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Anterior cruciate ligament injury risk is modified by the timing of the successful identification of directional cues

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"It was written I should be loyal to the nightmare of my choice."

- Joseph Conrad, Heart of Darkness

I suppose the nightmare of my choice was combining government service with a doctoral career in academia. This dissertation, let alone my entire career, would not have been possible without the trust, support, and patience of my friends, family, colleagues, supervisors, and mentors. But one individual provided me more support, attention, and patience beyond what any reasonable individual would expect. Ashley, you have been and continue to be my rock. I cannot begin to use words to describe how much you supported me. In many ways, this dissertation is as much your success as mine.

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ABSTRACT

Despite our best efforts, anterior cruciate ligament injury rates remain high in many athletic populations. Over the past two decades, investigations have sought to identify the potential role cognition may play in the functional injury mechanism. Across the body of literature, there is a general consensus that rapid, reactive environments found in team sports increase injury risk. But the precise biomechanical change in lower extremity control has been inconsistently identified across multiple investigations. We previously identified that an important, often uncontrolled component of rapid reactive movements is the timing of the directional cue to which the athlete responds. Reductions in time that the athletes have available to react to this directional cue undermines lower extremity control and may increase injury risk. In sport, this may be caused by a deceptive opponent masking their movement direction. We sought to further explore components of perception and action that may alter this available time to react. Across three investigations, we explored the potential effects of performance demands, erroneous movement direction predisposition, and more information-rich, probabilistic directional cues and their impacts on ACL injury risk factors. We identified that contexts that may delay the identification of the correct directional cue are likely to result in a reduction of lower extremity control, which may alter injury risk and decrease performance. We suggest that factors that may alter perception and action time, such as neurocognitive ability and sports expertise, be trained to reduce the risk of injury in reactive environments.

CHAPTER 1. GENERAL INTRODUCTION

The anterior cruciate ligament (ACL) is an oft-injured tissue within the human knee joint; injury often requires surgery and rehabilitation, yet subsequent debilitation is not uncommon. As such, biomechanical investigations have concentrated on this tissue for decades, identifying anatomically-associated injury mechanisms and potential injury prevention strategies to reduce incidence rates. Sadly, these attempts have not been successful; the prevention programs produce ambiguous results and injury rates continue to climb. Researchers have explored potential neuromuscular sources for increased injury risk, utilizing reactive movements to better emulate sport performances. As biomechanical assessments indicate that a multiplanar injury mechanism is likely, investigations have concentrated on movement directional changes that may exacerbate loading in multiple ways. These studies have produced ambiguous results, but investigations and information processing schemas from the cognitive sciences shed some light on the sources for this uncertainty.

Integrating this motor control literature with previous biomechanical investigations, this dissertation describes three novel studies implemented to better explore the potential effects of perception and action on biomechanical variables associated with ACL injury. Based on the foundation of our previous work, we methodologically approached these studies with fastidious temporal control of directional cues within a standardized approach built from the use of custom technologies.

This dissertation is organized accordingly: Chapter 2 provides an overview of the anatomical, biomechanical, and neuromuscular contributions to ACL injury and injury risk, contextualizing more recent investigations to a combined biomechanical and motor control perspective. This evidence was utilized in the development of three novel investigations. Chapter 3 describes an assessment of performance constraints within the context of reactive directional changes often found in sport contexts, identifying whether a functional tradeoff between performance and injury risk exists. Chapter 4 presents an extension of previous work that includes potentially erroneous directional movement predisposition in the directional cues used within this corpus of literature. Chapter 5 expands the potential external validity of this approach, utilizing a pseudo-continuous directional cue that potentially facilitates probabilistic prediction of movement directions. These three investigations progressively increase the potential complexity of the testing protocol utilized in reactive jump landing research that concentrates on ACL injury risk to better capture the role of perception and action. Chapter 6 summarizes the results of these three investigations, suggesting the predominating perceptional factors that impact ACL injury risk in this reactive context.

CHAPTER 2. LITERATURE REVIEW

The anterior cruciate ligament (ACL) of the human knee is a well-recognized musculoskeletal tissue (Clayton & Court-Brown, 2008) in sport and military biomechanical literature (Joseph et al., 2013; Owens, Mountcastle, Dunn, DeBerardino, & Taylor, 2007) that provides functional stability to the knee (Zantop, Petersen, Sekiya, Musahl, & Fu, 2006). Injury rates currently exceed 400,000 per year (Kibler, 2009) and medical treatments of ACL injuries are estimated to cost between three and four billion dollars per year in the United States alone (Brophy, Wright, & Matava, 2009; Gianotti, Marshall, Hume, & Bunt, 2009); surgical intervention is estimated to be less costly than more conservative rehabilitation strategies (Mather et al., 2013). Recovery is often difficult and time-consuming, requiring months to years to return to sport (Roi, Nanni, & Tencone, 2006); the majority of athletes do not regain pre-injury performance levels within twelve months of the injury (Ardern, Webster, Taylor, & Feller, 2011; Bak et al., 1997).

Post-injury, patients generally contend with a difficult recovery (Heijne, Axelsson, Werner, & Biguet, 2008) and fear of reinjury may mitigate adequate return to sport (Wierike, Sluis, Akker-Scheek, Elferink-Gemser, & Visscher, 2013). Post-injury depression is also not uncommon (Carson & Polman, 2008; Mainwaring, Hutchison, Bisschop, Comper, & Richards, 2010). Concerningly, an ACL tear may predispose the patient to subsequent injury in both the previous-injured and contralateral ACL (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012; Wright et al., 2007) independent of the surgical strategy (Spindler et al., 2004). ACL injury is also linked to increased meniscus injury risk, particularly in the medial compartment (Keene, Bickerstaff, Rae, & Paterson, 1993). Most concerningly, ACL and meniscus injuries are strongly associated with knee osteoarthritis later in life, vastly extending the impact of the injury (Lohmander, Englund, Dahl, & Roos, 2007; Simon et al., 2015).

The sex disparity in ACL injury rates also cannot be ignored. While males suffer ACL injury in larger numbers than females (Csintalan, Inacio, & Funahashi, 2008; Gianotti et al., 2009), normalized rates indicate that females are four to seven times more likely than males to experience ACL injury (Agel, Arendt, & Bershadsky, 2005; Hootman, Dick, & Agel, 2007). This is apparent across multiple sports, positions, and levels (Agel et al., 2005; Hootman et al., 2007; Messina, Farney, & DeLee, 1999; Myklebust, Maehlum, Holm, & Bahr, 1998; Powell & Barber-Foss, 2000). Multiple modifiable and nonmodifiable factors may contribute to this disparity (Price, Tuca, Cordasco, & Green, 2017). Yet despite this distinct bias in injury rates, females continue to be underrepresented in injury prevention research and application (Brookshire, 2016; Costello, Bieuzen, & Bleakley, 2014).

Due to these unfortunate realities, ACL injury prevention is of utmost priority and has been the subject of biomechanics research for the past several decades. This has led to a complex literature landscape as researchers have probed possible underlying factors that may contribute to ACL injury. Despite these efforts, rates of ACL injury continue to climb (Agel, Rockwood, & Klossner, 2016; Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017). As the majority of these injuries in multiple sport and military contexts occur without forces applied directly to the knee (Agel et al., 2005; Agel, Palmieri-Smith, Dick, Wojtys, & Marshall, 2007; Boden, Breit, & Sheehan, 2009; Krosshaug et al., 2007; Uhorchak et al., 2003), the majority of previous investigations have concentrated on non-contact ACL injuries to identify loading mechanisms and injury risk factors that may be successfully modifiable (Price et al., 2017).

The most direct assessment of this injury and the ACL's loading mechanisms can be derived from an anatomical analysis of the knee joint. This anatomical understanding serves as a foundation that more nuanced analyses were built upon, probing the potential effects of neuromuscular control on ACL injury risk. The current review will first explore the anatomical and biomechanical factors contributing to ACL injury, before delving into potential neurological and cognitive factors that represent the forefront of research aiming to prevent this catastrophic injury.

Functional anatomy

The human knee joint is actively articulated and stabilized by musculature that inserts onto the anterior and posterior aspects of the proximal tibia and fibula. Few insertions present with an appreciable lateral or medial moment arm, reducing the efficacy of active components' stabilization of frontal plane movements. In contrast, the medial and lateral collateral ligaments are extracapsular passive structures that provide frontal plane stability to contralateral stress (Kakarlapudi & Bickerstaff, 2000). Within the joint capsule, anterior and posterior cruciate ligaments are oriented within the intercondylar notch to primarily resist respective anterior and posterior translation of the tibia from the femur (Vahey & Draganich, 1991). The shape and width of this notch partially defines the load proportion transferred to the associated ligaments, with females placed at a disadvantage (Lund-Hanssen et al., 1994; Tillman et al., 2002). Other passive structures within the knee, including an anterolateral ligament only recently confirmed (Claes et al., 2013), also provide stability to the joint. But these tissues are not as commonly-injured in acute sports trauma, particularly when compared to the ACL (Gianotti et al., 2009; Majewski, Susanne, & Klaus, 2006).

As previously mentioned, the ACL is the primary passive structure that resists anterior translation of the tibia from the femur. The ACL alone is responsible for 85% of the force restraining this translation when the knee is flexed (Ellison & Berg, 1985). The precise origin and insertion of the ACL do not isolate its function to solely resisting anterior translation, however. The ligament is divided into anteromedial and posterolateral bundles. As Petersen and Zantop (2007) present, the anteromedial bundle originates in the anterior and lateral aspect of the femoral origin deep within the femoral intercondylar notch. It inserts as part of the anterior aspect of the tibial insertion and is the primary tibial anterior translation resistor as the knee flexes. In contrast, the posterolateral bundle originates more posteriorly within the intercondylar notch and inserts posteriorly and medially onto the tibia; this provides stability to the joint when it is near extension (Petersen & Zantop, 2007).

