANDS GENERALIZE ACROSS SPORT-SPECIFIC MOVEMENTS?

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C4.1 Introduction

Sports that exhibit high rates of non-contact anterior cruciate ligament (ACL) injuries [212] require athletes to execute multiplanar movements while managing whole-body positioning to minimize ACL loading [20, 21, 93, 213, 214]. Though the knee position at the instant of injury regularly consists of coupled extension, internal rotation, and medial collapse within a short time frame following initial ground contact [20, 21, 94, 96], the movements leading up to the point of injury (e.g., landing from a jump, sidestepping, etc.) vary appreciably [215]. This movement variability poses a challenge to lab-based motion assessments, which often do not characterize the full spectrum of injury risk [64, 65]. Researchers devote considerable effort to simulating the complex demands of sport by exploring the effects of different types of secondary tasks on movement performance. However, whether results from these lab-based assessment techniques transfer between movements remains unknown.

The attentional effort athletes devote to secondary tasks while competing in sport [77] leads to inefficiencies in movement performance [74, 103]. These inefficiencies can manifest as compromised neuromuscular control, including increases in medial knee collapse, stiffer landing at ground contact, and greater ground reaction forces [20, 94, 123, 216]. Dual-task research has explored a range of rapid decision-making [66, 87, 184], working memory [69, 86, 208], and motor-based [85] secondary tasks to divert attention away from sport-relevant movements like running sidesteps and jump-landings. More recent findings suggest that dual-task effects may depend on individual differences in cognitive function [85-87, 184]. This subject-specific approach to considering dual-task demands bolsters the notion that an athlete's ACL injury risk is an interaction of cognitive and biomechanical contributors coupled with secondary task demands [20, 27, 217]. What remains to be explored, however, is the extent to which identical secondary tasks elicit similar dual-task changes in knee mechanics across movements.

Limited positive correlations between the biomechanics of different movements (e.g., jump landing versus running sidestep) during single-task conditions suggest that the basic movement demands of open-skill movements may be similar [218-220], but it is unknown whether secondary task demands generalize across different movements. Dual-task effects are proposed to be dependent on individual differences in cognitive function [79], so it is possible that athletes may demonstrate similar dual-task effects when subjected to the same secondary task demands across movements. The central purpose of this study, therefore, was to identify whether dual-task effects are generalizable across different open-skill movements commonly used in sports biomechanics literature. This purpose gave rise to two research questions: **Research Question (RQ) 4.1**) Do relationships exist between cognitive function and knee mechanics when performing dual-task running sidesteps and **RQ4.2**) Are adaptations to secondary task requirements generalizable across sport movements? We hypothesized that 1) athletes with lower cognitive function would display increasingly deleterious effects on early-stance knee mechanics when presented with simultaneous working memory, rapid decision making, and motor secondary tasks, and that 2) identical dual-task demands would result in similar effects on ACL-relevant knee mechanics during sidestep and jump-landing movement assessments.

C4.2 Methods

Females who, at the time of study enrollment, participated in soccer three or more times a week or participated in soccer once or more a month and had prior competitive high school or college experience were eligible. Exclusion criteria included prior lower extremity surgeries, lower-extremity injury that required time away from activity or a concussion within the previous six months of data collection, or any pain during athletic movements.

Testing took place over three sessions on non-consecutive days. Participants completed cognitive tests during the first session and motion capture testing of running sidestep and jump-landing movements during the second and third sessions. To monitor for changes in physical and mental fatigue, participants were asked each collection session to report the number of hours they had slept the night before and to rate, on a scale from 1-10, their perceived levels of physical and mental fatigue and stress. Participants were also asked if they had suffered a concussion or other head trauma between sessions.

Session 1: Cognitive Assessments and Familiarization

Cognitive tests used in this study are described in detail in a previous study [221], but a brief overview is provided here. Processing speed was assessed using pen-and-paper letter comparison and pattern comparison tests [200]. To mitigate the effects of sacrificing speed for accuracy, a weighted score for each test was calculated using the formula: Score = (# Correct - # Incorrect)/Time to Complete [200]. Attentional control was assessed using anti-saccade [202] and visual Stroop [222] tests. Accuracy (anti-saccade and Stroop) and response time (Stroop only) were considered separately for further analysis. Primary memory was assessed with running digit and letter span tests [143, 201]. The outcome variable for these tests was the total count of items that participants could correctly recall across all sets within each test[143, 201]. Multitasking was assessed using the Control Tower test [223]. The outcome variable of interest for this test was the total number of primary tasks completed. Raw test scores from cognitive assessments were normalized within a cognitive domain using Z-scores to provide researchers with a robust estimate of participants' performance within the cohort for processing speed (**PS**), primary memory (**PM**), attentional control (**AC_Acc** and **AC_RT**), and multitasking (**MT**) [206]. All cognitive tests, except for processing speed, were administered through E-Prime computer testing software (Psychology Software Tools, Inc.; Pittsburgh, PA, USA).

After completing cognitive assessments, participants performed running 45° sidesteps off their non-dominant limb in the lab space while dribbling a soccer ball. The dominant limb was defined as the limb participants would use to kick a ball the farthest. A brightly-colored rubber disc was used to provide a reference point when participants should perform the sidestep cut. Participants were allowed as many practice trials as needed to feel comfortable with the task. After becoming comfortable with the task, participants completed five maximal effort sidesteps while custom timing gates connected to an Arduino® microcontroller recorded approach speed. A weighted average (**Eq. 4.1**) of these five sidestep cuts was used to standardize the approach speed for motion capture trials, with greater preference given to the last trial to account for practice effects. A similar approach was previously used to establish timing for stimuli in a jump-landing [221].

$$Approach\ Speed_{avg} = 0.25 * Approach\ Speed_5 + \frac{0.75 \sum_{i=1}^{4} Approach\ Speed_i}{4} \quad (\boldsymbol{Eq. 4.1})$$

<u>Sessions 2 & 3: Motion Capture</u>

Motion capture collections for sidestep (**RQ4.1, RQ4.2**) and jump-landing (**RQ4.2**) movements were completed on separate, nonconsecutive days following the cognitive assessment day. The order of sidestep and jump-landing testing days was randomized. A modified full-body plug-in gait marker set was used [198], with extra markers placed on the shoes over the head of the first metatarsal and the lateral aspect of the calcaneus to aid in tracking the foot segment. The same researcher placed all markers for each subject to maintain consistency. Marker data were collected at 250 Hz with a ten-camera system consisting of six Raptor-12 and four Kestrel cameras (Motion Analysis Corp.; Rohnert Park, CA, USA). Ground reaction force data were collected at 1000 Hz using two force plates (OPT464508-2K; Advanced Mechanical Technology, Inc.; Watertown, MA, USA).

The sidestep was conducted under a baseline and six dual-task conditions that presented working memory, rapid decision-making, and motor challenges (**Figure 4.1**). All working memory and rapid decision-making secondary tasks were administered through custom E-Prime 3.0 programs. During the baseline condition, participants performed the movement required with no secondary task. Secondary movement directions were given to participants before beginning each trial, and no additional task was required. During the unanticipated condition (**Figure 4.1a**), participants were required to react to a directional cue that appeared immediately prior to initial contact with the force plates (~400 ms [66]). The directional cue appeared on a monitor in front of the participant, in the form of an arrow pointing in the secondary direction and was triggered by the participant crossing through the first timing gate. During the ball-handling condition, participants dribbled a soccer ball while performing the running sidestep. Ball-handling conditions were always performed in an anticipated state.

Visual-spatial recall tests (**Figure 4.1b**) were used to challenge working memory during movement assessment. Before each trial began, participants were given their secondary movement direction, followed by a set of six dissimilar letters for 1000 ms [143]. The letters disappeared, and participants completed the movement as instructed. At the end of the trial, participants were shown one randomly-selected letter from the array that had been presented at the beginning of the trial and cued to recall the spatial position of that letter. Identify/recall tests (**Figure 4.1c**) were extensions of the recall condition that placed an additional visual constraint on participants during sidestepping. The response letter was presented ~400 ms prior to initial contact with the force plate, for a duration of 1000 ms, rather than at the end of the trial. The unanticipated recall condition (**Figure 4.1d**) was a combination of the previously-described unanticipated and recall tasks. Ball-handling recall trials were a combination of the recall and ball-handling conditions.

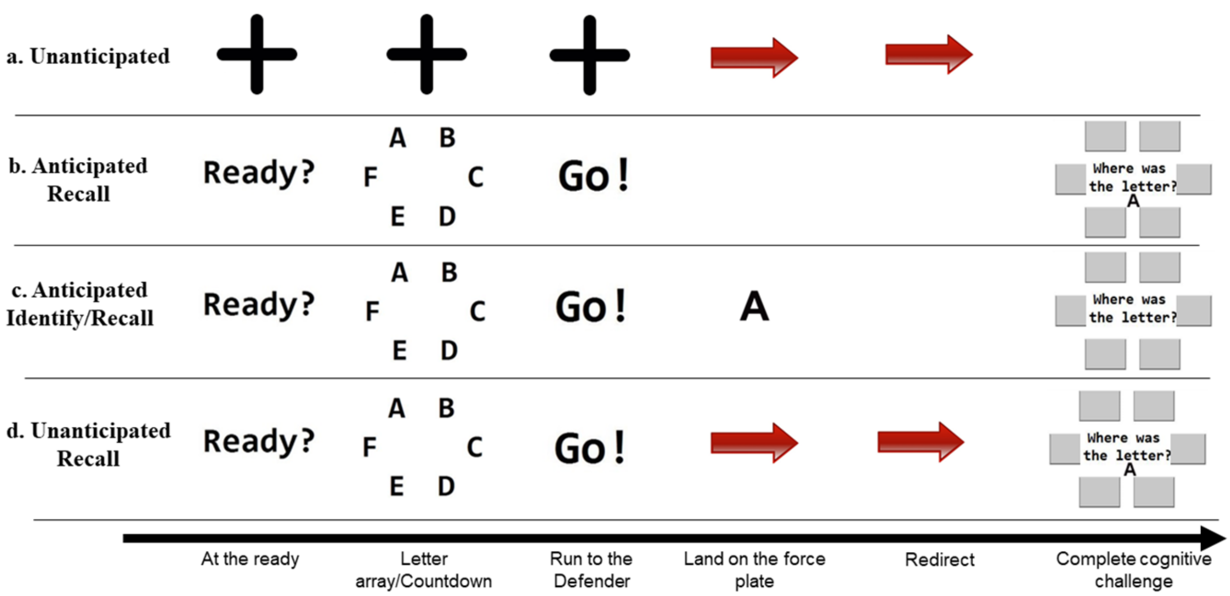

Figure 4.1: Trial progression order for the various unanticipated and working memory dual-task conditions. Where applicable, direction and letter cues were presented ~400 ms prior to initial contact with the force plates [66] and were triggered using the first timing gate.

Three acceptable trials for each condition were recorded. A trial was considered acceptable if the following criteria were met: foot strike within the force plates' boundaries, successful redirection, control of the soccer ball (when applicable), and maintaining an acceptable approach speed (within ±10% of their average approach speed from the initial assessment [85]). Conditions were block randomized to mitigate learning and fatigue effects.

All motion capture and force plate data were filtered in Visual3D using 4^{th} order, lowpass Butterworth filters with cutoff frequencies at 15 Hz [205]. An inverse kinematics model with a Quasi-Newton optimization method was used to compute biomechanical data for all dynamic trials [162]. Hip and knee joints were constrained to three degrees of freedom (X-Y-Z rotation: flexion/extension, abduction/adduction, and internal/external rotation), and each ankle joint was constrained to two degrees of freedom (plantarflexion/dorsiflexion and inversion/eversion). Joint angles were calculated using an X-Y-Z Cardan rotation sequence. Externally-defined knee joint moments were normalized to participant height and weight and were resolved in the proximal segment's coordinate system. Early-stance peak knee flexion angle (pKFA), knee abduction angle (pKAbA), and knee abduction moment (pKAbM) within a 50 ms time frame after initial contact of the non-dominant limb with the force plate were examined [94]. Initial contact was defined as the first frame where the vertical component of the force plate exceeded 10 N. Resulting pKFA, pKAbA, and pKAbM for the non-dominant (plant) limb for each participant and condition were averaged across three trials.

Data Processing and Statistical Analysis: RQ4.1

A power analysis [207], with the variability of our dataset and previously-established dual-task effects (changes of ~2° pKFA, ~2° pKAbA, ~1.5%BW*Height pKAbM) [85, 179, 182], resulted in statistical power to detect a main effect of condition exceeding 80% for all variables. A main effect of 'Condition' on pKFA, pKAbA, and pKAbM was tested using linear mixed models with 'Subject' as the random effect. Approach speed and cognitive Z-scores were introduced as covariates into the models, and ‘Condition’*cognitive Z-score interactions were included to consider the effects of baseline cognitive function on dual-task neuromuscular control. Post-hoc Tukey’s HSD tests were done for cases of significant main effects. Effect sizes were calculated using Cohen’s *d*.

As a quality control measure, linear mixed models with ‘Condition’ as the fixed effect, ‘Subject’ as the random effect, and approach speed as a covariate were used to test for main effects of ‘Condition’ on lead times (the amount of time between stimulus presentation and initial ground contact) and test accuracy for visually-demanding and working memory tasks, respectively.