The differences in insertion location in the frontal plane of each bundle predispose the ACL to loading with both frontal and transverse plane rotations. Abduction of the tibia from the femur, commonly referred to as knee valgus, is anatomically resisted by both the medial collateral ligament (Grood, Noyes, Butler, & Suntay, 1981) and the posterolateral bundle of the ACL (Hollis, Takai, Adams, Horibe, & Woo, 1991). Cadaver models demonstrated an amplification of ACL force in both bundles when valgus torques were combined with other planar loading (Berns, Hull, & Patterson, 1992; Markolf, Gorek, Kabo, & Shapiro, 1990). The splayed insertion of the ACL bundles also facilitates resistance to internal and external tibial rotation. Internal rotation has been demonstrated to load the ACL (Hirokawa, Solomonow, Lu, Lou, & D'Ambrosia, 1992; Kennedy, Hawkins, & Willis, 1977; Markolf et al., 1990) to a larger degree than external rotation, however (Markolf et al., 1995; Miyasaka, Matsumoto, Suda, Otani, & Toyama, 2002). A combination of anterior tibial translation at minimal knee flexion, valgus rotation, and interior tibial rotation is therefore particularly problematic for the posterolateral bundle. Increased knee flexion transitions much of this load to the anteromedial bundle (Zhang, Jiang, Wu, & Woo, 2008), moderately relieving the former bundle.

Biomechanical injury mechanism

Due to the multiplanar functionality of the ACL reviewed above, and exacerbated during dynamic movement, some ambiguity exists in determining the primary injury mechanism during a non-contact injury event. This ambiguity itself has been referenced in multiple reviews (Dai, Herman, Liu, Garrett, & Yu, 2012a; Quatman & Hewett, 2009; Quatman, Quatman-Yates, & Hewett, 2010). The modern body of biomechanical literature generally investigates ACL injury mechanisms from uniplanar and multiplanar perspectives, as reviewed below.

A plethora of literature attributes ACL injury to solely a sagittal plane injury mechanism. An explicit case of ACL injury with only sagittal plane action was recorded in three dimensional kinematics (Dai, Mao, Garrett, & Yu, 2015); researchers attributed the injury to a shallow knee flexion angle and stiff landing, concluding that valgus collapse and tibial rotation likely occurred after the injury (Yu & Garrett, 2007). *In vitro* analyses demonstrate that quadriceps femoris musculature activation also contributes to the anterior shear of the tibia (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004), which can be expected to counteract the occurrence of large external knee flexion moments in stiff landings that include a large posterior ground reaction force early in the landing phase (Sell et al., 2007). Multiple investigations have also identified bone bruising patterns after ACL injury that suggest shallow knee flexion without other unusual planar activity (Owusu-Akyaw et al., 2018; Viskontas et al., 2008), but this perspective has been criticized (Hewett & Schilaty, 2018) and other bone bruise analyses suggest a multiplanar injury (Kim et al., 2015).

Multiple analyses of sport video of ACL injuries instead support the premise of a multiplanar injury mechanism, identifying larger peak knee valgus angles than uninjured controls (Boden, Torg, Knowles, & Hewett, 2009; Hewett, Torg, & Boden, 2009; Koga et al., 2010; Krosshaug et al., 2007). This was specifically apparent in females, and the concept of sex-specific planar injury mechanisms was proposed (Quatman & Hewett, 2009). These kinematic investigations generally identified non-contact injuries occurring with shallow knee flexion angles and increased knee valgus angles near the time of injury. It should be noted that the accuracy of these two-dimensional kinematic analyses have been criticized previously due to potential three-dimensional extrapolation and temporal estimation errors (Dai, Mao, et al., 2015; Krosshaug & Bahr, 2005). Nonetheless, these multiplanar results are also reflected in large-sample medical interviews (Kobayashi et al., 2010) and the aforementioned functional anatomy. *In vitro* and simulation analyses have confirmed external knee valgus moments increase ACL loading (Kimura et al., 2012; Shin, Chaudhari, & Andriacchi, 2009; Withrow, Huston, Wojtys, & Ashton-Miller, 2006).

Independent of whether a sagittal, frontal, or multiplanar mechanism dominates ACL loading, evidence generally suggests that the injury itself occurs very rapidly. Estimations often time the injury within the first 50 ms of forceful ground contact (Dai, Mao, et al., 2015; Koga et al., 2010; Krosshaug et al., 2007). A sharp rise in peak vertical and posterior ground reaction forces generally occurs within this time window (Besier, Lloyd, Cochrane, & Ackland, 2001), and is specifically associated with anterior tibial translation that may load the ACL (Sell et al., 2007; Yu, Lin, & Garrett, 2006).

Despite the active exploration of the ACL injury mechanism, biomechanical literature is relatively spare as to what modifiable mechanisms (Price et al., 2017) may cause these kinematic and kinetic combinations to occur. An interesting proposal by Hashemi et al. (2011) suggests that the combination of a lack of knee flexion during a stiff landing with latent activation of the quadriceps and hamstrings muscle groups would cause an unusual combination of knee flexion and hip extension, leading to excess ACL loading. Furthermore, the delay in quadriceps, hamstrings, and hip abductor co-contraction in the presence of a large knee valgus moment allows for dynamic valgus collapse (Hewett et al., 2009; Ireland, 1999), reducing the dynamic coherence of the tibial plateau and femoral condyle and mitigating anterior tibial translation restriction (Hashemi et al., 2011).

The frontal plane action of this proposed mechanism is dependent on external knee valgus moments during lower extremity loading. Hashemi et al. (2011) suggest this must originate from lateral placement of the foot in relation to the center of mass (Hewett et al., 2009), but these external moments can also be due to trunk inclination lateral to the knee that can be found in rapid directional changes (Hewett & Myer, 2011; Hewett et al., 2009; Jamison, Pan, & Chaudhari, 2012). Twenty years ago, Patla, Adkin, and Ballard (1999) suggested that this trunk inclination may be a strategy human use to reorient movement directions without adequate time to prepare for that redirection. While this article did not appear to spur investigations on this subject, the concept that neuromuscular and cognitive considerations may play a role in ACL injury still became popular.

Neuromuscular contributions

Over the course of the past twenty years, a subset of ACL injury research has attempted to increase the ecological validity of the investigational methodology in a singular modality: As many team sports that commonly experience ACL injuries include elements of dynamic team interaction and unpredictability, researchers have included a reactive, decision making element in their movement tasks. Similar to the seminal work of Besier, Lloyd, Ackland, and Cochrane (2001), the majority of these investigations relied on a two-phase movement, whereas the direction of the latter phase was indicated to the participant only during the former phase. Pragmatically, this was performed with switches or timing gates triggering simple visual cues; some research utilized video of "opponents" on a monitor to elicit a directional change. This was justified to eliminate potential preplanning capabilities of the participant; this manipulation was found to increase external frontal and transverse plane moments about the knee in the first work on the subject (Besier, Lloyd, Ackland, & Cochrane, 2001). The authors concluded the importance of training athletes in unanticipated directional changes that required decision making to potentially mitigate this increased injury risk.

These results were not unilaterally confirmed in other literature, however. As Almonroeder, Garcia, and Kurt (2015) summarize in their cross-sectional systematic review, the thirteen investigations exploring the effects of decision making on knee biomechanics generally presented ambiguous or contrasting results. For example, external knee flexion moments were significantly increased in unanticipated conditions in only two (Kim et al., 2014; McLean & Samorezov, 2009) of the thirteen investigations. Six identified the unanticipated condition significantly increased external knee valgus moments (Besier, Lloyd, Ackland, et al., 2001; Khalid, Harris, Michael, Joseph, & Qu, 2015; Kim et al., 2014; Lee, Lloyd, Lay, Bourke, & Alderson, 2013; McLean, Borotikar, & Lucey, 2010; Mornieux, Gehring, Fürst, & Gollhofer, 2014), yet three did not (Brown, Palmieri-Smith, & McLean, 2009; Cortes, Blount, Ringleb, & Onate, 2011; Kipp, Brown, McLean, & Palmieri-Smith, 2013). The reviewers describe other, nuanced differences in results between these independent investigations, ultimately concluding that the body of literature suggests that a lack of anticipation of changes in movement direction increases ACL injury risk (Almonroeder, Garcia, & Kurt, 2015).

Almonroeder, Garcia, and Kurt (2015) did explore some possible sources for the ambiguous and contrasting results across the reviewed investigations. First, these investigations utilized different samples, some relying on males (Besier, Lloyd, Ackland, et al., 2001; Kim et al., 2014; Lee et al., 2013; Mornieux et al., 2014), others females (Borotikar, Newcomer, Koppes, & McLean, 2008; Cortes et al., 2011; Kipp et al., 2013; McLean et al., 2010; McLean & Samorezov, 2009; Park, Lee, Ryue, Sohn, & Lee, 2011; Weinhandl et al., 2013), and some a cohort of both sexes (Brown et al., 2009; Khalid et al., 2015). It should be noted that the two investigations that compared the effects of anticipation between the sexes did not identify any significant main effects for external knee joint moments.

These investigations also utilized different levels of experience, ranging from recreational (Besier, Lloyd, Ackland, et al., 2001; Brown et al., 2009; Weinhandl et al., 2013) to National Collegiate Athletic Association (NCAA) athletes (Borotikar et al., 2008; Cortes et al., 2011; Kipp et al., 2013; McLean et al., 2010; McLean & Samorezov, 2009). Across the spectrum of expertise, some investigations controlled for sport specialization (basketball, soccer, and/or volleyball, with soccer most common). No investigation explored the effects of sport specialization on anticipation effects, but Kipp et al. (2013) did compare female recreational athletes to a cross-section of female NCAA athletes in anticipated and unanticipated land-cut movement. Results of basic biomechanical variables did not indicate significant interactions between experience level and decision making. Through functional data analysis, the authors identified that unanticipated conditions did amplify peak knee valgus moments compared to anticipated conditions for only recreational athletes (Kipp et al., 2013).

In contrast to a smaller previous review (Brown, Brughelli, & Hume, 2014), studies utilizing both run-cut and land-cut maneuvers were included in the review by Almonroeder, Garcia, and Kurt (2015). The effects of decision making between these two movements has not been explored. Investigations also utilized different visual stimuli, with the majority relying on simplistic arrows and lights (Besier, Lloyd, Ackland, et al., 2001; Borotikar et al., 2008; McLean et al., 2010; McLean & Samorezov, 2009; Weinhandl et al., 2013) and two using “opponent” video to indicate requisite movement direction (Cortes et al., 2011; Lee et al., 2013). Lee et al. (2013) compared simplistic illuminated arrow stimuli to video, identifying significant differences in lower extremity kinetics and kinetics between the two.

In parallel to the movement performed and stimuli presented, researchers also utilized different time delays between the presentation of the directional stimuli and impact with the ground. Some investigations did not specify a delay (Kim et al., 2014; Park et al., 2011), others adjusted the delay per participant (Besier, Lloyd, Ackland, et al., 2001; Khalid et al., 2015), and a larger selection of literature specified a temporal delay ranging from 350 to 850 milliseconds (Borotikar et al., 2008; Brown et al., 2009; Cortes et al., 2011; Kipp et al., 2013; Lee et al., 2013; McLean et al., 2010; McLean & Samorezov, 2009; Mornieux et al., 2014; Weinhandl et al., 2013). Notably, no study that specified a precise time delay provided methodological details, validations, or indications of variability in these time points. Brown et al. (2009) manipulated the timing of the stimuli in a land-cut task between 600 to 400 ms but did not identify significant changes in lower extremity biomechanics as the timing of the unanticipated stimuli were manipulated. They suggest a threshold likely exists outside of this range.

Almonroeder, Garcia, and Kurt (2015) recognized this inconsistency of stimuli timing in the knee biomechanics literature that included decision making and posited that unanticipated conditions that provide more available time than 600-800 ms before landing/cutting may not affect knee loading. It is possible that temporal delays longer than this threshold may allow the athlete to completely implement a new motor plan in response to the directional stimuli, potentially integrating injury prevention strategies (Mornieux et al., 2014). Echoing Brown et al. (2009), Almonroeder, Garcia, and Kurt (2015) suggest this threshold is likely dependent on the task complexity and the experience of the athlete but provide no further guidance on the source of this phenomena.

Reactive latency and information processing

Some evidence does exist in the biomechanical literature to suggest this requisite timing threshold is due to neuromuscular considerations. McLean et al. (2010) explored the electromyographically-indicated pre-motor reaction time of the lower extremity musculature in a simple choice reaction task. Participants were required to jump to the right or left based on simple, unanticipated visual stimuli. Lower extremity musculature activations were latent 333-551 ms from the presentation of the stimuli, notably slower than in simple reaction time sport testing (Mero & Komi, 1990). The additional pre-motor delay in the lower extremity musculature appears to be associated with the complexity of the task (Wheaton et al., 2007). This concept is supported by classic psychological literature: More than 60 years ago, researchers Hick and Hyman identified that reaction time was positively logarithmically related to the number of potential choices (Hick, 1952; Hyman, 1953). More recently, this relationship has been neurologically confirmed (Wu et al., 2018).

The "Hick-Hyman Law," as it is commonly referred to, is often cited in psychological and motor control literature but is rarely referenced in biomechanical investigations. One of my own previous investigations utilized the law to guide the exploration of this potential temporal threshold (Stephenson et al., 2018). Manipulating the time period between the presentation of the visual stimuli and landing from 400 to zero ms, we identified and subsequently functionally confirmed a threshold of 300 ms (Stephenson et al., 2018; Stephenson, Zhu, & Dai, 2016). Unlike the aforementioned pre-motor thresholds identified by McLean et al. (2010), our threshold was derived from kinematic and kinetic variables: Directionally-related biomechanical measures converged to generic values not specialized to the movement direction indicated to the participant. This evidence supported the premise that athletes did not have enough time to completely implement a motor plan in response to the visual stimuli (Almonroeder et al., 2015; Mornieux et al., 2014), leading to potential injury (McLean et al., 2010).

This research reinforced the importance of information processing in ACL injury risk. Represented in multiple forms, information processing is generally modeled to consist of three pseudo-linear steps: Stimulus identification, response selection, and response programming (Wickens, 1992). Our 2018 work demonstrated the importance of the response selection phase, but any phase of informational processing could potentially delay the response and alter acute injury risk (McLean et al., 2010; Miller & Clapp, 2011; Stephenson et al., 2018). Given visual stimuli, such as an incoming opponent on a sport field, the athlete must first identify and interpret pertinent directional cues (Abernethy, 1990; Desimone, 1998) before utilizing these cues to select an appropriate movement in response. This process is mediated by experience, whereas more experienced athletes more appropriately and selectively observe cues (Fujii, Shinya, Yamashita, Kouzaki, & Oda, 2014; Savelsbergh, Williams, Van der Kamp, & Ward, 2002) and perform this perception-action linkage more quickly (Miller & Clapp, 2011). This may justify the experience offset Kipp et al. (2013) identified in their unanticipated land-cut investigation.

The information processing model also demonstrates that attention modulates the performance of each of the three phases (Wickens, 1992). As attention is generally considered a limited resource (Tsotsos, 1997), increasing attentional demands risk mitigating information processing performance. This has been demonstrated in contexts pertinent to ACL injury: Both arbitrary (Dai et al., 2018; Shinya, Wada, Yamada, Ichihashi, & Oda, 2011) and sport-specific (Almonroeder et al., 2017) dual task contexts alter lower extremity kinematics and kinetics in ways that may increase ACL injury risk. Situations where an athlete's attention has been divided has often been identified during ACL injury in sport settings (Boden, Torg, et al., 2009; Stuelcken, Mellifont, Gorman, & Sayers, 2016). It should be noted, however, that this effect may not be amplified in athletes post-ACL injury (Mohammadi-Rad et al., 2016; Negahban et al., 2009).

Interestingly, information processing and attention literature also justifies the increase in ACL injury risk in reactive situations when athletes are physically fatigued. The effects of fatigue on ACL injury risk during acute decision-making testing paradigms has been the subject of multiple investigations, but these investigations have indicated ambiguous results (Borotikar et al., 2008; Collins, Almonroeder, Ebersole, & O'Connor, 2016; Khalid et al., 2015; McLean & Samorezov, 2009; Mejane, Faubert, Romeas, & Labbe, 2018; Santamaria & Webster, 2010). It is possible that this ambiguity may be due to different levels of fatigue used by researchers; it appears that only the more severe protocols with minimal rest results in increased ACL injury risk (Almonroeder, Tighe, & Lanning, 2018). In fact, the positive effects of exercise on reaction time and other cognitive performance until the onset of fatigue is well-documented (Brisswalter, Collardeau, & René, 2002; Féry, Ferry, Hofe, & Rieu, 1997; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996). But the onset of laboratory-confirmed physical fatigue is associated with specific decrements in response time, perceptual skills (Moore, Romine, O'connor, & Tomporowski, 2012), and attentional resources (Stephenson, Ostrander, Norasi, & Dorneich, Accepted). If these negative effects of fatigue were combined with other sources of increased attentional load, ACL injury risk may increase (Mejane et al., 2018).

The perspective provided by the information processing literature provides some explanation to the underlying factors that ACL injury researchers have superficially revealed. In summary, these neurocognitive investigations provide explanatory power to the observed slower reaction time (Swanik, Covassin, Stearne, & Schatz, 2007) and potential neurological differences (Diekfuss et al., 2019; Herman & Barth, 2016) in ACL-deficient athletes. Furthermore, this perspective further justifies the injury risk disparity between the sexes, as females may have a neurocognitive disadvantage that amplifies injury risk (Grooms & Onate, 2016) and is aggravated by hormonal changes (Kumar, Mufti, & Kisan, 2013). Overall, these bodies of research reinforce the need to consider the perception-action coupling and reaction time in ACL injury research, and validate past researchers' attempts to increase the ecological validity of investigations through careful methodological design.

Ineffective prevention

ACL injury prevention strategies have been classically structured in a simplistic manner: By identifying predominant injury mechanisms in non-contact scenarios, athletes can be trained in prevention programs to mitigate these injury mechanisms. This training generally takes place around practice sessions and is expected to adequately reduce injury risk in performance settings. The neuromuscular and neurocognitive investigations reviewed earlier led to general suggestions to include neurocognitive training as part of these prevention programs (Dai et al., 2018; Grooms & Onate, 2016; Sugimoto et al., 2015; Wilkerson, Simpson, & Clark, 2016). While analyses indicate that these prevention programs are effective in altering kinematics and kinetics associated with ACL injury (Dai, Herman, Liu, Garrett, & Yu, 2012b; Thompson et al., 2017), effects on actual ACL injury rates are ambiguous (Barber-Westin & Noyes, 2018; Emery, Roy, Whittaker, Nettel-Aguirre, & Mechelen, 2015; Stevenson, Beattie, Schwartz, & Busconi, 2015).

There are a myriad of potential reasons these prevention programs have been ineffective at reducing ACL injury rates, but the question of ecological validity of foundational research that informs the design of these programs should not be forgotten. It is possible that athletes may adequately model safe kinematic and kinetic patterns during testing, but are unable to implement these motor programs if they have been inadequately neurocognitively trained (Grooms & Onate, 2016; Miller & Clapp, 2011). Care should be taken to properly capture an athlete's on-field experience for injury prevention. While previous endeavors to encapsulate reactive environments were steps in the right direction, they may have still oversimplified environmental contexts (Almonroeder et al., 2015; Grooms & Onate, 2016; Miller & Clapp, 2011). As such, it is necessary to further explore factors that may affect an athlete's perception and action performance to identify if other pertinent neurocognitive training should be included in injury prevention programs.