Significance was set at $\alpha = 0.05$ for all statistical tests.

Data Processing and Statistical Analysis: RQ4.2

On a separate day, participants completed single- and dual-task jump-landings [48, 184]. Of the four dual-task conditions performed during the jump-landing, three were identical to those used in the sidestep methodology (**Figure 4.1a-c**). A full report of the jump-landing protocol can be found elsewhere [221]. Dual-task costs (DTC) of the non-dominant limb were calculated for the sidestep and jump-landing dual-task conditions as the percent change in biomechanical values between single-task and dual-task measures (**Eq. 4.2**):

$$DTC\ (\%) = 100 * \frac{Measure_{Dual-task} - Measure_{Single-task}}{Measure_{Single-task}} \qquad (\boldsymbol{Eq. 4.2})$$

DTC was chosen to quantify normalized subject-specific adaptations associated with working memory and rapid decision-making secondary tasks.

DTC data normality was checked using the Anderson-Darling normality test. Because the data were often not normally distributed within a condition, Spearman’s rank correlations were used to investigate DTC relationships across movements (e.g., recall pKFA DTC during jump-landing vs. running sidestep). Cognitive dual-tasks were identical across sidestep and jump-landing assessments for Unanticipated, Anticipated Recall, and Anticipated Identify/Recall conditions, resulting in nine total correlation tests (three each for pKFA, pKAbA, and pKAbM). Power analysis for our correlation results with a sample size of 22 (the smallest number of available data points for correlation analysis) resulted in 80% statistical power for detecting small effects/low correlation ($r_{critical} = \pm 0.35$) [224]. Positive correlations indicate consistent subject-specific dual-task effects across jump landing and sidestep movements. Significance was set at $\alpha = 0.05$.

C4.3 Results

Study approval was provided through the Montana State University Institutional Review Board. Thirty-nine female recreational and competitive soccer athletes provided informed consent for participation. Seven did not return after completing cognitive assessments. Two participants did not complete the sidestep assessment. Analog data for the sidestep from two participants were corrupted and unusable, leaving a final study population of 28 for the sidestep analysis. (**Table 4.1**). Fifty-nine out of the 588 collected trials (3 trials x 28 participants x 7 conditions) were excluded from the data set for quality-control reasons (double-limb support, motion capture/analog data asynchrony, erroneous stimulus presentation). Kinetic data from 11 additional trials were excluded, due to an incomplete foot strike on the force plate. The final sidestep data set contained 28 data points for four conditions (Baseline, Unanticipated, Ball-Handling Recall, Recall) and 26 data points for three conditions (Identify/Recall, Unanticipated Recall, Ball-Handling). No differences in sleep, perceived physical or mental fatigue, or stress existed across data collection sessions (all $p > .050$; **Table 4.1**). No participants reported a concussion or head trauma between data collections.

Table 4.1: Twenty-eight recreational and competitive female soccer players completed study participation. Basic characteristics and self-reported physical and mental status (Scale: 1 – minimal effects; 10 - maximal effects) were collected (Average ± SD).

Age (yrs)	20.4 ± 2.7		
Height (m)	1.68 ± 0.07		
Mass (kg)	1.68 ± 0.07		
No. of years competitive high school soccer experience	3.3 ± 1.1		
No. of years competitive college soccer experience	0.5 ± 1.0		
No. of soccer games and practices per week (at time of study enrollment)	1.6 ± 0.9		
	Cognitive Assessments	**Running Sidestep**	**Jump Landing**
No. of hours slept	7.2 ± 1.7	7.5 ± 1.2	7.0 ± 1.3
Perceived physical fatigue (1-10)	2.4 ± 1.4	2.7 ± 1.2	2.8 ± 1.3
Perceived mental fatigue (1-10)	2.7 ± 1.5	2.8 ± 1.6	3.0 ± 1.7
Perceived stress (1-10)	2.6 ± 1.6	2.7 ± 1.8	2.5 ± 1.3

RQ4.1: Cognitively-Demanding Dual-Task Effects on Sidestep Performance

A main effect of 'Condition' was observed for pKAbA (F = 3.69, $p = .002$; **Table 4.2**). Post-hoc comparisons found that participants demonstrated greater pKAbA (**Figure 4.2**) during the unanticipated running sidestep compared to the baseline (Cohen's *d*: 0.35, $p = .006$) and the anticipated identify/recall (Cohen's *d*: 0.35, $p = .008$). No other pairwise comparisons reached statistical significance. No cognitive covariates and no cognitive Z-score*'Condition' interactions were observed (all $p > .050$).

A main effect of 'Condition' was observed for pKAbM (F = 3.28, $p = .005$). Post hoc comparisons found that participants demonstrated greater pKAbM (**Figure 4.2**) during the unanticipated running sidestep compared to the anticipated recall (Cohen's *d*: 0.44, $p = .013$) and the anticipated identify/recall (Cohen's *d*: 0.45, $p = .004$). A difference in pKAbM between the unanticipated and baseline running sidesteps trended towards significance (Cohen's *d*: 0.34, $p = .053$). No other pairwise comparisons reached statistical significance. No cognitive covariates and no cognitive Z-score*'Condition' interactions were observed (all $p > .050$).

No main effect of 'Condition' was observed for pKFA (F = 1.28, $p = .273$; **Table 4.2**). No cognitive covariates and no cognitive Z-score*'Condition' interactions were observed (all $p > .100$).

Table 4.2: Average (SD) pKFA, pKAbA, and pKAbM for all conditions. *Indicates significant difference from Baseline, $^{+}$indicates significant difference from Recall, $^{!}$indicates significant difference from Identify/Recall.

	Baseline	**Unanticipated**	**Ball-Handling**	**Recall**	**Identify/ Recall**	**B.H. Recall**	**U.A. Recall**
pKFA (°)	39.7 (7.1)	40.4 (7.0)	38.4 (6.1)	39.7 (6.2)	38.9 (7.5)	39.1 (5.5)	39.0 (7.1)
pKAbA (°)	8.9 (3.8)	10.4 (4.6)$^{*,!}$	8.6 (4.1)	9.2 (3.8)	8.9 (3.8)	9.1 (4.1)	10.0 (4.7)
pKAbM (%BW*Height)	2.1 (2.0)	2.8 (2.5)$^{+,!}$	1.9 (1.7)	1.9 (1.6)	1.8 (1.9)	2.0 (2.4)	2.5 (2.3)

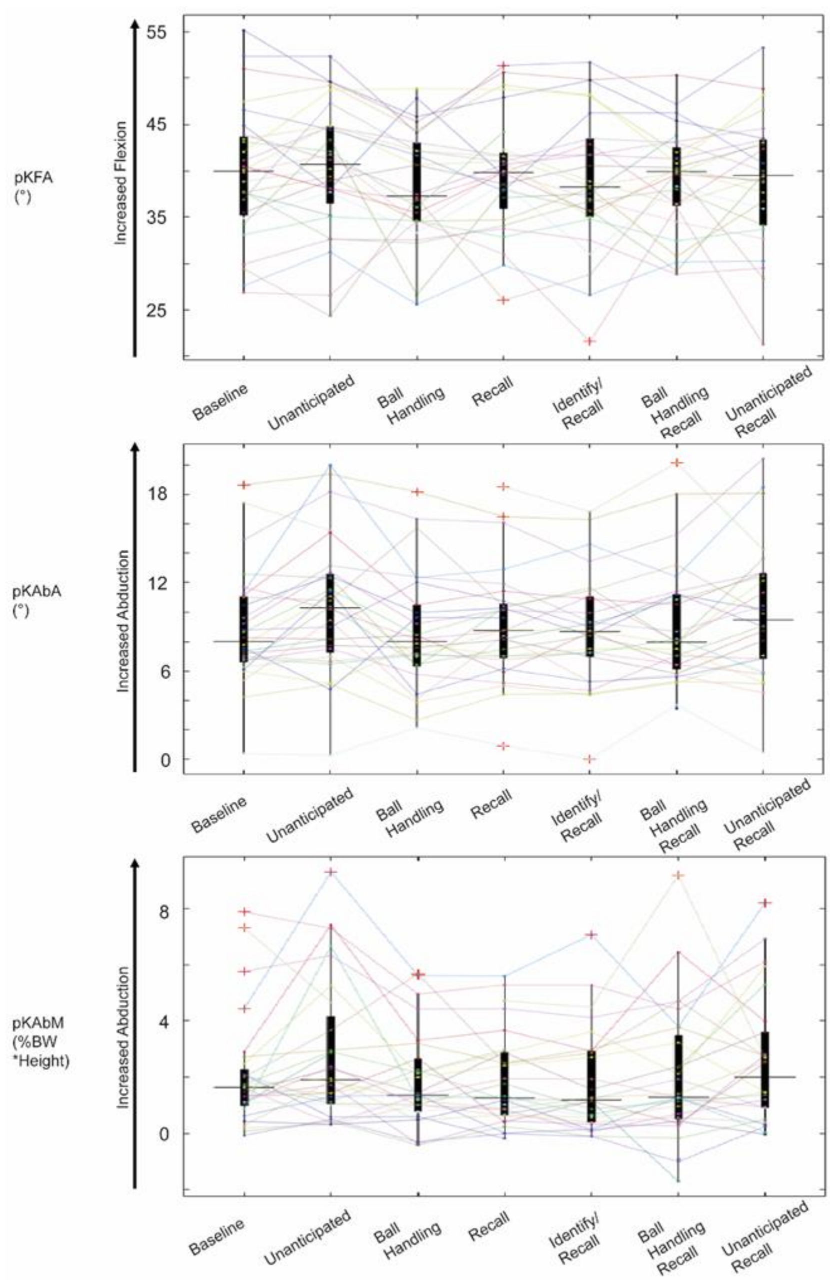

Figure 4.2: Box plots with median lines (group data) with overlaid line plots (subject-specific changes across conditions) indicating pKFA (top), pKAbA (middle), and pKAbM (bottom) across sidestep conditions. Unanticipated conditions were associated with small-medium increases in knee abduction compared to anticipated conditions. Red crosses indicate outliers in the data set.

Table 4.3: Cohen's D effect sizes for all condition comparisons (positive effect size indicates column condition was greater than the row condition it was compared against). The introduction of additional reactionary demands was associated with small to medium effects on knee abduction relative to anticipated tasks (*indicates *p* < .050).

pKFA	**Baseline**	**Unanticipated**	**Ball-Handling**	**Recall**	**Identify/ Recall**	**B.H. Recall**
U.A.	0.10	-	-	-	-	-
Ball-Handling	-0.20	-0.31	-	-	-	-
Recall	0.00	-0.11	0.22	-	-	-
Identify/ Recall	-0.11	-0.21	0.08	-0.11	-	-
B.H. Recall	-0.09	-0.21	0.13	-0.10	0.03	-
U.A. Recall	0.10	-0.20	0.10	-0.10	0.01	-0.02
pKAbA	**Baseline**	**Unanticipated**	**Ball-Handling**	**Recall**	**Identify/ Recall**	**B.H. Recall**
U.A.	0.35*	-	-	-	-	-
Ball-Handling	-0.07	-0.40	-	-	-	-
Recall	0.08	-0.28	0.15	-	-	-
Identify/ Recall	0.00	-0.35*	0.07	-0.08	-	-
B.H. Recall	0.06	-0.29	0.12	-0.02	0.06	-
U.A. Recall	0.25	-0.08	0.31	0.19	0.25	0.20
pKAbM	**Baseline**	**Unanticipated**	**Ball-Handling**	**Recall**	**Identify/ Recall**	**B.H. Recall**
U.A.	0.34	-	-	-	-	-
Ball-Handling	-0.09	-0.43	-	-	-	-
Recall	-0.10	-0.44*	0.00	-	-	-
Identify/ Recall	-0.12	-0.45*	-0.03	-0.03	-	-
B.H. Recall	-0.03	-0.34	0.05	0.06	0.08	-
U.A. Recall	0.22	-0.13	0.31	0.32	0.33	0.23

There was no main effect of 'Condition' on recall test scores (**Table 4.4**; $F = 0.60$, $p = 0.616$). There was a main effect of 'Condition' on lead times (**Table 4.4**; $F = 6.07$, $p = 0.004$). Post-hoc comparisons found the *Identify/Recall* lead times were shorter than the *Unanticipated* ($p = 0.004$) and *Unanticipated Recall* ($p = 0.047$) lead times. Lead times did not differ between the unanticipated and unanticipated recall conditions ($p = 0.489$).

Table 4.4: Average (SD) approach speeds, lead times, and working memory task scores.