Current research

Three key aspects in sport performance have yet to be captured in the methodological design of ACL injury research: **(1)** The intensity of activity can be modulated relative to task complexity and injury risk on the field, although this may sacrifice sport performance. **(2)** Opponent attempts to deceive an athlete may predispose them to incorrect movement directions until later in the movement, amplifying injury risk. **(3)** Unlike previous investigations that utilize discrete directional stimuli, athletes continuously evaluate changing stimuli to create and revise motor plans, potentially confounding reaction time effects. This dissertation seeks to explore each of these topics, identifying the potential effects on lab-based estimations of ACL injury risk. The background and specific aims of each are reviewed below.

ACL injury prevention research has demonstrated that athletes are capable of modifying landing patterns to reduce injury risk, often only with acute feedback (Dai, Garrett, et al., 2015; Gokeler, Seil, Kerkhoffs, & Verhagen, 2018). While this effect is potentially beneficial, performance measures also suffer: Movements become slower and athletes' reactive strength indices (a pragmatic measure of plyometric performance) are reduced (Dai, Garrett, et al., 2015; Stephenson et al., 2018). Participants may be willing to sacrifice performance in a lab-based setting that inadequately controls performance, but it may be unrealistic to assume the same in competitive settings. Relative increases in plyometric performance may increase ACL injury risk (Dai et al., 2019), effectively rendering lab-based estimates conservative.

As such, the first investigation sought to identify the potential interaction of performance and decision making. Participants performed preplanned and reactive jump landings, and subsequent reactive jump landings with plyometric movement speeds restricted to the faster performances previously-identified in the preplanned conditions (Stephenson et al., 2018). Based on the results of previous investigations (Dai et al., 2019; Dai, Garrett, et al., 2015), it was hypothesized that restricting plyometric performance to faster levels would amplify kinematics and kinetics associated with ACL injury risk in the more challenging reactive conditions. A pilot investigation indicated this may not be the case (Stephenson & Gillette, 2017), but research utilizing a larger sample is presented in Chapter 3.

In sport settings, athletes also attempt to reduce opponent performance through deception of intended movement direction. It appears that experienced athletes accomplish this goal of misdirection by exaggerating non-pertinent peripheral segment movement to disguise actual center of mass trajectory and compromise opponent spatial cueing (Brault, Bideau, Kulpa, & Craig, 2012; Wright & Jackson, 2014). No previous investigations utilizing simplistic visual stimuli have explored the effects of this deception predisposing athletes to an incorrect movement direction; passive elements of deception may have been included in the two previous video stimuli investigations (Cortes et al., 2011; Lee et al., 2013), but this effect was not explicitly identified.

The second investigation of this dissertation sought to explore a parsimonious implementation of deception via erroneous movement directional predisposition to identify whether it impacted ACL injury risk. Participants performed a standardized jump-landing maneuver in preplanned and reactive conditions, with the potential that the initially-indicated direction was incorrect. It was hypothesized this incorrect predisposition would require late significant revisions to participants' motor programs, compromising landing biomechanics when the correct direction was indicated late in the movement. Further exploration of preliminary evidence (Stephenson & Gillette, 2018) indicates if this "re-direction" occurs too late in the movement, participants may be incapable of adequately responding to the correct movement direction.

Finally, a glaring inconsistency between previous neuromuscular and neurocognitive ACL research and sport performance exists in the presentation of the directional stimuli. The vast majority of previous work presented a single, instantaneous change in visual stimuli to indicate the movement direction (Almonroeder et al., 2015); this change was generally instantaneous and absolute, implying a single information processing iteration with a Boolean outcome. Yet in sport settings, athletes must continuously evaluate their environment, reassessing and updating their motor plans (Miller & Clapp, 2011); some evidence indicates eliminating this continuous process may place athletes at a disadvantage (Smeeton & Williams, 2012; Williams, Davids, Burwitz, & Williams, 1994), and therefore overestimate injury risk (Lee et al., 2013). While the few video stimuli investigations did provide this continuous feedback, researchers did not distinguish movement pattern indicators from the video or control for potential reaction time. As reaction time has been demonstrated as a key factor in changes in ACL injury risk factors in reactive performances, this lack of control may significantly undermine the accuracy of the previous investigations' results.

The third and final investigation therefore sought to implement a pseudo-continuous visual directional cue that allows participant anticipation in a controlled and quantifiable manner. By utilizing an array of serial visual indicators, participants may be able to extrapolate a directional "vector" to predict the requisite movement direction. It was expected that confirmatory and high probability indications of the terminal movement direction that occur before the perceptual temporal threshold (Hick, 1952; Stephenson et al., 2016) would result in performance similar to early-indication reactive conditions. In contrast, ambiguous or late terminal direction indications would force participants to rely on nonspecialized movement patterns that mitigate performance (Stephenson et al., 2018) and may increase risk of ACL injury.

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CHAPTER 3. PERFORMANCE CONSTRAINTS DO NOT APPRECIABLY ALTER REACTIVE LOWER EXTREMITY LANDING BIOMECHANICS

Abstract: Anterior cruciate ligament injury rates have maintained at a high level. Previous investigations have indicated that there appears to be a tradeoff between sports performance and injury risk. Athletes may choose to prioritize the former over the latter in sport contexts, but this is unlikely to occur in lab-based testing. This investigation compared constrained and unconstrained jump landing performance in preplanned and reactive jump landings to explore this potential effect. Of the ACL injury risk factors assessed, only knee flexion angles in jumps lateral to the dominant leg significantly differed between conditions: Flexion decreased an average of 5° from early to late reactive conditions independent of performance constraints. Participants were also unable to reduce stance time, an analog to movement performance, completely to the target time in conditions with little available time to react to directional cues. In parallel to the increased stance time, participants also decreased the initial velocity for a subsequent jump, suggesting a relationship between performance variables. These results suggest no increased injury risk in performance constrained sport contexts, but further investigation is suggested to explore these potential effects in male and female athletes separately.

Introduction

Injury risk to the anterior cruciate ligament (ACL) has continued to present challenges to athletic populations for decades (Agel, Rockwood, & Klossner, 2016; Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017). The financial burden of reconstructive surgery and rehabilitation is extreme (Brophy, Wright, & Matava, 2009; Gianotti, Marshall, Hume, & Bunt, 2009), and the risk of subsequent re-injury and further knee pathologies create a grim outlook for these unfortunate athletes (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012; Simon et al., 2015). As such, injury prevention strategies targeting modifiable risk factors in non-contact injury events are quite well justified (Price, Tuca, Cordasco, & Green, 2017). Many previous investigations have explored potential biomechanical ACL injury mechanisms (Dai, Herman, Liu, Garrett, & Yu, 2012; Quatman, Quatman-Yates, & Hewett, 2010), although some ambiguity does exist on the primary contributor towards the injury event itself (Dai et al., 2012; Quatman et al., 2010).

Across the corpus of ACL injury mechanism literature, past investigations have identified anterior proximal tibial shear force as an important ACL loading mechanism (Lin et al., 2009; Markolf et al., 1995; Sell et al., 2007; Yu, Lin, & Garrett, 2006), linked to small knee flexion angles upon landing (Hashemi et al., 2011; Kim et al., 2015; Owusu-Akyaw et al., 2018) and large vertical and posterior ground reaction forces (Sell et al., 2007; Yu et al., 2006). This mechanism may be exacerbated by large quadriceps activation in response to external knee flexion moments during a stiff landing (DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004; Hashemi et al., 2011). Injury appears to occur within the first 50 ms of landing (Dai, Mao, Garrett, & Yu, 2015; Koga et al., 2010), and often occurs with valgus collapse and some degree of tibial rotation (Boden, Torg, Knowles, & Hewett, 2009; Koga et al., 2010; Krosshaug et al., 2007). There is some argument to whether the injury mechanism is sex-dependent (Quatman & Hewett, 2009).

Much of this injury mechanism evidence has been observed in sport settings (Boden et al., 2009; Hewett, Torg, & Boden, 2009; Koga et al., 2010; Krosshaug et al., 2007), often in combination with rapid, unforeseen directional changes in response to opponents and evolving game dynamics (Almonroeder, Garcia, & Kurt, 2015; Boden, Dean, Feagin, & Garrett, 2000; Sasaki, Koga, Krosshaug, Kaneko, & Fukubayashi, 2018). This reactive context has been further explored by previous investigations, generally concluding that reactive directional changes may increase ACL injury risk compared to pre-planned directional changes (Almonroeder et al., 2015). Some ambiguity does exist within this literature as well but may be explained by varying available choice reaction time in the methodological implementation of the movement (Stephenson et al., 2018; Stephenson, Zhu, & Dai, 2016).

Within our own investigation on this topic of reactive directional changes, we identified that jump landing performance decreased in parallel to a potential increase in ACL injury risk (Stephenson et al., 2018, 2016). Specifically, results indicated a decrease in jump distance and increase in movement time, which could hinder sports performance. Previous investigations suggest that there may be a functional trade-off between attempts of athletes to reduce this injury risk and their performance in jump landings (Dai et al., 2019; Dai, Garrett, et al., 2015) by modulating joint stiffness (Butler, Crowell III, & Davis, 2003). If this is the case, it may be realistic to assume some athletes may acutely prioritize performance over reduced injury risk during a play in competitive sport (McIntosh, 2005). Functionally, this may place some control of injury risk within the grasp of the athletes. Yet as the competitiveness of sport is contextualized to the social environment of the performance, athletes may unfortunately de-prioritize injury prevention for the sake of the game (Dai et al., 2019; McIntosh, 2005; Wiese-Bjornstal, 2010). This may contribute to the sustained high injury rates previously identified.

Concerningly for modern biomechanical injury risk research, this effect may also undermine the accuracy of investigational injury risk estimations. As lab-based procedures may not provide the same social context that demands competitively high performance (Wiese-Bjornstal, 2010), research participants may reprioritize their performance to complete safer movements (Dai, Garrett, et al., 2015). Some previous investigations attempted to standardize or control for performance (Dai et al., 2019; Stephenson et al., 2018), but the validity or success of these attempts were rarely reported. In fact, performance measures are generally not reported in parallel to classic measures in most ACL injury studies.

If participants are indeed making these prioritization changes, biomechanical investigations may be underestimating ACL injury risk. Potentially more problematically, participants may modulate this risk in conditions designed specifically to exacerbate injury risk, effectively leading to underestimations or nonsignificant changes that may otherwise exist in competitive sport settings. For example, if performance were maintained at the same level in challenging reactive jump landings as found in preplanned conditions in our previous investigation (Stephenson et al., 2018), we estimate that the reductions in available time to react to a directional stimulus would have more uniformly increased injury risk.

As such, the current investigation was implemented to determine if ACL injury risk increases in reactive jump landings when performance is maintained at higher levels found in less challenging, preplanned jump landing tasks. This was methodologically implemented by estimating stance time on the ground in non-reactive jump landing tasks that demanded participants move as quickly as possible. Participants then performed in more demanding, reactive jump landings that were previously identified to slow movement speeds (Stephenson et al., 2018), but they were required to move as quickly as the previous condition. We hypothesized that this would result in an increase in ACL injury risk-related factors, such as magnified external knee flexion and valgus moments, potentially caused by a stiffer landing (Butler et al., 2003; Dai et al., 2019; Dai, Garrett, et al., 2015).

Methodology

This study was implemented as an acute, repeated-measures investigation to determine the effects of performance constraints on ACL injury risk factors and jump landing performance. In order to increase comparative capability, the methodological design was consistent with our previous investigation and includes multiple overlapping conditions for validation. All data collections were performed in the Iowa State University, Department of Kinesiology Biomechanics Lab. The Institutional Review Board of Iowa State University approved the use of human participants in this study (see the Appendix).

Participants

The moderate effect sizes calculated from previous investigations (Dai et al., 2019; Stephenson et al., 2018) suggested a requisite sample size of 24 to detect significant differences in frontal and sagittal plane knee moments with a Type I error rate of no more than 5% and Type II error rate of no more than 20%. As such, 25 participants were recruited from the university student population (15 female and 10 male; mean ± standard deviation: 21.5 ± 2.1 years; 72.9 ± 14.5 kg; 1.69 ± 0.09 m). Participants were required to be without current or past significant lower extremity musculoskeletal injury or concussion. They were required to consistently perform at least 150 minutes of moderate intensity, or 75 minutes of high intensity, aerobic activity per week. Volunteers provided written informed consent to participate and were tested individually.

Protocol

After providing informed consent and completing a health and injury questionnaire, participants completed a standardized dynamic warmup consisting of a 5-minute light jog on the treadmill and dynamic stretches targeting the range of motion and activation of the hip and knee flexors, extensors, and abductors (Stephenson et al., 2018). Participants then practiced and performed the following protocol.

The fundamental movement at the core of this protocol was based on a standardized jump landing protocol. Participants stood on a 30 cm tall block, with the anterior edge of the block placed 50% of the participant's height away from the posterior edge of the landing area on the ground. This landing area was instrumented with two force platforms (Advanced Mechanical Technology, Inc. Watertown, MA, USA). Participants jumped from this block, landing bilaterally in the landing area with a foot on each force platform. As rapidly as possible, participants then fluidly jumped laterally or medially to the dominant limb at a 60° angle from anterior. Participants were encouraged to jump as far as possible on the latter jump, but to primarily prioritize speed by minimizing the stance time on the ground between jumps. Participants were provided a minimum of 30 seconds of rest between these movement trials to mitigate the risk of fatigue (Oliveira et al., 2019).

The direction of the latter jump was indicated to the participant by one of two light-emitting diodes (LEDs) mounted at approximately eye-height in front of the performance area; the illumination of the right LED indicated a jump to the right, and the illumination of the left LED indicated a jump to the left. The directional LED was illuminated in one of three timing conditions (Stephenson et al., 2018): **Preplanned**, where the LED was illuminated well before the participant was prompted to jump; **early reactive**, where the LED was illuminated the instant the participant jumped off of the 30 cm tall block; and **late reactive**, where the LED was illuminated the instant the participant landed on the ground between jumps.

The 30 cm tall block participants initially stood on was also instrumented with a force platform (Advanced Mechanical Technology, Inc. Watertown, MA, USA). The analog signal of the vertical ground reaction force from all three force platforms was routed to an Arduino Uno Rev3 microcontroller (Smart Projects, Strambino, Ivrea, Italy). This microcontroller monitored these forces to identify the discrete timing of takeoff and landing for both jumps in the protocol by detecting the instant the vertical ground reaction force was below or above 18 N. The system was preliminarily validated to demonstrate temporal accuracy within one millisecond. The takeoff and landing events were then used by the microcontroller to illuminate the LED dependent on the condition, and to calculate both the flight time during the first jump and stance time on the ground between jumps. Preliminary testing indicated the LED was fully illuminated within 2 ms of event detection.

After practice, participants first performed three trials in each timing condition for each jump direction (for a total of 18 recorded trials). The order of tested conditions was double-blind randomized by the microcontroller, using a Durstenfeld shuffle technique (Durstenfeld, 1964). Trials with erroneous performance were discarded, and that trial's condition was randomized into the remaining trials. After the 18 successful recorded trials, participants performed another three trials in each jump direction for both the early and late reactive timing conditions (for a total of 12 additional trials) to serve as performance **constrained conditions**. These later trial performances were restricted such that the stance time between trials was required to be within 15% of the mean stance time from the previously performed preplanned trials. After each performance the microcontroller indicated whether the performance was "too slow," "acceptable," or "too fast" and the participant was asked to perform that condition and direction again (randomly in the remaining future performances) if it was not within target margins. If the participant was entirely unable to perform within the target margin, the fastest three trials of the maximum nine recorded for that condition were later analyzed.

Three-dimensional kinematic data of 21 spherical retroreflective markers placed on bony landmarks and mid-segment locations on the shoulders, pelvis, and dominant thigh, shank, and foot were recorded at 160 Hz by 8 infrared cameras (Vicon Motion Systems Ltd, Oxford, UK) via the Vicon Nexus 1.8.5 software; three-dimensional ground reaction force data from the landing force platforms were synchronously recorded via Nexus as well. Leg dominance was self-indicated by the participant as the leg they would choose to kick a ball with (Dos'Santos, Bishop, Thomas, Comfort, & Jones, 2019).

Analysis

Similar to previous research, kinematic and kinetic data were initially filtered with a 4th order, zero-phase Butterworth filter with low-pass cutoffs at 15 Hz and 200 Hz respectively (Yu, Gabriel, Noble, & An, 1999). Cardan joint angles were calculated following a sagittal/frontal/transverse plane rotation order (Grood & Suntay, 1983). Joint angles identified from a static anatomical position were used to define neutral alignment for each participant. Kinematic and kinetic data were then utilized in a bottom-up inverse dynamics model to calculate external moments about the knee joint, under inertial and mass estimations (de Leva, 1996). Moments were normalized to participant mass. In cases where the left limb was dominant (and therefore assessed), jump directions were inversely coded to coincide with matching medial and lateral movements (Stephenson et al., 2018).

Previous investigations have associated sagittal and frontal plane kinematics and kinetics with ACL injury risk. Notably, injuries have been recorded within the first 50 ms of a forceful landing (Dai, Mao, et al., 2015; Koga et al., 2010). It is likely that the peak posterior ground reaction force (PPGRF) occurs early within this time window and contributes to sagittal plane knee moments and subsequent ACL loading via an anterior shear force at the proximal tibia caused by a combination of PPGRF and disproportionate quadriceps activation (Lin et al., 2009; Sell et al., 2007; Yu et al., 2006), particularly if the knee joint is relatively stiff at a shallow flexion angle (Dai, Mao, et al., 2015; Hashemi et al., 2011; Kim et al., 2015; Sell et al., 2007; Yu & Garrett, 2007). This may then allow a frontal plane valgus collapse (Hashemi et al., 2011; Markolf et al., 1995), within the subsequent milliseconds after landing (Dai, Mao, et al., 2015; Koga et al., 2010; Krosshaug et al., 2007).

Following this specific mechanism, knee flexion angles and external moments were identified at the instant of PPGRF force during the initial landing phase. Within 50 ms after PPGRF, the peak knee valgus angles and external moments were identified. Sagittal plane knee joint stiffness was calculated as the change in internal moment divided by the change in angle from the instant of touchdown to the time of PPGRF. Finally, to reflect on movement performance, the stance time between jumps and the resultant exit velocity of the pelvis at the end of ground contact between the two jumps was identified. Resultant pelvis velocity was calculated from the mean position of the left and right anterior and posterior iliac spines (Dai et al., 2019).

The aforementioned dependent variables were analyzed across jump directions and timing conditions for preplanned, reactive, and performance constrained trials. A 2 x 5 repeated measures analysis of variance was performed on the averages of the three trials for each dependent variable. In the cases where the assumption of Sphericity was violated, Greenhouse-Geisser corrections were implemented. Significant main effects were subsequently analyzed via pairwise t-tests, and a study-wise type I error rate of 0.05 was maintained via the false discovery rate methodology (Benjamini & Hochberg, 1995).