	Baseline	**Unanticipated**	**Ball-Handling**	**Recall**	**Identify/ Recall**	**B.H. Recall**	**U.A. Recall**
Approach Speed (m/s)	3.49 (0.43)	3.39 (0.46)	3.33 (0.41)	3.49 (0.45)	3.50 (0.41)	3.38 (0.47)	3.45 (0.47)
Lead Time (ms)	-	494 (94)	-	-	425 (123)	-	472 (94)
Working Memory Score (%)	-	-	-	54.3 (28.5)	57.7 (25.8)	56.6 (22.1)	53.2 (28.8)

RQ4.2: Generalizability of Dual-Task Effects

One significant relationship was observed in pKAbM DTC for the *Anticipated Identify/Recall* ($\rho = -0.57$, $p = .007$) condition. The negative correlation indicates participants demonstrated opposite dual-task effects between the jump-landing and sidestep in terms of changes in knee mechanics (i.e., higher pKAbM for jump-landing, but less pKAbM for sidestep in the presence of the *Anticipated Identify/Recall* challenge). No significant relationships were observed in any between-movement comparisons of pKFA or pKAbA DTC (**Figure 4.3;** all $|\rho| < 0.40$, all $p < .050$). Using Grubb's outlier test, an outlier was noted for seven of the nine comparisons (**Figure 4.4**), and subsequent correlations were investigated with the data point in question excluded. After subsequent analysis, one additional relationship was observed that had not been present in the original data set: larger pKAbA DTC in unanticipated jump landings were associated with larger pKAbA DTC in unanticipated sidesteps (ρ = 0.47, p = .042; **Table 4.5**). No other relationships appreciably changed following outlier exclusion.

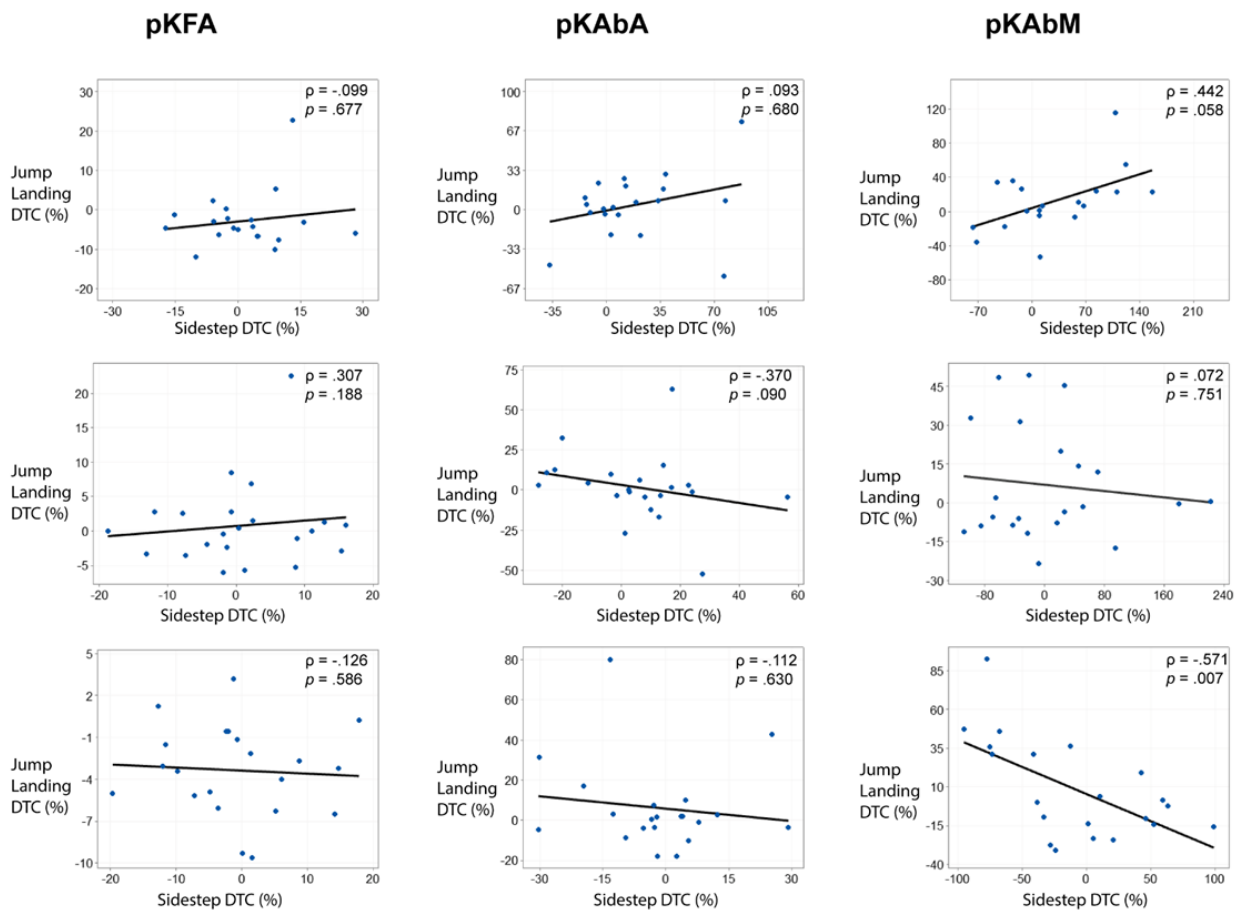

Figure 4.3: Spearman's rho correlations between sidestep and jump-landing DTC for the *Unanticipated* (top row), *Anticipated Recall* (middle row) and *Anticipated Identify/Recall* (bottom row) conditions. Correlations consistently did not suggest that dual-task effects are generalizable in the current population. No dual-task effects on pKFA or pKAbA were related across the different movements, and the one significant relationship in pKAbM indicated that participants had directly opposite postural responses between the different movements for the Identify/Recall task demands.

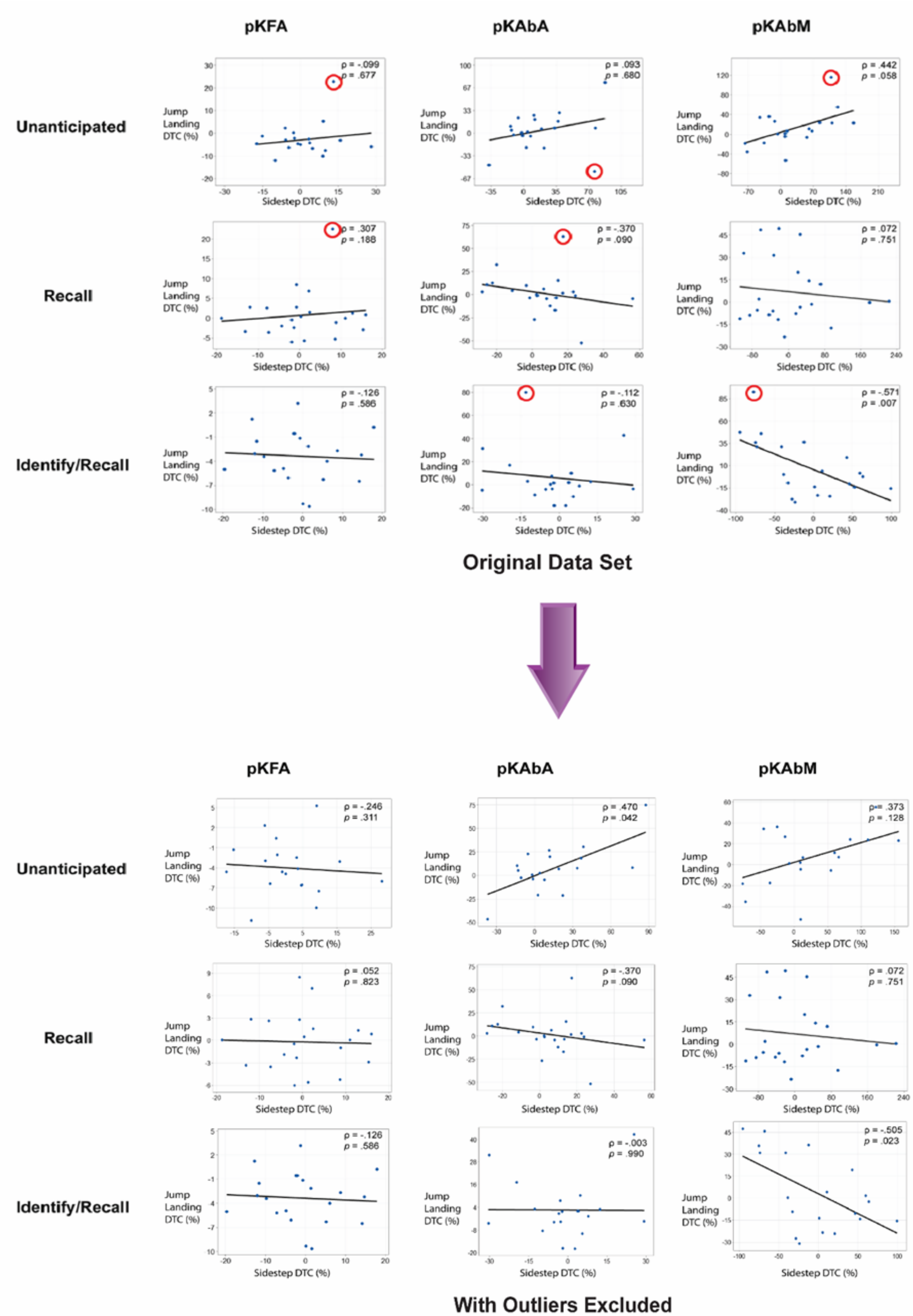

Figure 4.4: Outliers (circled in red) were noted in seven of the nine investigated relationships. Removal of the outliers did not result in widespread change of the correlations tested.

Table 4.5: Changes in Spearman's ρ following the exclusion of noted outliers. One additional relationship reached significance following the exclusion of the outlier noted in the data set (see Figure 4.4); however, the lack of consistent positive correlations among the tested relationships means that the interpretation of the results remains unchanged.

	pKFA	pKAbA	pKAbM
Unanticipated	ρ: -.099 → -.246 *p*: .677 → .311	ρ: .093 → .470 *p*: .680 → .042	ρ: .442 → .373 *p*: .058 → .128
Recall	ρ: .307 → .052 *p*: .188 → .823	ρ: -.370 → -.370 *p*: .090 → .090	No outlier noted
Identify/Recall	No outlier noted	ρ: -.112 → -.003 *p*: .630 → .990	ρ: -.571 → -.505 *p*: .007 → .023

C4.4 Discussion

The two research questions addressed in the current study were "what are the effects of working memory, rapid decision-making, and motor secondary tasks on early-stance sidestep performance?" and "how do dual-task demands generalize across open-skill movements?". We expected to observe changes in pKFA, pKAbA, and pKAbM with the introduction of secondary cognitive-motor tasks during the sidestep. We also hypothesized that DTC arising from identical secondary tasks would positively correlate between jump-landings and running sidesteps, indicating subject-specific dual-task effects that are pervasive across different movement assessments.

The presence of a rapid decision-making task influenced early-stance pKAbA and pKAbM during the sidestep. Small-moderate effects were observed between all anticipated and unanticipated conditions, though not all pairwise comparisons reached statistical significance (**Table 4.3**). Deleterious effects of removing an athlete's ability to pre-plan movement has been previously documented [225]. The added presence of concurrent working memory tasks here is novel, however, and was introduced in an effort to simulate the more complex demands of competitive sport. Although the recall test presented an appreciable challenge (**Table 4.4**), it is likely that the working memory demands did not directly interfere with individual attention devoted to completing the required movement. Cognitive function is a construct of different domains that must retain the flexibility to interact with a complex environment [226]. As such, all domains do not contribute to every task in the same capacity (e.g., a fast reaction time is not essential to performing a complex memory task) [75]. It is plausible that the cognitive demands of competitive sport are partially independent. In order to elicit compounding dual-task effects, researchers should consider similarities in cognitive demands between primary and secondary task requirements when using dual-task paradigms.

The lack of effect of anticipation on pKFA and the lack of effect of secondary motor and working memory tasks for any of the chosen biomechanical variables is at odds with previous research. Other groups have found adverse effects on pKFA from rapid decision-making tasks during running sidestep performance [176, 199, 225, 227]. Researchers have also previously reported effects of secondary motor and working memory tasks in both running sidestep [85, 173] and jump-landings [69, 73, 87]. Plausible contributions to these conflicting findings could be the chosen sample population of recreational athletes combined with our choice to standardize running speed to each participant's maximal effort while dribbling a soccer ball. The most limiting speed observed in the current study was while ball-handling (**Table 4.4**). We controlled for approach speed to mitigate its effects as a confounding factor [228], but a consequence of this standardization was that participants performed the non-ball handling tasks at a slower speed than they would have otherwise preferred. The central goal of this work was to understand how cognitive-motor function influences injury risk, but it may be that such relationships vary across populations of differing skill level [229, 230]. More research is needed to understand how these cognitive-motor relationships generalize across skill levels and their associated differences in movement speed, shifts in attentional load, and types of movement.

No cognitive function*'Condition' interactions were observed, and no measure of cognitive performance factored in as a covariate. This is at odds with previous findings characterizing lower-extremity injury risk in athletes and findings of cognitive function associating with subject-specific dual-task effects [27, 80-82, 85]. It is possible that the cognitive domains we chose to assess did not sufficiently capture the processes involved in movement performance [226]. Simple reaction time is the cognitive process most commonly associated with injury risk [27, 81] but is not a domain we directly assessed. Processing speed was assessed in the current study, which may be considered an analogue to simple reaction time due to the task demands of both assessments (completing repeated expected tasks as quickly as possible). However, a key distinction between the two is that processing speed assessments require an extra cognitive step (e.g., comparing two sets of letters) before initiating the desired response. Other cognitive domains we chose to characterize (i.e., primary memory, attentional control) have not yet been directly associated with elevated ACL injury risk, but are of interest as they pertain to higher-order executive function [226] and have previously been associated with subject-specific differences in dual-task effects [85, 87, 144]. The lack of significant cognitive-motor relationships here, again, point to the notion that secondary task demands may exist on a continuum and may be influenced to different degrees by factors that were not accounted for in the current study (e.g., differences in skill level). The cognitive tasks used here may also not have sufficiently challenged participants during the running sidestep, thereby not eliciting noticeable changes in neuromuscular control. Future work revisiting reaction time as a cognitive domain of interest is warranted.

One correlation yielded a significant relationship (**Figure 4.3**), with one additional relationship reaching significance after the removal of an outlier (**Table 4.5**), which runs counter to our hypothesis that identical dual-task effects would elicit similar adaptations across movements. However, these findings add a unique take to existing literature discussing the generalizability of movement performance across unique movement types [218-220]. Realizing that dual-task knee mechanics could be described using DTC, change scores (the difference between dual-task and single-task condition estimates), or the raw estimates for each condition, we performed post-hoc correlations for the alternate choices of dependent variable (i.e., dual-task change scores and raw condition estimates; **Table 4.6**). The change score analysis reflected the same lack of correlations as the DTC; however, several positive correlations were identified using the raw condition estimates for several conditions across pKFA, pKAbA, and pKAbM (ρ: 0.135 – 0.943, **Table 4.7**). Positive relationships for raw condition estimates between movements with similar dual-task conditions extends prior findings that examined single-task movement performance [218]. It is possible that differential measures like DTC and change scores, when considering peak knee mechanics during a ballistic movement, are not sensitive enough to resolve out meaningful relationships across unique movements [231].

Table 4.6: Spearman's ρ based on change scores between dual-task and single-task measures

	pKFA	pKAbA	pKAbM
Unanticipated	ρ: -0.108 *p*: .650	ρ: 0.365 *p*: .113	ρ: 0.352 *p*: .128
Recall	ρ: 0.107 *p*: .636	-ρ: 0.286 *p*: .196	ρ: 0.132 *p*: .559
Identify/Recall	ρ: -0.082 *p*: .724	ρ: -0.092 *p*: .691	ρ: -0.188 *p*: .414

Table 4.7: Spearman's *ρ* based on raw values. Biomechanical measures demonstrated small-moderate correlations between jump-landing and sidestep tasks with identical secondary tasks (underlined). Dual-task measures of one movement were strongly correlated with both baseline and dual-task measures of the same movement. (*indicates *p* < .050).

		Baseline		Unanticipated		Recall		Identify/Recall
pKFA		**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**
Baseline	**Sidestep**	0.475*	-	-	-	-	-	-
U.A.	**Jump-Land**	0.874*	0.524*	-	-	-	-	-
	Sidestep	0.307	0.799*	0.286	-	-	-	-
Recall	**Jump-Land**	0.895*	0.559*	0.929*	0.340	-	-	-
	Sidestep	0.370	0.798*	0.370	0.913*	0.388	-	-
Identify/ Recall	**Jump-Land**	0.904*	0.669*	0.871*	0.502*	0.908*	0.533*	-
	Sidestep	0.339	0.842*	0.255	0.861*	0.269	0.817*	0.453*
pKAbA		**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**
Baseline	**Sidestep**	0.481*	-	-	-	-	-	-
U.A.	**Jump-Land**	0.916*	0.479*	-	-	-	-	-
	Sidestep	0.320	0.813*	0.441*	-	-	-	-
Recall	**Jump-Land**	0.925*	0.366	0.895*	0.296	-	-	-
	Sidestep	0.390	0.872*	0.384	0.834*	0.227	-	-
Identify/ Recall	**Jump-Land**	0.943*	0.312	0.901*	0.135	0.884*	0.230	-
	Sidestep	0.467*	0.940*	0.530*	0.814*	0.300	0.888*	0.382
pKAbM		**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**	**Sidestep**	**Jump-Land**
Baseline	**Sidestep**	0.360	-	-	-	-	-	-
U.A.	**Jump-Land**	0.770*	0.293	-	-	-	-	-
	Sidestep	0.506*	0.668*	0.474*	-	-	-	-
Recall	**Jump-Land**	0.923*	0. 440*	0.721*	0.616*	-	-	-
	Sidestep	0.571*	0.734*	0.566*	0.730*	0.689*	-	-
Identify/ Recall	**Jump-Land**	0.826*	0.253	0.782*	0.291	0.746*	0.312	-
	Sidestep	0.484*	0.883*	0.400	0.703*	0.545*	0.897*	0.242

A few limitations within this study should be noted. First, this study did not control for multiple comparisons between jump-landing and sidestep measures; correlational results, particularly those with marginal significance, should be interpreted with caution. There is a discrepancy in stimulus presentation times between the current sidestep study (~400 ms prior to initial contact) and the previous jump-landing study (~250 ms prior to initial contact), potentially confounding the correlations between unanticipated dual-task effects. Stephenson *et al.* noted that stimulus presentation times beyond ~300 ms resulted in landing patterns resembling anticipated jump-landings [71], but a review by Almonroeder *et al*. noted that stimulus presentation times used in cutting-based tasks range between ~350 and ~600 ms [225]. The current study followed previously-established stimulus presentation times noted in 45° run-to-cut studies for the sidestepping stimulus presentation times [199, 230]. This was done after pilot studies with a 250 ms presentation time proved untenable for the sidestep with the desired population. This study population considered only healthy, recreationally-active female soccer players, limiting the degree to which the current findings may be extended. The *a priori* decision to analyze only a few injury-relevant biomechanical variables and cognitive function measures was made to minimize Type I error. However, the authors acknowledge that ACL injuries are dependent on a range of biomechanical variables of the hip, knee, and ankle [20, 232], and cognitive function consists of a variety of low-level and high-level processes [226]. Despite these considerations, the results presented in this study shed crucial light on the complex nature of cognitive-motor relationships during injury-relevant movements.

DECOUPLING VISUAL CONSTRAINT FROM RAPID DECISION-MAKING EFFECTS DURING A JUMP-LANDING

Contribution of Authors and Co-Authors

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C5.1 Introduction

Rapid decision making (e.g., recognizing and responding to an incoming opponent) is a common task in sport environments that requires attentional resources and has also been associated with ACL injury risk and high-risk knee mechanics [66, 173, 174]. To replicate this scenario, researchers have focused on identifying how athletes adapt their movement patterns in response to rapid decision-making secondary tasks. The reduced ability to pre-plan the movement presents an appreciable motor control problem for athletes, who rely on visualizing the desired movement prior to its execution to efficiently activate the proper muscles and produce coordinated movement [185, 188, 233]. These unanticipated scenarios, where athletes are required to respond to the delayed presentation of a directional cue rather than pre-plan the movement, have consistently shown deleterious effects on different sport-specific movement (e.g., landing and sidestepping) mechanics [31, 66-68, 173-175, 198, 199]. These adverse changes in knee mechanics (decreases in early-stance knee flexion, increases in knee abduction, increases in lateral trunk lean, increases in posterior ground reaction forces) translate to increased loading at the ACL [40, 113].

Unanticipated conditions can be broken out into two overarching categories: sport-specific (e.g., a video recording of opponents changing position [199]) and general (e.g., an arrow indicating secondary direction [184]) modalities. One commonality between sport-specific and general unanticipated modalities is that visual stimuli are used to deliver the directional cue to participants, whether that be a set of lights, an arrow, or a simulated defender [229, 230]. Notably, visual constraints in anticipated movement settings have induced similar effects on drop-jump and jump-landing biomechanics as unanticipated tasks [67, 73, 221]. Fischer *et al.* (2020) reported similar small decreases in early-stance knee flexion angle between visually-constrained working memory tasks with and without a directional cue, and Almonroeder *et al.* (2018) reported similar increases in peak knee abduction angle between simulated rebound targets and unanticipated task demands [67, 221]. Therefore, it is possible that directing an individual's gaze away from their intended path of travel independently contributes to knee mechanics in unanticipated protocols, but no study has directly attempted to decouple the effects of visual constraint from rapid decision-making dual-tasks during an open-skill movement. Revealing the role of visual constraint on landing mechanics is necessary to refine the understanding of prior literature on the influence of unanticipated conditions on knee mechanics. By decoupling contributions of constraining visual gaze from rapid decision-making demands, new insight that guides novel testing and intervention approaches may be possible.

The purpose of this study, therefore, was to quantify the effects of unanticipated and visually-constrained dual-task demands on jump-landing mechanics. We hypothesized that (1) isolated effects of visual constraint and lack of movement pre-planning would be associated with less early-stance peak knee flexion angle (pKFA) and greater early stance peak knee abduction angle (pKAbA) and moment (pKAbM) , and (2) combined effects of visual constraint and lack of movement pre-planning would be appreciably greater than either effect in isolation.

C5.2 Methods

This study's protocol was approved by the Institutional Review Board at Montana State University. An *a priori* power analysis was conducted in the GLIMMPSE software package to determine a minimum sample size [207]. The power analysis found that, to observe a main effect of 'condition' on the chosen dependent variables with similar changes in knee mechanics to previously-published findings (2° change in pKFA, pKAbA; 2%BW*Height change in pKAbM) with 80% statistical power and an alpha level of 0.05, a sample size of 35 was needed [67, 221]. Participants were eligible for study participation if they were free of lower-extremity surgeries, had no lower-extremity injuries within three months of study participation, had no concussions or traumas to the head within six months of study participation, were free of uncorrected hearing or vision problems, and self-reported a score of 12+ on the Marx activity scale to quantify frequency of out-of-plane movement demands [234]. Men and women were both eligible for study participation. Study participation involved one lab visit lasting between 2.5-3 hours.

Cognitive Assessments

At the beginning of the lab visit, participants completed four assessments of baseline cognitive performance, challenging their simple reaction time and selective attention. Measures of cognitive function were recorded to investigate subject-specific differences in dual-task effects, as cognitive function has been tied to elevated levels of ACL injury risk and dual-task effects [27, 79]. All tests were administered using the E-Prime 3.0 computer program (Psychology Software Tools, Inc.; Pittsburgh, PA, USA). During the simple reaction time assessments, participants were instructed to press a button immediately after being presented an image (**Visual_SRT**) or tone (**Auditory_SRT**) [81]. The primary outcome variable for the reaction time assessments was average reaction times (ms). During selective attention assessments, participants completed visual and auditory Stroop tests where they vocally responded to word-color pairs (Visual Stroop) or word-tone pairs (Auditory Stroop) as quickly and accurately as possible [203, 222, 235]. Participants were required to respond to the color (Visual Stroop) or tone (Auditory Stroop) of the presented stimulus while suppressing the stronger inclination to repeat the stimulus (e.g., participants should respond “GREEN” to the word “BLUE” written in green letters (Visual), or

"High" to the vocalized word "Low" played in a high tone). Selective attention outcome variables were average reaction time (ms) and response accuracy (%) of the incongruent stimuli (e.g., the word "BLUE" written in green letters). All outcome variables were normalized within the cohort using *Z*-scores for inclusion into statistical modeling [206]. This approach yielded candidate covariates: four for reaction time (**Visual_SRT, Auditory_SRT, VisualStroop_RT, AuditoryStroop_RT**) and two for test accuracy (**VisualStroop_ACC, AuditoryStroop_ACC**). Positive reaction time Z-scores were associated with faster reaction times; positive accuracy Z-scores were associated with greater test accuracy.

Jump-Landing

After completing cognitive assessments, motion capture and ground reaction force data were collected for a jump-landing assessment following a protocol previously established by Herman and Barth [184, 221]. A researcher attached fifty-nine reflective markers to the surface of participants' skin using double-sided tape, following a modified full-body Plug-in Gait model [198]. Additional markers were added bilaterally on the shoe, above the lateral aspect of the calcaneus and the head of the first metatarsal to aid in tracking the foot segment. Anatomical markers placed bilaterally at the medial femoral epicondyles and medial malleoli were removed following the collection of a static calibration trial. Motion capture data were collected using a 10-camera system (6 Raptor-12, 4 Kestrel cameras) recording at 250 FPS (Motion Analysis Corp.; Rohnert Park, CA, USA), and bilateral ground reaction force data were collected at 1000 Hz using two force plates (OPT464508-2K; AMTI; Watertown, MA, USA). For the jump-landing assessment, participants began on top of a 30-cm box placed a distance equal to one-half their height away from the force plates. They then jumped to the force plates and, immediately upon contacting the ground, jumped as 'high and as hard as they could' to one of three secondary landing zones: forward 1 m and 45° to the left of the force plates, forward 1 m and 45° to the right of the force plates, or straight up and landing within the boundaries of the force plates a second time. Jump-landing assessments were performed under five conditions, a single-task baseline and four dual-task conditions consisting of different visually-constrained and rapid decision-making dual-task demands. Conditions were block-randomized to mitigate learning and fatigue effects, and participants were allowed as many practice trials for each condition as they needed to feel comfortable with each task.