Results

Throughout this section, results are presented as mean (standard error). Main effect p-values from the repeated measures analysis of variance have had Greenhouse-Geisser corrections applied as necessary, and p-values from pairwise t-tests have been adjusted following the false discovery rate methodology. As such, p-values can be compared directly to the study-wise significance cutoff of 0.05. Performance measures are presented below first to reflect on the success of the described methodology in controlling stance time. These results are followed by the analyzed factors associated with ACL injury risk. All variables are summarized in two tables, each relating to a specified latter jump direction.

Performance measures

Performance measures of the jump landing and subsequent jump were assessed to reflect on the success of controlling stance time and to determine the subsequent effect on the initial velocity of the next jump. Both medial and lateral jumps (Tables 3.1-2 respectively) demonstrated significant main effects for both stance time and exit velocity $p < 0.0001$ for all main effects. Patterned responses were generally similar between jump directions.

In both medial and lateral jumps, the preplanned condition resulted in the shortest stance time between jumps, which was successfully statistically matched in the early constrained condition. In both jump directions, the early and late reactive conditions each resulted in significant incremental increases in stance time (all $p < 0.03$). Participants were not capable, on average, of restricting stance time to that similar to the preplanned condition in the late constrained condition. For medial jumps, the late constrained condition was faster than the late reactive condition ($p < 0.0001$), but slower than the early reactive condition ($p = 0.001$). In lateral jumps, the late constrained stance time was not dissimilar to the early reactive condition ($p = 0.39$), but different from all others ($p < 0.03$).

Table 3.1: Mean (standard error) of knee kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across preplanned, reactive, and performance-constrained conditions in jumps medial to the tested limb.

	Preplanned	Early Reactive	Late Reactive	Early Constrained	Late Constrained
Kinematic					
Flexion (°)	30.7 (2.5)	28.6 (1.7)	27.2 (1.7)	28.9 (2.2)	27.3 (1.6)
Valgus (°)	5.9 (0.9)	5.6 (1.0)	5.7 (0.9)	5.4 (1.0)	6.0 (0.8)
Kinetic					
Flexion (Nm/kg)	1.5 (0.3)	1.7 (0.3)	1.5 (0.2)	1.4 (0.3)	1.6 (0.2)
Valgus (Nm/kg)	0.6 (0.1)	0.6 (0.1)	0.6 (0.1)	0.7 (0.1)	0.6 (0.1)
Stiffness (Nm/kg/°)	20.9 (5.7)	19.2 (4.8)	16.8 (3.8)	22.6 (5.9)	17.7 (4.1)
Performance					
Stance Time (ms)	380 (27)$^{\mathbf{D}}$	442 (29)$^{\mathbf{C}}$	606 (27)$^{\mathbf{A}}$	395 (27)$^{\mathbf{D}}$	513 (21)$^{\mathbf{B}}$
Exit Velocity (m/s)	2.6 (0.1)$^{\mathbf{A}}$	2.6 (0.1)$^{\mathbf{A}}$	2.1 (0.1)$^{\mathbf{C}}$	2.5 (0.1)$^{\mathbf{B}}$	2.2 (0.1)$^{\mathbf{C}}$

Statistically significant differences indicated as A>B>C>D at false discovery rate-adjusted Type I error no more than 5%.

Exit velocity followed similar patterns of change independent of jump direction. The resultant velocity was highest in preplanned and early reactive conditions ($p = 0.15$); this was significantly reduced in the early constrained condition ($p < 0.01$). The late reactive and late constrained conditions did not statistically differ ($p > 0.28$) and were significantly slower than all other conditions ($p < 0.03$).

Injury risk factors

Kinematic and kinetic measures associated with ACL injury risk were assessed between preplanned, reactive, and performance-constrained reactive conditions. As non-contact ACL injury has been identified to occur within the first 50 ms of landing and likely coincides with the peak posterior ground reaction force within that timeframe, injury risk variables were assessed at and around this precise timepoint. PPGRF occurred at the average time of 19 (3) ms after ground contact; this did not significantly differ (p > 0.20) between conditions or jump directions.

Table 3.2: Mean (standard error) of knee kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across preplanned, reactive, and performance-constrained conditions in jumps lateral to the investigated limb.

	Preplanned	Early Reactive	Late Reactive	Early Constrained	Late Constrained
Kinematic					
Flexion (°)	33.0 (3.0)$^{\mathbf{A}}$	32.8 (2.5)$^{\mathbf{A}}$	28.2 (1.7)$^{\mathbf{B}}$	34.0 (3.2)$^{\mathbf{A}}$	28.4 (1.7)$^{\mathbf{B}}$
Valgus (°)	6.3 (1.0)	6.1 (0.9)	6.0 (0.8)	5.6 (1.2)	5.6 (0.7)
Kinetic					
Flexion (Nm/kg)	1.3 (0.2)	1.5 (0.3)	1.7 (0.2)	1.4 (0.2)	1.5 (0.2)
Valgus (Nm/kg)	0.6 (0.1)	0.7 (0.1)	0.6 (0.1)	0.7 (0.1)	0.5 (0.1)
Stiffness (Nm/kg/°)	19.6 (4.5)	17.0 (3.6)	16.5 (3.7)	19.3 (4.3)	15.5 (3.5)
Performance					
Stance Time (ms)	400 (27)$^{\mathbf{C}}$	467 (30)$^{\mathbf{B}}$	549 (34)$^{\mathbf{A}}$	394 (22)$^{\mathbf{C}}$	497 (24)$^{\mathbf{B}}$
Exit Velocity (m/s)	2.4 (0.1)$^{\mathbf{A}}$	2.4 (0.1)$^{\mathbf{A}}$	1.8 (0.2)$^{\mathbf{C}}$	2.2 (0.1)$^{\mathbf{B}}$	2.0 (0.1)$^{\mathbf{C}}$

Statistically significant differences indicated as A>B>C at false discovery rate-adjusted Type I error no more than 5%.

Jumps medial to the investigated limb did not exhibit statistically significant main effects for knee flexion angles (p = 0.27) or external flexion moments (p = 0.45) at PPGRF. Peak knee valgus angles or external moments within 50 ms after PPGRF were also not statistically significantly different (p = 0.81 and 0.48, respectively). Sagittal plane knee stiffness from ground contact until PPGRF also did not significantly differ between conditions (p = 0.34). Means and standard errors are presented in Table 3.1.

Lateral jumps demonstrated changes across conditions. Knee flexion angles at PPGRF did demonstrate a significant main effect (p = 0.02); as illustrated in Table 3.2, preplanned, early reactive, and early constrained conditions resulted in a statistically significantly larger knee flexion angle than the late reactive and late constrained conditions (p < 0.04). Otherwise, kinematic and kinetic results were similar to medial jumps: Knee flexion moments at PPGRF (p = 0.09), peak knee valgus angles (p = 0.62), peak external knee valgus moments (p = 0.08), and sagittal plane joint stiffness (p = 0.54) did not demonstrate significant main effects.

Discussion

The purpose of this investigation was to determine whether speed performance constraints during a reactive jump landing protocol used to explore ACL injury risk factors significantly altered kinematic and kinetic factors associated with the injury. Based on the results of previous investigations, we expected a functional tradeoff; if performance was constrained in demanding, reactive jump landing conditions, participants would rely on a stiffer landing to enhance speed performance. This may subsequently increase ACL injury risk, particularly if the knee is not deeply flexed. Results were only marginally supportive of this hypothesis. As described below, participants were not entirely capable of increasing jump speed to the targeted level; later reactive conditions appear to inhibit this capability. Performance constraints also do not appear to change ACL injury risk factors.

Performance measures

Stance time on the ground between jumps during the task increased from preplanned to early and late reactive conditions, similar to our previous investigation. Interestingly, the participants in the current investigation were generally faster than the previous (Stephenson et al., 2018); this may be due to the 60° cutting angle, in contrast to 90°, allowing the participant to utilize a portion of their anterior momentum in the cutting performance. In both jump directions, participants were capable of constraining their stance time to the preplanned condition when given more directional forewarning in the early constrained condition. Participants were not this effective in the late constrained condition, however; in medial jumps, stance time was increased to that between early and late reactive conditions. In lateral jumps, it was similar to early reactive conditions.

In parallel to this change in stance time, participants' velocity as they left the ground for the second jump slowed. Preplanned and early reactive conditions demonstrated similar, rapid exit velocities. Yet in the early constrained condition, participants appear to have reduced their exit velocities in lieu of more rapid stance times. As the exit velocity of a jump is a prime determinant of jump performance (Komi & Bosco, 1978), the parallel reduction of both may be an indication that the reactive strength index, an indicator of explosive strength (Flanagan & Comyns, 2008; McMahon, Jones, Suchomel, Lake, & Comfort, 2018), is maintained at a relatively constant value between the early constrained and reactive conditions.

The late reactive and constrained conditions in both jump directions resulted in a decreased exit velocity, however. As stance time was not lengthened in constrained conditions to the same degree as the late reactive condition, the explosive strength of the participants was likely lower than in preplanned and early conditions but not reduced to the degree demonstrated in the late reactive condition. Overall, these performance variables suggest that a reduction in an available time to react to visual stimuli can hinder jump performance (Stephenson et al., 2018), but participants may be capable of increasing performance to a limited degree.

This capability may be undermined as the available time to react to visual stimuli is reduced to landing and subsequent reactive performance. As it is expected that reactive movements may demand time for information processing to determine a proper reaction to a directional stimulus (Miller & Clapp, 2011; Stephenson et al., 2018), late manifestations of this process may require this to occur during a portion of stance time. These results suggest this may delay movement time by approximately 100 ms; we expect this may increase with the complexity of the performance environment and the potential number of reactive choices (Hick, 1952).