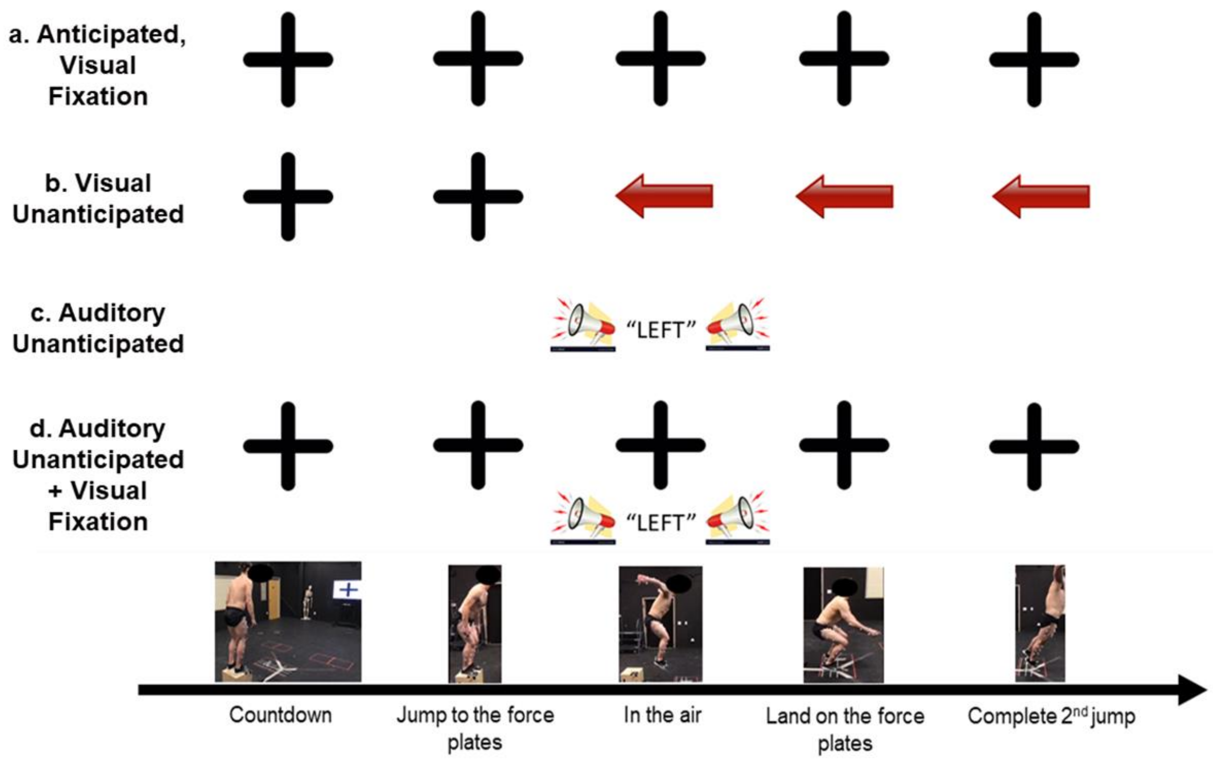

Figure 5.1: Trial progression of all dual-task conditions from beginning the trial to completing the second jump. Directional cues were triggered ~250 ms prior to initial contact with the force plates.

During the *Baseline* condition, participants were told, before beginning each trial, whether they were to jump to the left, to the right, or straight up after contacting the force plates. They jumped to the force plates, and immediately jumped in the required secondary jump direction as ‘high and as hard as they could’. Participants were encouraged to focus visual attention on the landing zone during the *Baseline* condition.

During the *Anticipated Visual Fixation* (*VisFix)* condition (**Figure 5.1a**), participants performed the anticipated jump-landing following the same basic steps as during the *Baseline* condition, with one alteration. During each trial, participants were required to fixate on a static image directly in front of them throughout each trial. A second researcher confirmed that participants maintained their gaze on the static image during the *VisFix* trials. The *VisFix* condition was introduced to be a visually-constrained anticipated condition to decouple visual constraint from unanticipated task demands [236].

During the *Visual Unanticipated (VisUA)* condition (**Figure 5.1b**), participants were not told which direction to jump following their initial landing. Instead, a visual cue was triggered ~250 ms prior to initial contact with the ground [71]. The visual cue was an arrow pointing in the direction of the secondary jump and reflects a commonly-used method of visual directional cues to induce rapid decision-making. Directions were chosen at random using a custom E-Prime 3.0 program, with each direction being equally likely to appear each trial.

During the *Auditory Unanticipated (AudUA)* condition (**Figure 5.1c**), participants were not told which direction to jump following their initial landing. Instead, an auditory cue was triggered ~250 ms prior to initial contact with the ground The auditory cue was a pre-recorded voice command, lasting 150 ms, stating “UP”, “LEFT”, or “RIGHT”. Participants were encouraged to focus visual attention on the landing zone during the *AudUA* condition. The *AudUA* condition was introduced to induce the same cognitive challenge of rapid decision-making without the potentially confounding factor of visual constraint [67, 73, 221].

During the *Auditory Unanticipated with Visual Fixation (AudUA+VisFix)* condition (**Figure 5.1d**), participants performed the jump-landings following the *AudUA* methodology, with the alteration that they were required to fixate on a static image directly in front of them throughout each trial. Again, a second researcher confirmed that participants maintained their gaze on the static image during each *AudUA+Fix* trial. The *AudUA+Fix* condition was introduced as an alternative method of investigating the combined effects of rapid-decision making and visual constraint on open-skill movement performance, to explore the potential differences in interpreting auditory and visual signals [237].

Data Processing and Analysis

Three good trials for each condition, in each secondary jump direction (right, left, straight up), were collected. A trial was considered acceptable if the participant completed the secondary jump in the correct direction and a complete foot strike within the boundaries of the force plate was measured for both right and left legs. The landing from the initial jump off the box was the focus of analysis, with this study focusing only on trials with straight up secondary jump directions. Motion capture and ground reaction force data were filtered in Visual3D at 15 Hz using 4th order, low-pass, zero-lag Butterworth filters [205]. Kinematic and kinetic data were calculated using an inverse kinematics model, with hip and knee joints restricted to three degrees of freedom (*x-y-z* rotation corresponding to flexion/extension, adduction/abduction, and internal/external rotation, respectively) and ankle joints restricted to two degrees of freedom (*x-z* rotation corresponding to plantar/dorsiflexion and inversion/eversion, respectively). Inverse kinematics models were optimized using a quasi-Newtonian optimization method [162]. Early-stance (within 50 ms following initial ground contact) peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and peak knee abduction moment (pKAbM) were identified for each trial using a custom MATLAB program [20, 21, 94]. Knee joint angles were calculated using an *x*-*y*-*z* Cardan rotation sequence, corresponding to flexion/extension, adduction/abduction, internal/external rotation. Externally-defined knee joint moments were resolved in the proximal segment's coordinate system and normalized to participant's body weight and height.

Linear mixed models were used to test for main effects of 'Condition' on pKFA, pKAbA, and pKAbM; 'Subject' was introduced into the models as a random effect. Composite *z*-scores were included as covariates, and interactions between 'condition' and composite *z*-scores were investigated. Primary models for each dependent variable were selected as the ones that minimized AICc and BIC criteria (see **Appendix A** for model fit characteristics) [238]. Where a main effect of 'Condition' was present, pairwise comparisons were investigated using Tukey's HSD tests. As a measure of quality control, differences in lead times (the amount of time between stimulus presentation and initial ground contact) were investigated for the *VisUA*, *AudUA*, and *AudUA+Fix* conditions using a linear mixed model with 'Condition' as the main effect and 'Subject' as the random effect. Differences between conditions were quantified using Cohen's *d* effect size [239]. Significance for all tests was set at $\alpha = 0.05$.

C5.3 Results

Thirty-six recreational athletes provided written informed consent for study participation (**Table 5.1**). Of the 540 jump-landing trials that were collected (36 participants x 5 conditions x 3 trials), 21 were excluded after follow-up examination showed they were unfit for inclusion in the data set (incomplete foot strike on force plate, asynchronous analog data). The excluded trials were broken down as such: *Baseline* (0), *VisFix* (5; one participant excluded), *AudUA* (4), *AudUA+Fix* (7; one participant excluded), *VisUA* (5; one participant excluded). This resulted in 36 data points for two conditions (*Baseline, AudUA*) and 35 data points for three conditions (*VisFix, AudUA+Fix, VisUA*). An outlier was observed in the auditory Stroop data and, to reduce the influence of this point on driving modelled relationships, the point was excluded from final data analysis (**AuditoryStroop_ACC:** score – 35%, Grubb's outlier = 3.76, p = .022; **AuditoryStroop_RT:** RT – 1437.6 ms, Grubb's outlier = 3.62, p = .040). It is worth noting that the significant results remained the same with or without omitting the outlier. Descriptive statistics for all collected cognitive and biomechanical data are provided in **Tables 5.1** and **5.2**.

Table 5.1: Study cohort characteristics and cognitive scores given as: Average (SD)

Gender (M/F)	23/13
Age (yrs)	21.4 (3.9)
Height (m)	1.79 (0.09)
Mass (kg)	75.70 (15.32)
Marx Activity Score (0-16)	13.97 (1.84)
Visual RT (ms)	263.4 (34.2)
Auditory RT (ms)	247.3 (24.4)
Visual Stroop – Accuracy (%)	94.2 (7.4)
Visual Stroop – RT (ms)	742.5 (114.7)
Auditory Stroop – Accuracy (%)	89.5 (11.0)
Auditory Stroop – RT (ms)	814.8 (134.2)

Table 5.2: Descriptive statistics of collected biomechanical data. Results have been given as: Average (SD). Condition abbreviations are: VisFix (Anticipated, visual fixation), AudUA (Unanticipated, auditory cue, no visual fixation), AudUA+Fix (Unanticipated, auditory cue, visual fixation), VisUA (Unanticipated, visual cue)

	Baseline	**VisFix**	**AudUA**	**AudUA+Fix**	**VisUA**
pKFA (°)	59.92 (6.22)	59.11 (6.03)	56.96 (5.33)[a,b]	56.49 (5.52)[a,b]	57.32 (5.83)[a,b]
pKAbA (°)	11.56 (4.88)	11.51 (5.39)	11.80 (4.20)	11.78 (4.43)	12.09 (4.41)
pKAbM (%BW*Height)	4.17 (2.21)	4.53 (2.36)	4.69 (2.52)	4.77 (2.46)	4.97 (2.84)[a]

[a]indicates significant difference (p < .050) from *Baseline*. [b]indicates significant difference from *VisFix*.

A main effect of 'Condition' was observed for pKFA (F = 21.03; *p* < .001; **Figure 5.2**). The *Baseline* condition was associated with greater early-stance pKFA than the *AudUA* (d: 0.54, *p* < .001), *AudUA+Fix* (d: 0.61, *p* < .001), and *VisUA* (d: 0.45, *p* < .001) conditions. The *VisFix* condition was associated with greater early-stance pKFA than the *AudUA* (d: 0.42, *p* < .001), *AudUA+Fix* (d: 0.49, *p* < .001), and *VisUA* (d: 0.34, *p* < .001) conditions. No significant changes were observed between *Baseline* and *VisFix* (d: 0.12, *p* = .963) or between any unanticipated conditions (all d < 0.20, all *p* > .200) for pKFA. **AuditoryStroop_ACC** was a significant covariate in the model, with better accuracy scores associated with less pKFA (F = 6.26, *p* = .019; **Figure 5.3**). No other cognitive measures were significant covariates, and no cognitive domain-by-'Condition' interactions were observed (all *p* > .050).

A main effect of 'Condition' was observed for pKAbM (F = 2.50; *p* = .047; **Figure 5.2**). Small increases were observed for the *VisUA* condition relative to the *Baseline* condition (d: -0.29, *p* = .039). No other effects reached statistical significance (all *p* > .050). **AuditoryStroop_ACC** was a significant covariate in the model, with better accuracy being associated with greater pKAbM across conditions (F = 5.76, *p* = .024; **Figure 5.3**). No other cognitive covariates reached statistical significance, and no cognitive domain-by-'Condition' interactions were observed (all *p* > .100).

No main effect of 'Condition' was observed for pKAbA (F = 0.45; *p* =.773; **Figure 5.2**). No cognitive covariates or cognitive domain-by-condition interactions were observed (all *p* > .150).