Injury risk factors

The aforementioned changes in jump performance suggest that reactive performances may be modifiable to only some degree. As previous literature indicated that increasing jump performance may alter ACL injury risk (Dai et al., 2019; Dai, Garrett, et al., 2015), we expected performance-constrained conditions would increase landing stiffness within the injury-critical first 50 ms of landing. If this occurred with a shallow knee flexion angle, subsequent increased knee valgus collapse was expected. In combination, this would increase ACL injury risk.

Generally, results did not support this hypothesis. The only significant kinematic change between conditions occurred in lateral jumps; knee flexion angles were reduced in the late reactive and late constrained conditions compared to all other conditions. This reduction in late reactive conditions is similar to our previous investigation (Stephenson et al., 2018), although there was also a significant reduction in knee flexion angles from the preplanned to early reactive conditions in these previous results. Two other previous investigations identified an *increase* in knee flexion in temporally-undefined reactive conditions in a time period likely to coincidence with PPGRF (Besier, Lloyd, Ackland, & Cochrane, 2001; Cortes, Blount, Ringleb, & Onate, 2011). But two other investigations did not identify significant changes between preplanned and reactive conditions (Brown, Palmieri-Smith, & McLean, 2009; Weinhandl et al., 2013). Multiple other investigations explored these potential effects, but did not limit the analysis to the initial, injury-critical time period in the jump landing (Almonroeder et al., 2015; Brown, Brughelli, & Hume, 2014).

Our previous investigation identified that knee valgus angles and moments changed depending on jump direction, particularly from preplanned and early reactive conditions to late reactive conditions (Stephenson et al., 2018). The results of the current study, however, did not identify significant changes in kinematics or kinetics in the frontal plane. Other investigations that only considered the initial portion of landing were also ambiguous, whereas one investigation noted an increase in peak valgus angles but not moments (Cortes et al., 2011), while other investigations did not identify significant differences (Brown et al., 2009; Weinhandl et al., 2013).

Knee joint stiffness is not commonly reported in investigations comparing preplanned and reactive jump landing protocols (Almonroeder et al., 2015; Brown et al., 2014). The lack of significant change in knee joint stiffness from the current investigation was surprising, however, given the very modest increases in knee flexion range of motion and larger increases in sagittal plane moments between the early and late reactive conditions in our previous investigation (Stephenson et al., 2018). Furthermore, previous research indicated an increase in peak knee joint stiffness when performing for movement speed, but assessed this stiffness over a time period likely longer than 50 ms (Dai et al., 2019). Furthermore, the analysis performed in Dai et al. (2019) was likely insensitive to the rapid increase in external knee flexion moments associated with ground reaction forces found in the initial phase of landing (Besier, Lloyd, Cochrane, & Ackland, 2001). The current results suggest this may be invariant to reactive timing.

The decrease in knee flexion at PPGRF suggests an increase in ACL injury risk for late reactive and late constrained conditions during jumps lateral to the investigated limb. The lack of differences between reactive and constrained conditions ultimately refutes the hypothesis of the current investigation. Previous investigations that identified a functional tradeoff between performance and injury risk but did not utilize a reactive task to emulate on-field, team game contexts with rapid decision making. It is possible that these tradeoffs only exist in contexts with looser constraints on performance, and reactive decision-making places too large of a constraint on an athlete to allow this flexibility. If so, an athlete's contextual prioritization of performance (McIntosh, 2005) over mitigating injury risk may not play a role in increasing ACL injury risk.

This conclusion should be cautiously considered, however. The current investigation's jump landing protocol may not generalize well to team sport directional changes. Importantly, it may place constraints on the participant's movements that limit the effect of the manipulations in the current investigation (Wilkie, Stephenson, & Gillette, 2017). Furthermore, by investigating both male and female participants in the same sample, significant kinematic and kinetic changes may be statistically masked due to the proposed differences in movement strategies between the sexes (Brown et al., 2009; Quatman & Hewett, 2009). Subgroup analyses on the current data did not identify characteristic differences between the sexes, but the investigation was not intended to provide statistical power for this exploration. Previous investigations have also identified that ACL injury risk factors in reactive protocols may be dependent on athlete experience (Kipp, Brown, McLean, & Palmieri-Smith, 2013). Because this investigation allowed a large range of sports experience, significant effects may further be masked. Finally, the methods used to identify specific dependent variables during the jump landing are relatively uncommon in the reactive jump landing literature. Utilizing PPGRF as the key time period to identify ACL injury risk magnitudes corresponds strongly with previous investigations that identified the role of PPGRF in ACL loading and other investigations that identified how rapidly ACL injury is to occur. But comparing the magnitudes of ACL injury risk factors from the instant of PPGRF to peak magnitudes over the entire stance time may be misleading, particularly if these latter magnitudes are determined by the subsequent performance (such as a second jump) instead of the landing itself (Hovey, Wang, Judge, Avedesian, & Dickin, 2019).

Conclusion

ACL injury risk poses a significant musculoskeletal threat to athletes in team sports. Previous literature has demonstrated that rapid decision making can aggravate this injury risk. In these contexts, athletes may prioritize sports movement performance over caution that may prevent injuries. But this investigation demonstrates that performing reactive directional changes more rapidly by decreasing the time in contact with the ground between jumps may not increase ACL injury risk. It does appear that this change may mitigate the performance on the subsequent jump, however. Further investigation is warranted to explore these potential effects in each sex individually, as this conclusion may not be uniformly generalizable.

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CHAPTER 4. ERRONEOUS DIRECTIONAL MOVEMENT PREDISPOSITION ALTERS ACL INJURY RISK VIA DELAYED DIRECTIONAL CUEING

Abstract: Team sports often demonstrate the use of deception when opponents tactically vie for control. Previous research identified an increased risk of anterior cruciate ligament injury in these contexts. This investigation sought to expose female athletic participants to this effect, by employing an erroneous visual directional cue that reversed to the correct direction at different times in a jump landing movement. While it was expected that this erroneous movement predisposition would increase injury risk, results indicate that this effect is instead solely due to delays in directional cueing instead of the erroneous predisposition itself. Similar to the conclusion of our previous investigation, injury risk is characteristically altered as participants are provided less time to react to a directional cue; in specific movement cases, these alterations increase injury risk factors and decrease subsequent performance. This preliminary evidence is only of moderate value, however, as on-field sensory information is often more feature-rich and may significantly modulate this effect. Further research using more complex, but precise temporally controlled visual stimuli is suggested.

Introduction

Anterior cruciate ligament (ACL) injury rates have maintained at an unacceptably high level for more than a decade (Agel, Rockwood, & Klossner, 2016; Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017), posing long-term physical, financial (Brophy, Wright, & Matava, 2009), and psychological (Carson & Polman, 2008) risk to athletes in a variety of sports. This injury disproportionally impacts female athletes, due to multiple complicating factors (Agel, Arendt, & Bershadsky, 2005; Hootman, Dick, & Agel, 2007; Quatman &

Hewett, 2009). Multiple interventions and screening tools to curtail injury risk have been proposed and implemented (Donnell-Fink et al., 2015; Fox, Bonacci, McLean, Spittle, & Saunders, 2016; Stevenson, Beattie, Schwartz, & Busconi, 2015), generally targeting non-contact injury mechanisms due to the potentially modifiable nature of this context (Price, Tuca, Cordasco, & Green, 2017). The efficacy of these interventions is questionable, however, as evidence for associated decreases in injury are relatively sparse and may be dependent on specific populations (Silvers-Granelli, Bizzini, Arundale, Mandelbaum, & Snyder-Mackler, 2017; Stevenson et al., 2015).

More recently, motor control paradigms have been integrated into ACL injury risk research in pursuits to explore potential complications of injury mechanism that may yet to be integrated into injury prevention efforts (Almonroeder, Garcia, & Kurt, 2015; Brown, Brughelli, & Hume, 2014; Monfort et al., 2019). It has been increasingly recognized that the rapid decision-making performed in team sports may play a role in ACL injury risk (Almonroeder et al., 2015; Miller & Clapp, 2011; Swanik, 2015). Delays in selecting and executing a motor response to an oncoming opponent (Brophy, Stepan, Silvers, & Mandelbaum, 2015; Waldén et al., 2015), if improperly timed such that the change in kinematics occurs relatively closely to a forceful landing, may undermine an athlete's lower extremity control (Stephenson et al., 2018). It is possible that this effect may be aggravated by peripheral fatigue as well (Almonroeder, Tighe, & Lanning, 2018; Borotikar, Newcomer, Koppes, & McLean, 2008; Collins, Almonroeder, Ebersole, & O'Connor, 2016).

These previous investigations considered temporal aspects of reactive jump-landings and run-cut maneuvers through a relatively simplistic paradigm: A directional cue would indicate a change in direction, itself associated with increased injury risk (Almonroeder et al., 2015), momentarily before a lower extremity loading event that included the directional change. Multiple investigations posited that this may occur in response to an unpredictable or deceptive opponent (Almonroeder et al., 2015; Fujii, Yamashita, Yoshioka, Isaka, & Kouzaki, 2014; Fujii, Yoshioka, Isaka, & Kouzaki, 2015; Sasaki, Koga, Krosshaug, Kaneko, & Fukubayashi, 2018; Stephenson et al., 2018; Waldén et al., 2015). If this is the case, however, it is likely that the athlete assumes and prepares for an initial movement direction and modifies this assumption as further clarifying information is presented instead of delaying preparatory actions until absolute confirmation of movement (Fujii, Yoshioka, et al., 2015; Miller & Clapp, 2011). This feedforward preparation likely plays a role in enhancing performance (Fujii, Yamashita, Kimura, Isaka, & Kouzaki, 2015; Mornieux, Gehring, Fürst, & Gollhofer, 2014).