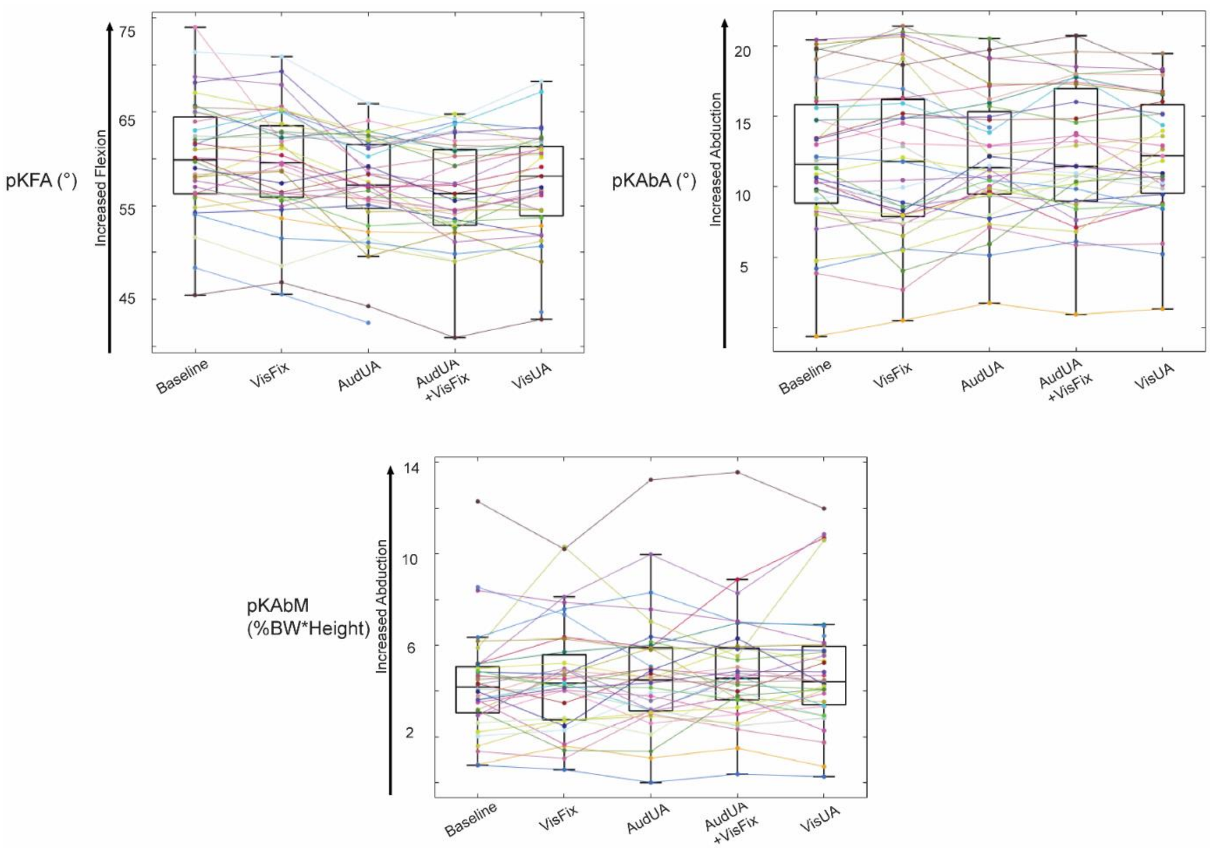

Figure 5.2: Boxplots overlaid with individual line plots for pKFA (top left), pKAbA (top right), and pKAbM (bottom).

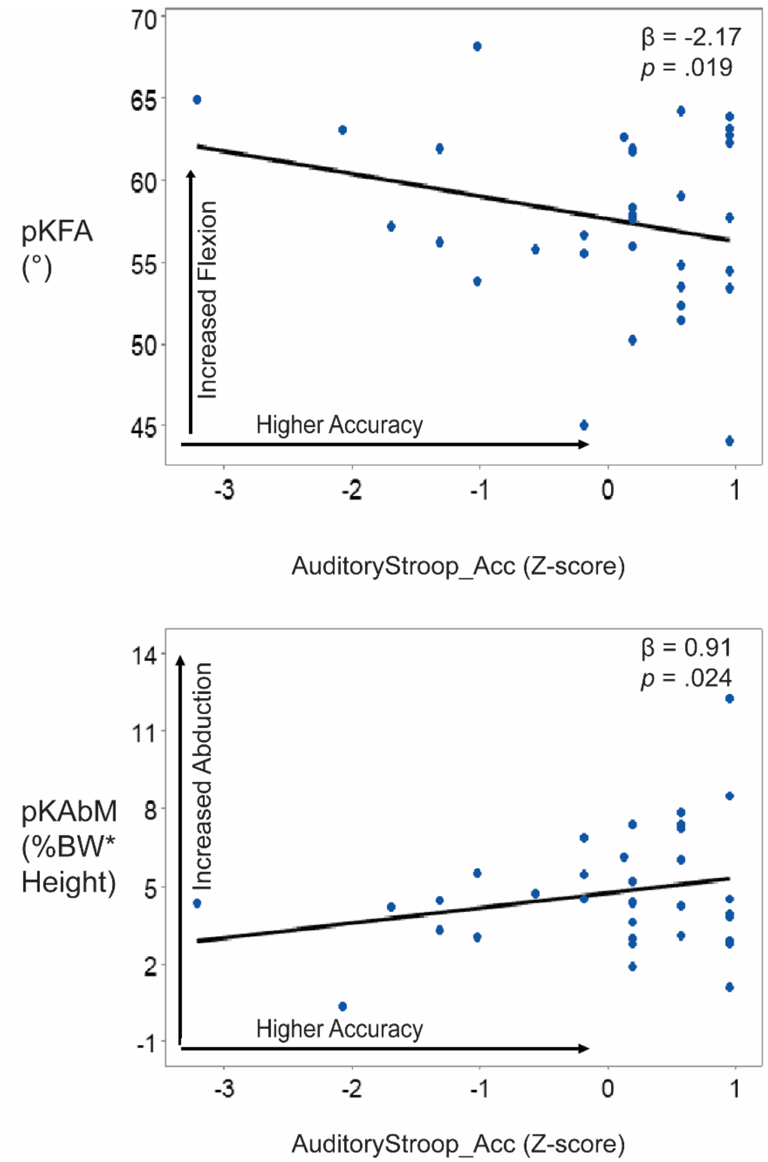

Figure 5.3: Auditory-based attentional control accuracy measures were a significant covariate in pKFA and pKAbM models (results reported as mixed model coefficients and *p*-value). Worse average landing mechanics (decreased pKFA, increased pKAbM) across all conditions were associated with better accuracy performance

A main effect of 'Condition' was observed for lead times between the unanticipated conditions (**Table 5.3;** F = 107.59, $p < .001$). Lead times for the *VisUA* condition were longer by approximately 100 ms than the lead times for *AudUA* ($p < .001$) and *AudUA+Fix* ($p < .001$) conditions. This discrepancy was due to the time it took to play the audio file completely and represents the most conservative estimate of accounting for any added time participants needed to interpret the verbal directional cue. No differences were observed between *AudUA* and *AudUA+Fix* conditions (p = .924).

Table 5.3: Average (SD) lead times across unanticipated conditions. *indicates significant difference (p < .050) from *VisUA*.

	AudUA	**AudUA+VisFix**	**VisUA**
Lead time (ms)	147.4 (86.9)*	143.0 (73.6)*	263.0 (84.2)

C5.4 Discussion

The purpose of this study was to investigate the effects of visual constraint and rapid decision-making on early-stance landing mechanics during a jump-landing. It was hypothesized that visual constraint and rapid decision-making demands would both have measurable effects on pKFA, pKAbA, and pKAbM, and that the combined effects of visual constraint and rapid decision-making on these variables would be appreciably greater than either secondary task demand by itself. The results of this study demonstrate rapid decision-making played a larger, more discernable role on pKFA than visual constraint during jump-landings. Additionally, inconclusive findings were observed for pKAbM, where simultaneous visual constraint and rapid decision-making had an appreciable impact on landing mechanics between the *Baseline* and *VisUA*, but not *AudUA+Fix* conditions.

The results of the current study suggest that isolated visual constraint may not play a dominant role in altering landing mechanics. Prior studies, as well as this one, have proposed that the requirement of restricting visual gaze negatively influences neuromuscular control by limiting a critical information source from the central nervous system's feedback loop during movement.[67, 73, 189, 221] Early-stance landing mechanics during pre-planned movements are influenced by the presence of a goal-relevant visual fixation, that is, a target needed for the completion of a secondary task (e.g., a response letter or basketball). However, the current results do not suggest that a neutral visual constraint, where gaze was confirmed by a second researcher, has an appreciable, independent effect on landing mechanics (Cohen's |*d*|: 0.02 – 0.12). The neutral image was intended to introduce an external target that participants could fixate without introducing a cognitively-demanding secondary task or external motivation to jump differently (e.g., reaching up to retrieve a ball). With no appreciable increase in attentional demands beyond maintaining focus on this external target, central processing was likely unhindered in its primary goal of completing the desired movement. These findings suggest that visual constraints are more likely to influence landing mechanics if the stimuli are coupled to some goal-relevant stimulus (e.g., a directional cue, suspended ball, or response letter).

The results of this study provide additional insight into the nature of rapid decision-making in lab-based assessments, due to the direct comparison of auditory and visual unanticipated tasks. The use of different directional cue modalities resulted in a common adaptation of decreased pKFA during landing. These findings suggest that the central demands of the unanticipated task, which are interpreting the directional cue and rapidly adjusting the individual's movement strategy to complete the required secondary jump, may play a larger role in terms of eliciting changes in landing mechanics in a healthy population than the modality (auditory vs. visual) of the directional cue. Notably, pKAbM differences were specific to *VisUA*, however, suggesting that some nuances of stimulus modality dependency likely exist. Auditory stimuli elicit faster responses than visual stimuli for simple task demands [240, 241]. However, this difference may not translate to the motor demands of a whole-body task like jump-landing. Determining a lead time threshold for what constitutes an “unanticipated condition” is warranted for auditory directional cues, although both auditory and visual unanticipated cues were presented below the 300 ms cutoff suggested for visual unanticipated conditions [71].

Better performance on an auditory-based attentional control assessment was associated with less early-stance pKFA and greater pKAbM across jump-landing conditions (**Figure 5.3**). This finding provides further insight into how cognitive function relates to open-skill movement performance. One of Giesche *et al.*’s findings during unanticipated single-limb landing found that higher working memory and executive function (which includes attentional control) were associated with greater instability after landing [87, 145]. The authors suggested that cognitive function may have afforded an advantage in interpreting directional cues to higher performing individuals, who would then have been able to consciously adjust their landing mechanics to complete the desired movement [87]. This conscious control of, or internal focus towards, movement performance may have been the driving cause behind the adverse landing mechanics observed in the current study [242, 243]. Internal focus, indicative of more top-down control of an individual’s movement performance, is associated with increased postural sway and smaller positive changes in landing mechanics [244, 245]. Fischer *et al.* found no discernable relationship between measures of cognitive function and knee mechanics during jump-landings, however, suggesting that the nuances of attentional control’s role need more work to be fully understood [221]. Attentional control has not yet been identified as a predictor of non-contact ACL injury risk, though its role as an indicator of task engagement (i.e., how “present” an individual is to the task at hand) and its contribution to different cognitive domains motivates the need to further develop its relationship to cognitive-motor function in athletes [246].

No relationships between the reaction time measures and jump-landing mechanics were observed in the final statistical models for the dependent variables, despite a previously-established association in the literature between slower reaction times and elevated rates of non-contact ACL and other lower-extremity injuries in athletes [27, 81]. However, it is notable that a number of alternate, albeit suboptimal, statistical models for pKFA that included reaction time covariates without also including attentional control accuracy covariates identified reaction time on the visual Stroop test as a significant covariate ($p < 0.05$; **Appendix A**). The significance of the reaction time covariate was not maintained when attentional control accuracy measures were included in the model, which yielded the best fit model. Given that attentional control has pervasive relationships with other cognitive processes [247], it may be that some shared variance is explained by the reaction time and attentional control accuracy covariates, with the accuracy measure seeming to have stronger evidence for its relationship. Attentional control has strong evidence for predicting cognitive multitasking performance [75, 248], and future research is needed to understand the role of attentional control more completely in cognitive-motor scenarios.

A few limitations with this study should be noted. First, the difference in lead times between auditory and visual unanticipated conditions may be overly conservative. It is currently unknown how much of the prerecorded cue participants needed to discern the desired secondary direction. This means that the difference between auditory and visual presentation times may be shorter than 150 ms (**Table 5.3**), mitigating the potential impact of this difference. Despite this conservative approach to determining lead times, all three directional cues were presented within previously-established suggestions for inducing unanticipated scenarios in a jump-landing [71]. The authors also acknowledge that sex differences in lower-extremity mechanics have been established in the literature, however including sex as a covariate in our statistical models did not appreciably change the core findings of this study [41, 198, 209, 249, 250].

C5.5 Conclusions

The purpose of this study was to investigate the individual and combined effects of visual constraint and rapid decision-making on knee mechanics during a jump-landing. The current results demonstrated rapid decision-making effects on pKFA are similar across auditory and visual directional cues during jump-landings. The effects observed on pKAbM (i.e., an effect from visual, but not auditory unanticipated) suggest this rapid decision-making effect is more nuanced than simply stating that unanticipated paradigms are generalizable across modalities. Results also suggest visual constraints may need to be goal-relevant to induce appreciable changes in neuromuscular control during open-skill movement performance. Better attentional control performance here demonstrated a maladaptive effect on landing mechanics. These findings provide additional context to previous research on the unanticipated movement paradigm and its relationship to lower-extremity neuromuscular control.

A SUMMARY DISCUSSION ON THE CURRENT RESULTS AND THEIR RELATIONSHIP TO THE STATE OF COGNITIVE-MOTOR RESEARCH

The central purpose of this research was to broaden the understanding of how cognitive-motor function relates to ACL injury-risk factors. The studies presented within this dissertation were designed to address key gaps in knowledge pertaining to cognitive-motor function as they relate to non-contact ACL injuries. The central hypothesis was twofold: 1) that athletes would demonstrate adverse changes in neuromuscular control (decreased pKFA, increased pKAbA and pKAbM) as a result of cognitive and motor dual-task demands, and 2) that these neuromuscular control changes would be associated with individual baseline cognitive function. Dual-task effects observed in the three studies of this dissertation generally supported the first hypothesis. Inconsistent cognitive-motor relationships offered marginal support of the second hypothesis. The key contributions of these studies are summarized in **Table 6.1**.

Table 6.1: Summary of key findings and contributions to cognitive-motor function research.

Ch. 3	Visually-demanding secondary tasks during a jump-landing showed decreases in pKFA	Cohen's |*d*|: 0.29-0.34
	Changes in pKFA were negligible between anticipated and unanticipated visually-demanding conditions	Cohen's |*d*|: 0.01-0.03
Ch. 4	Unanticipated demands during a running sidestep showed increases in early-stance pKAbA and pKAbM	Cohen's |*d*|: 0.20-0.45
	Individuals largely responded differently to dual-task challenges during jump-landing versus running sidestep movements	Spearman's ρ: -0.505 – 0.470
Ch. 5	Unanticipated jump-landing showed decreases in early-stance pKFA, increases in early-stance pKAbM	Cohen's |*d*|: 0.35-0.57
	Isolated effects of visual fixation on pKFA, pKAbA, and pKAbM were negligible	Cohen's |*d*|: 0.02-0.12
	Effects of directional cue modality on pKFA, pKAbA, and pKAbM were negligible	Cohen's |*d*|: 0.02-0.14
	Better attentional control was associated with poorer landing mechanics	β_{pKFA} = -2.17 °/Z-score β_{pKAbM} = 0.91 %BW*Height/Z-score

Ch. 6.1: Developments in Dual-Task Design

The current studies examined several novel dual-task demands in the context of non-contact ACL injury mechanics. These dual-tasks included visuospatial recall tests (**Ch. 3, 4**), auditory unanticipated tasks (**Ch. 5**), and neutral visual constraints (**Ch. 5**). Previously, most dual-task paradigms used in sport-relevant movement studies have been limited to a direct recreation of an aspect of the competitive sport environment (**Table 2.1**). Such paradigms predominantly consist of either motor-based secondary tasks (i.e., handling sport equipment during movement) or visually-demanding rapid decision-making (i.e., the unanticipated paradigm). The chosen secondary tasks, therefore, were investigated in order to establish the effects of unexplored cognitive demands (e.g., visuospatial demands like recalling teammate positions) and decouple potential confounding factors from established paradigms (i.e., the contribution of visual constraint to altered neuromuscular control).

Unanticipated tasks were associated with the most pervasive dual-task effects, demonstrating appreciably worse knee mechanics (decreased pKFA, increased pKAbA and pKAbM) across all three studies, two unique open-skill movements, and different visual and auditory modalities. Consistent effects of unanticipated demands on pKFA were observed for jump-landing mechanics across different populations of interest (**Ch. 3** and **5** – Cohen's |*d*|: 0.22-0.61), while small-to-medium effects for pKAbA and pKAbM were observed for running sidestep mechanics (**Ch. 4** – Cohen's |*d*|: 0.19-0.45). These findings corroborate previous research into the effects of rapid decision-making during injury-relevant movements and extend them by demonstrating their presence across visual and auditory modalities [66, 173].

Working memory tasks did not consistently influence knee mechanics. The *Identify/Recall* task demands were associated with small-to-medium effects on jump-landing pKFA (Cohen's *d*: 0.33) but had negligible effects on running sidestep performance (Cohen's |*d*|: 0.00-0.12). This finding was surprising, but note the discrepancy in lead times between the jump-landing and sidestep for this condition (lead $time_{Jump\text{-}Landing}$: 272 ± 83 ms, lead $time_{RTC}$: 425 ± 123 ms), and the consistency with which identify/recall tasks were accurately completed ($accuracy_{Jump\text{-}Landing}$: 55.4 ± 24.3%, $accuracy_{RTC}$: 57.7 ± 25.8%). As the identify/recall is a previously-unexamined dual-task paradigm, no standard yet exists to inform best practices when attempting to induce dual-task effects. The additional 150 ms present in the sidestep was likely enough time for participants to identify the response letter before shifting focus back to the movement task at hand [240]. The additional time allowed for task-switching would also help to explain the lack of appreciable effects present during the recall task for both jump-landing and sidestep. Effects of the visuospatial *Recall* task used in **Ch. 3** and **4** were negligible across jump-landings and sidesteps (Cohen's |*d*|: 0.00-0.17). When feasible, participants may have been better poised to switch between the demands of the primary movement and secondary task (i.e., a reliance on passive maintenance of the studied array during movement before bringing the array back to conscious attention to complete the response task) [251]. Such an approach would afford participants the requisite attentional capacity to complete the movement with minimal compromises to neuromuscular control [252]. When considering dual-task demands in relation to ACL injury-relevant neuromuscular control, it is likely important to introduce dual-task demands that temporally overlap with the demands of the movement being examined (i.e., focusing conscious attention on identifying a response letter while contacting the ground).

A limitation of the current findings is that, beyond accuracy scores, we are not able to quantify neurological function across the movements studied here. Differences in electrocortical activation are observed between athletes at high- and low-risk for ACL injuries, with high-risk athletes demonstrating more deterministic neural behavior [217]. Deterministic neural behavior represents task "rigidity", or being at a disadvantage when switching from the cognitive demands of one task to another [253]. Future work examining neural activation during dual-task movement performance in this ACL injury setting would be able to shed more light on how different dual-task demands are managed by athletes across the completion of different movements.

It is also worth examining the relevance of whether visual gaze is restricted by movement- or cognitive task-critical information. In addition to **Ch. 2**'s discussion on the unanticipated paradigm being an established dual-task method, previous literature has identified the use of goal-relevant targets in the simulated rebound to induce changes in lower extremity mechanics. The simulated rebound motivates the need for consistent whole-body exertion to retrieve a ball and represents a common non-contact ACL injury scenario [94]. Previous studies suggested that the simple task demands of focusing visual attention away from the landing zone, a key component of the simulated rebound task, elicited adverse changes in neuromuscular control [67, 189, 221]; this gap in knowledge is what motivated the work found in **Ch. 5**. Visual attention has a role to play in maximizing athletic performance and mitigating injury risk [14, 254, 255]. However, the findings of **Ch. 5** suggest no isolated effect of visual constraint (**Table 6.1**). One explanation for this finding is that the attentional demands are coupled with the athlete's central motivation to maintain visual fixation on that target (e.g., suspended ball, response letter) to elicit altered landing mechanics (greater peak ground reaction force, decreased peak knee flexion, increased knee abduction), like those reported previously [67, 73, 189, 221]. The visual constraint demands of the Unanticipated, Identify/Recall, and Neutral Visual Constraint secondary tasks of **Ch. 3** and **5** were identical (i.e., maintaining gaze on a television screen directly in front of them), but the resulting effects on early-stance landing mechanics were not. A central motivator for introducing the neutral visual constraint was to quantify the isolated effects of visual constraint as a confounding factor to both previous research and the findings of **Ch. 3**, however no isolated effects were observed. Rather, the results suggest that visually-demanding secondary tasks are not confounded by limiting the visual information available to the athlete and may instead be linked to a central motivation to the coupled demands of the movement and the secondary task.

Dual-task paradigms in sports biomechanics research provide valuable insight into the environmental demands of competitive sport and how those demands influence athletes' neuromuscular control. However, dual-tasks used in this dissertation have displayed varying, sometimes negligible, effects on knee mechanics. These effects depended largely on the complexity of the secondary task and the degree to which the secondary task was tied to the primary demands of the movement. Taken together, the results of the three studies suggest that secondary task demands must be coupled to the success of a movement or cognitive task to lead to consistent effects on neuromuscular control.

Ch. 6.2: Cognitive-Motor Relationships with Dual-Task Paradigms

Cognitive function was investigated in the context of dual-task paradigms because commercially-available cognitive function assessments indicate disparity in ACL injury risk in otherwise healthy competitive athletes [27]. Dual-task demands are used to capture injury-relevant movement more faithfully in a sport-specific context. Differences in ACL injury rates that depend on subject-specific cognitive function, combined with the understanding that dual-task demands affect movement performance motivates the need to investigate how subject-specific these dual-task demands may be. A more complete picture of athletic performance, secondary task demands, and cognitive function would provide clinicians with an improved understanding of targeted interventions to pursue to lessen the incidence of non-contact ACL injuries. The cognitive domains considered here were chosen to characterize aspects of cognitive function that have yet to be thoroughly investigated in the context of injury-relevant movements.

Findings across the three studies of this dissertation marginally supported the hypothesis that cognitive function is related to ACL injury-relevant knee mechanics. Better attentional control was associated with decreased knee flexion angles and increased knee abduction moments (i.e., landing mechanics that predispose the ACL to greater loading) during jump-landings [120], though this finding was inconsistent across studies. Processing speed, primary memory, simple reaction time, and computer-based multitasking all did not associate with knee mechanics during jump-landings or running sidesteps. No cognitive-motor interactions were observed for any dual-task demands. Two key takeaways may be observed from these findings: raw cognitive measures may be inconsistent in their ability to resolve out cognitive-motor relationships, and multitasking demands are not generalizable from computer-based to whole-body demands. Each takeaway will be discussed in its own context, with a concluding discussion on the limitations of this work at the end.

The results of **Ch. 5** build off of previous findings suggesting that better cognitive function plays an adverse role in neuromuscular control, while the results of **Ch. 3-4** did not [87]. Attentional control is a cognitive process that mediates an individual's ability to concentrate on the task at hand and underpins each of the identified domains of cognition [256]. When comparing the results of this work together, however, attentional control does not appear to play a consistent role in describing injury-relevant knee mechanics. Additionally, no interactions between trial type and cognitive performance measures were observed across any of the studies, suggesting that biomechanical dual-task effects were not influenced by cognitive function. Raw cognitive assessments, even when normalized to provide a more consistent measure within a cohort, may be limited in their ability to quantify cognitive-motor relationships, especially in small sample sizes like the ones used in the current biomechanical literature. Future work with larger populations (see *C6.3* for in-depth discussion of this limitation) and examining latent constructs of underlying cognitive processes, rather than using raw performance scores, is needed to address this limitation and provide stronger evidence to the role cognitive processes play on injury-relevant knee mechanics.

Computerized multitasking performance has been previously associated with measures of primary memory and attentional control [75, 144, 248], and those same patterns were observed in the dual-task study cohort (**Ch. 3-4**). For participants in these studies, higher attentional control and primary memory, as well as faster processing speed, were associated with better multitasking performance on the Control Tower assessment (**Figure 6.1**). This finding indicates that cognitive multitasking ability is tied to the interaction of several cognitive processes. Better multitasking ability during computerized assessment did not, however, translate to better landing or sidestepping mechanics. Taken together, these results suggest that the cognitive demands of injury-relevant movement may not be adequately captured by a computerized assessment of multitasking ability. It is possible that the whole-body motor demands of open-skill movement, coupled with the secondary motor and cognitive demands investigated here, were influenced by a combination of the assessed cognitive performance measures and other considerations that have yet to be assessed in the context of dual-task demands [226, 257, 258].

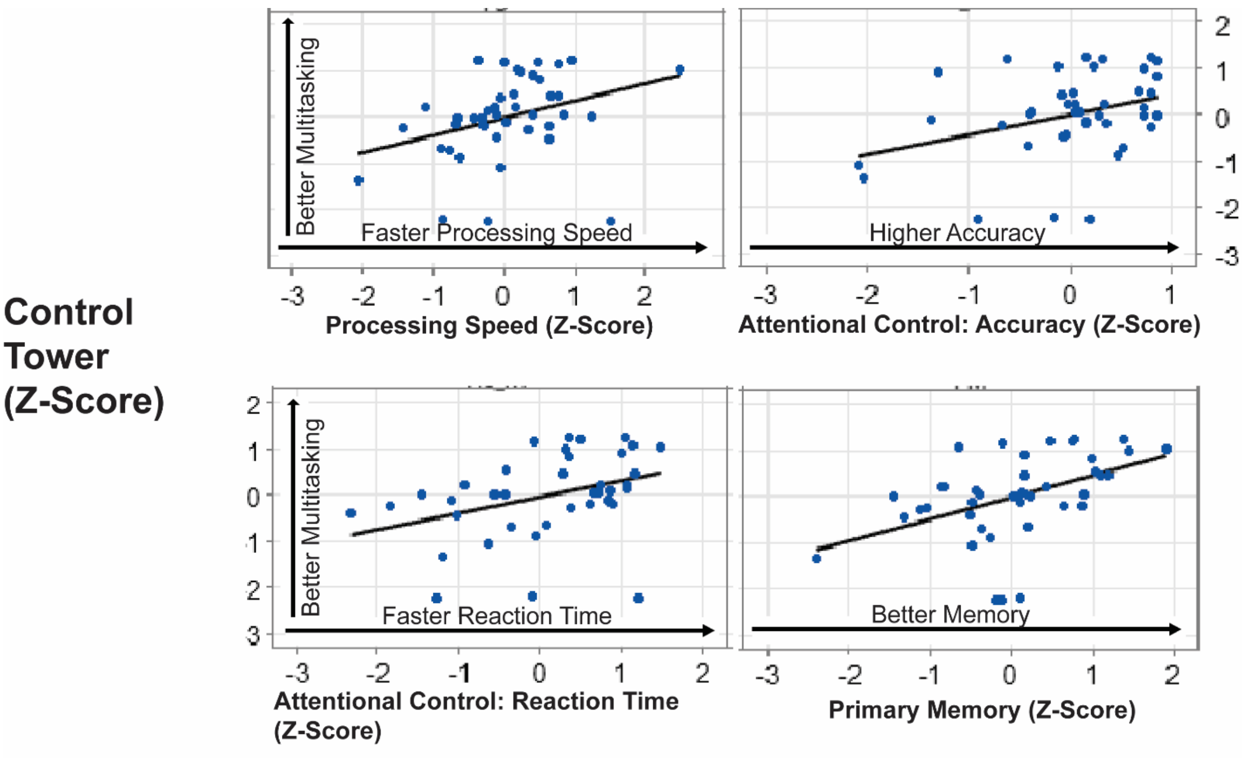

Figure 6.1: Processing speed (r = 0.337, p = .031), attentional control accuracy (r = 0.350, p = .025) and reaction time (r = 0.367, p = .020), and primary memory (r = 0.459, p = .003) were all positively associated with Control Tower test performance.

Cognitive-motor function has an appreciable, if not fully understood, role to play in efforts to mitigate ACL injury risk in athletes. The findings of this dissertation suggest two key takeaways: that cognitive-motor relationships may be underpinned by cognitive processes that extend across different domains of cognitive function, and that these relationships may be influenced by additional factors than have yet to be established in the biomechanics literature. Methodological limitations like small sample sizes and the use of raw performance scores rather than latent constructs motivate the need for further research to fully develop how cognitive-motor relationships contribute to ACL injury risk in athletic populations.

Ch. 6.3: Future Directions and General Conclusions

The findings of this research expand on an underdeveloped area of ACL injury-relevant research by providing new insight into cognitive-motor relationships during open-skill movements. The findings here suggest that cognitive processes that underpin different domains of cognition have an appreciable role to play in understanding an individual's susceptibility to open-skill movement demands. However, the methods used to quantify cognitive performance need to be revisited to address existing limitations. Because the current work focused on a few specific measures of cognitive function and neuromuscular control, ample room is left for future research to further develop these findings. A comprehensive understanding of cognitive-motor function's role to play in ACL injury mechanics, in turn, would provide new clinical targets for improving ACL injury risk mitigation.

A central limitation of this research was the *a priori* decision to limit analysis to peak knee mechanics variables within a narrow, injury-relevant time frame immediately following initial contact of the stance limb with the ground. This decision was made to constrain the focus of the investigation to what occurred at the knee joint itself, but the onset of an ACL injury is not dependent on knee mechanics alone [20]. Herein lies a future opportunity to examine the effects of similar dual-task paradigms on additional contributors to ACL strain and injury onset [20, 23, 123]. One such approach that would serve a benefit is examining the cognitive-motor relationships between the chosen baseline cognitive function measures and coupled hip-knee and knee-ankle motion. Non-contact ACL injuries are the product of coupled motion at the ankle, hip, and knee [21, 93, 94]. It is possible that the dual-task effects elicited by the paradigms explored in this research translated to a more complex postural adaptation than could be explained by examining changes in knee mechanics. Future work examining more nuanced cognitive-motor relationships that account for realistic joint-coupled motion would contribute greatly to explaining the relationship between cognitive function and ACL injury rates.

Additionally, to obtain robust cognitive performance differences, best practices in cognitive psychology research strongly encourage sample sizes numbering in the hundreds of participants [259], with additional validation measures performed for each cognitive assessment to verify measure reliability. Examining latent factors quantifying the underlying cognitive domain is also encouraged to improve robustness and ease of interpretation [260-263]. Recommended sample sizes far outnumber the largest study cohort that has been so far examined in the biomechanics literature, and no study thus far has reported on an internal validation of their cognitive assessments in a subset of the study population. Additionally, cognitive-motor relationships as they pertain to ACL injury mechanics have only considered raw cognitive performance measures. Herein lies a twofold future direction for cognitive-motor research. Expanding sample sizes to meet cognitive psychology best practices, where feasible, and incorporating internal validation of each measure would strengthen the interpretability of cognitive-motor research. These steps would position future research to provide more definitive insight into relationships between cognitive-motor research and ACL injury mechanics.

The results found in the current research motivate the need to expand the development of new dual-task paradigms to investigate the effects of different cognitively-challenging secondary tasks. The effects of working memory secondary task demands observed in **Ch. 3** and **4** demonstrate the need to explore targeted cognitive secondary tasks that sufficiently divert attentional resources away from an athlete’s primary movement goal. Effects from working memory challenges were observable when the secondary task was temporally constrained and/or sufficiently coupled to the primary movement goal. The effects of the auditory unanticipated conditions observed in **Ch. 5**, meanwhile, demonstrate that rapid decision-making effects are tied to central (i.e., mode-independent) cognitive demands. By expanding the unanticipated dual-task paradigm to challenge different modes of stimulus reception (visual vs. auditory), researchers can hope to gain a more complete understanding of how athletes adapts to the temporal constraints of reacting to a rapidly-changing sport environment [264].

Another future direction that may be pursued is the examining of cognitive-motor relationships using musculoskeletal modeling methods. Musculoskeletal modeling provides opportunities for an in-depth analysis of the active stabilization of the knee joint throughout ACL injury-relevant movements, as well as how that active stabilization translates to simulated loading in the ACL itself [40, 127, 265]. In the context of the current research presented here, musculoskeletal modeling would provide insight into any potential compensatory measures adopted by low cognitive performers, which would allow for a better understanding of why low cognitive performance was associated with better landing mechanics (**Ch. 5**).

The contributions of this dissertation motivate the need for several next steps to maximize the impact of cognitive-motor research on ACL injury prevention. The most immediately pressing next step in this line of research is to investigate more robust cognitive performance measures in the context of these injury-relevant movements. Following this investigation, it would be worthwhile to investigate how such cognitive-motor relationships associate with ACL injury rates in prospective cohorts of recreational and competitive athletes. These two efforts would combine to provide a foundation from which to establish the efficacy of richer cognitive assessments to establishing ACL injury risk and dual-task paradigms to injury risk mitigation efforts.

Dual-task biomechanics research represents a key piece to improving clinical efforts to prevent non-contact ACL injury mechanics. These contributions aim to support the long-term efforts of reducing ACL injury rates in competitive and recreational athletes. The improved understanding regarding cognitive-motor relationships gained through this dissertation expands the existing understanding on the topic and provides future directions aimed at developing more effective injury prevention strategies.

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APPENDIX A

AUDIO-VISUAL DATA SET - MODEL FIT SUMMARY

Table A.1: Summary of all resulting Akaike Inclusion Criteria (AIC), Bayesian Inclusion Criteria (BIC), and model fits (R-squared) for all iterations of potential cognitive covariates

	pKFA			pKAbA			pKAbM		
Model	AIC	BIC	R-squared	AIC	BIC	R-squared	AIC	BIC	R-squared
Condition Only	876.7	882.92	90.65	787.85	794.07	92.03	624.43	630.66	86.38
Condition + Vis RT	852.16	858.31	90.5	766.16	772.31	91.95	610.42	616.57	86.41
Condition + Aud RT	831.48	837.58	90.33	735.66	741.75	90.34	593.55	599.34	85.55
Condition + RT (both)	824.27	830.34	90.27	732.58	738.65	90.28	591.45	597.52	85.47
Condition + Vis AC_ACC	852.71	858.86	90.5	766.82	772.97	91.95	609.36	615.51	86.41
Condition + Vis AC_RT	847.44	853.59	90.49	765.23	771.38	91.95	607.8	613.95	86.4
Condition + Vis AC (both)	845.82	851.96	90.44	763.09	769.23	91.9	606.54	612.68	86.32
Condition + Aud AC_ACC	809.16	815.24	91.33	748.17	754.25	92.04	593.71	599.8	86.38
Condition + Aud AC_RT	807.85	813.94	91.33	747.87	753.95	92.04	593.54	599.62	86.38
Condition + Aud AC (both)	802.38	808.45	91.27	746.34	752.41	92	590.18	596.26	86.29
Condition + AC_Acc (both)	807.29	813.36	91.28	745.96	752.04	92	593.04	599.11	86.3
Condition + AC_RT (both)	800.25	806.33	91.27	743.59	749.66	91.99	591.24	597.31	86.3
Condition + AC (all)	807.29	813.36	91.28	745.96	752.04	92	593.04	599.11	86.3
Condition + RT (all)	773.44	779.42	91.02	709.4	715.38	90.28	572.6	578.58	85.22
Condition + Vis domains	843.9	850.02	90.39	759.8	765.92	91.85	606.25	612.37	86.25
Condition + Aud domains	780.52	786.52	91.08	713.33	719.32	90.34	570	575.99	85.28
Condition + all domains	764.39	770.35	90.89	705.85	711.8	90.16	566.08	572.04	85.01

Table A.2: Summary of all resulting AIC, BIC, and R-squared for all iterations of potential cognitive covariates and 'Condition'-by-cognitive domain interactions. The highlighted cells indicate the model fit for the selected models reported in Ch. 5

	pKFA			pKAbA			pKAbM		
Model	AIC	BIC	R-squared	AIC	BIC	R-squared	AIC	BIC	R-squared
Condition + Vis RT	851.86	857.96	90.48	767.6	773.7	91.96	617.36	623.46	86.2
Condition + Aud RT	830.01	836.04	90.39	731.02	737.06	90.81	599.91	605.94	85.34
Condition + RT (both)	818.47	824.44	90.17	724.01	729.97	90.76	597.18	603.15	85.27
Condition + Vis AC_ACC	851.84	857.94	90.53	768.77	774.87	91.94	613.78	619.88	86.48
Condition + Vis AC_RT	844.66	850.76	90.65	754.69	760.79	92.68	610.21	616.31	86.67
Condition + Vis AC (both)	842.72	848.75	90.59	755.01	761.04	92.61	613.54	619.58	86.65
Condition + Aud AC_ACC	811.36	817.4	91.17	752.59	758.62	91.86	599.41	605.44	86.29
Condition + Aud AC_RT	809.68	815.72	91.18	745.61	751.64	92.28	589.54	595.58	87.3
Condition + Aud AC (both)	806.1	812.07	90.96	747.86	753.83	92.08	593.24	599.21	86.99
Condition + AC ACC (both)	808.7	814.66	91.15	752.3	758.27	91.78	603.42	609.38	86.22
Condition + AC RT (both)	793.64	766.61	91.53	731.82	737.78	92.77	590.43	596.39	87.17
Condition + AC (all)	786.25	792.08	91.2	733.21	739.04	92.56	596.9	602.72	86.83
Condition + RT (all)	758.87	764.62	91.29	690.45	696.2	91.5	574.79	580.54	86.08
Condition + Vis domains	840.09	846.06	90.53	752.53	758.5	92.63	620.24	626.21	86.33
Condition + Aud domains	782.77	788.6	90.8	710	715.83	90.93	579.56	585.38	85.8
Condition + all domains	751.56	757.15	90.88	692.37	697.96	91.15	578.81	584.4	85.61

Table A.3: Several alternate models determined that reaction time on the visual attentional control test factored in as a significant covariate in pKFA for the methods reported in Ch. 5 (indicated in red). Results in the cells are given as *p*-values from the resulting linear mixed model analyses.

		Covariates - No Interactions							Covariates - Interactions Considered					
Model	Condition	VisRT	AudRT	Vis AC_ACC	Vis AC_RT	Aud AC_ACC	Aud AC_RT	Condition	VisRT	AudRT	Vis AC_ACC	Vis AC_RT	Aud AC_ACC	Aud AC_RT
Condition Only	0.0001							0.0001						
Condition + Vis RT	0.0001	0.462						0.0001	0.465					
Condition + Aud RT	0.0001		0.862					0.0001		0.861				
Condition + RT (both)	0.0001	0.045	0.069					0.0001	0.046	0.069				
Condition + Vis AC_ACC	0.0001			0.96				0.0001			0.96			
Condition + Vis AC_RT	0.0001				0.023			0.0001				0.022		
Condition + Vis AC (both)	0.0001			0.991	0.025			0.0001			0.985	0.024		
Condition + Aud AC_ACC	0.0001					0.151		0.0001					0.067	
Condition + Aud AC_RT	0.0001						0.067	0.0001						0.151
Condition + Aud AC (both)	0.0001					0.055	0.026	0.0001					0.055	0.026
Condition + AC_Acc (both)	0.0001			0.706		0.146		0.0001			0.706		0.145	
Condition + AC_RT (both)	0.0001				0.022		0.932	0.0001				0.021		0.935
Condition + AC (all)	0.0001			0.49	0.011	0.015	0.617	0.0001			0.497	0.011	0.015	0.617
Condition + RT (all)	0.0001	0.488	0.577		0.104		0.913	0.0001	0.494	0.585		0.1		0.92
Condition + Vis domains	0.0001	0.616		0.983	0.032			0.0001	0.619		0.989	0.031		
Condition + Aud domains	0.0001		0.803			0.075	0.036	0.0001		0.801			0.074	0.036
Condition + all domains	0.0001	0.271	0.365	0.532	0.114	0.019	0.5	0.0001	0.276	0.37	0.538	0.11	0.019	0.504