This effective directional predisposition may complicate the information processing of the athlete if that predisposition was erroneous (Miller & Clapp, 2011). Preparatory movements for an incorrect movement direction that are only revised close to loading the lower extremity may create kinematic changes detrimental to safety, as it may effectively delay the available time to react to the correct cue (Mornieux et al., 2014; Stephenson et al., 2018). Concerningly, a psychological refractory period may drastically delay movement corrections if correct and relevant cues are presented during motor response selection in reaction to the initial, erroneous information (Broadbent & Gregory, 1967; Pashler, 1994). As reported by previous research, this effect may also disproportionately impact females over males due to sex-specific limitations in attentional resources (Laguë-Beauvais, Gagnon, Castonguay, & Bherer, 2013). It is possible that if participants attempt to alter movement direction after the leg is loaded with bodyweight (Fujii, Yoshioka, et al., 2015), they can accomplish this predominantly with a latent trunk inclination in the revised direction of movement (Fujii, Yamashita, et al., 2014; Patla, Adkin, & Ballard, 1999). As lateral trunk inclination has been associated with frontal plane knee joint moments also associated with ACL injury risk (Hewett & Myer, 2011), this may in turn increase risk of injury for the athlete if the kinematic alterations occur within a limited temporal window after forceful loading (Dai, Mao, Garrett, & Yu, 2015; Koga et al., 2010). Furthermore, unexpected stimuli may alter the control of knee joint stiffness (DeAngelis et al., 2015), increasing injury risk if the knee is loaded closer to full extension (Hashemi et al., 2011; Owusu-Akyaw et al., 2018).

As such, the current investigation sought to explore whether erroneous movement predisposition, and the latent revision of this movement direction, altered ACL injury risk within the critical window that injury is likely to occur. As this mechanism is likely tied closely to alterations in frontal plane loading of the knee (Hewett & Myer, 2011; Patla et al., 1999), and it has been proposed that this injury mechanism may disproportionately affect female athletes (Quatman & Hewett, 2009), only female athletes were recruited for this investigation. It was hypothesized that erroneous directional predisposition would result in an increase in knee abduction angles and external moments compared to more simplistic reactive conditions. Similarly, we expected the latent unexpected stimuli would result in a stiffer landing in the sagittal plane. In combination, these kinetic and kinematic effects would increase ACL injury risk. But as this effect is likely to only occur if the athlete implements a directional change via trunk declination once the foot is already bearing weight, this effect is likely to only occur if the error in movement direction is realized relatively late in the movement preparation phase immediately before landing.

Methodology

The methodological implementation of this investigation followed a repeated-measures design to acutely assess the potential effects of erroneous movement direction predisposition in reactive jump landings. Both preplanned and reactive conditions similar to previous research (Stephenson et al., 2018) were included to provide a foundation of comparison and validation. Data were exclusively collected in the Iowa State University Kinesiology Biomechanics Lab. The University's Institutional Review Board approved this investigation's use of human volunteers as participants (see Appendix).

Participants

Evidence from our previous investigation (Stephenson et al., 2018) identified moderate effect sizes and moderate to strong within-participant correlations for knee joint moments in the frontal plane between early and late reactive conditions that suggested a minimum sample size of 20 participants to maintain a Type I error rate of 5% and a Type II error rate below 20%. This is likely an overestimation of requisite sample sizes, given the heterogeneous sex and diverse sports experience of the participants from the previous investigation. In contrast, this investigation recruited 22 female athletes (mean ± standard deviation: 20.7 ± 1.3 years; 62.9 ± 6.1 kg; 1.67 ± 0.08 cm). They were required to be minimally active 150 minutes per week (or 75 minutes of higher intensity activity), which included at least two hours per week of sports and activities that included reactive, rapid directional changes (such as basketball, soccer, tennis, volleyball, etc.). Volunteers were required to not have lower extremity or torso injuries, or a concussion, over the past six months, and be unfatigued at the time of testing. Volunteers provided informed written consent and completed an injury and physical activity questionnaire to verify eligibility.

Protocol

Tested individually, participants performed a standardized jump-landing protocol after a dynamic warm-up. Starting on a 30 cm tall block instrumented with a force platform (Advanced Mechanical Technologies, Inc. Watertown, MA, USA), they jumped forward at their discretion a distance equal to 50% of their height. They landed bilaterally, with each foot on in-ground force platforms (Advanced Mechanical Technologies, Inc. Watertown, MA, USA). In a rapid, continuous motion, they then jumped to the left or right at an angle 60° from the anterior. Participants were encouraged to maintain high performance in this jump by minimizing the time on the force platforms between jumps and to maximize the distance of the second jump (Stephenson et al., 2018). Participants practiced this basic protocol and all conditions described below before data collection commenced.

The direction of the second jump was indicated to the participant with one of two light-emitting diodes (LEDs) mounted in front of the performance area. These LEDs were identical in color and intensity, and precisely timed to coincide with the task conditions for this investigation. For the **preplanned condition**, the LED was illuminated well-before the participant was asked to perform the trial. In the **early reactive condition**, the LED was illuminated the instant they left the 30 cm block in their forward jump, providing the entirety of the initial jump's flight time (average of 382 ± 11 ms) to process and react to the stimulus. In the **late reactive condition**, the LED was illuminated at the instant the participant landed on the in-ground force platforms between jumps; this condition represented a worst-case scenario, whereas they were only able to process and react to the cue once lower extremity loading had started commenced. Finally, two erroneous predisposition conditions were also investigated, whereas an initially-illuminated LED indicated an incorrect movement direction. This LED was extinguished, and the other LED illuminated either at the instant of takeoff or the instant of landing, similar to the reactive conditions. These **early and late predisposition conditions** were initially indistinguishable from the preplanned condition.

The illumination of these LEDs was controlled with an Arduino Mega 2560 Rev3 operating a custom program that monitored the analog vertical ground reaction force from the force platforms. This program was previously validated to fully illuminate the LEDs within two milliseconds of the discrete events that coincided with force thresholds equivalent to 8 N. The Arduino Mega's program also randomized the tested conditions and jumping order via a Durstenfeld technique (Durstenfeld, 1964), effectively double-blinding the investigation. If errors in the performance occurred, the program re-randomized the trial condition in the remaining trials such that it could not be predicted; if this occurred near the end of the data collection, it interjected an extra trial to eliminate the possibility of the participant correctly assuming the trial condition. Finally, a series of "catch" trials were also randomly injected into the conditions; in this condition, no LED was illuminated, and the participant was instructed to not perform a second jump in this situation.

Participants completed a total of 3 successful trials in each cue condition for each jump direction, for a total of 30 trials (plus 3-5 catch trials). Participants were required to rest a minimum of 30 seconds between jumps; this has been demonstrated to eliminate the risk of accruing fatigue (Oliveira et al., 2019). The kinematic performance in each trial was recorded with eight infrared cameras (160 Hz, Vicon Motion Systems Ltd, Oxford, UK) recording the position of 19 retroreflective markers placed on the dominant foot, shank, leg, as well as the pelvis and shoulders. Kinetic data were recorded from the in-ground force platforms at 1600

Hz. All kinematic and kinetic data were synchronized and recorded through Vicon Nexus 1.8.5.

Analysis

Kinematic and kinetic data were processed following a standardized protocol. Kinematic marker data and kinetic data from the force platforms were filtered with a 4^{th} order, zero-lag Butterworth filter with respective cutoff frequencies of 15 and 200 Hz (Yu, Gabriel, Noble, & An, 1999). Joint angles were first calculated from static calibration trials with the participant in a relatively anatomically neutral standing posture; values were used to determine the individual participant's neutral alignment. Euler-Cardan joint angle calculations were performed with a sagittal, frontal, and then transverse plane rotation order (Grood & Suntay, 1983). Combined with the landing kinetic data from the force platforms, the kinematic data were then used to estimate inertial and mass distributions (de Leva, 1996) and locations for a bottom-up inverse dynamics model. External knee joint moments were calculated and normalized to the participant's mass. Participant data in which the left limb was analyzed were coded directionally reversed, such that the movement lateral or medial to the limb matched participant data that assessed the right limb (Stephenson et al., 2018).

Both measures associated with jump landing performance and ACL injury risk were assessed for changes across conditions. The resultant velocity of the mean position from the five markers placed on the pelvis was used to assess exit velocity at the instant the participant left the in-ground force platforms for the second jump (Dai et al., 2019). The stance time on the force platforms between jumps was also calculated. ACL injury risk has been associated with the peak posterior ground reaction force (PPGRF), and the kinematics and kinetics that occur at this time (Lin et al., 2009; Sell et al., 2007; Yu, Lin, & Garrett, 2006). This peak force also generally occurs within the first 50 ms of landing, which has previously been identified as a critical time period for ACL injury risk (Dai et al., 2015; Koga et al., 2010). Previous research suggests that valgus collapse may occur late within this time period, particularly if the landing demonstrated a shallow flexion angle and sagittal plane knee joint stiffness (Dai et al., 2015; Hashemi et al., 2011; Krosshaug et al., 2007).

As such, knee flexion angles and moments were extracted at the instant of PPGRF and peak knee valgus angles and moments were extracted within 50 ms after PPGRF. Knee joint stiffness was assessed two ways: The change in internal knee extension moment divided by the change in knee flexion angle from the instant of landing until PPGRF, and and a proposed kinematic ratio of hip joint angular velocity to knee joint angular velocity at the instant of PPGRF (Hashemi et al., 2011). These dependent variables were statistically compared via a 5x1 repeated measures analysis of variance for each jump direction. Mauchly's Test was utilized to assess the assumption of sphericity; in cases that it was violated, Greenhouse-Geisser corrections were implemented. Significant ($p < 0.05$) main effects were subsequently explored with pairwise t-tests; to reduce the rate of false discovery, Benjamini & Hochberg corrections were used (Benjamini & Hochberg, 1995).

Results

Results are presented below as means (standard error) in two tables, each including data for separate jump directions. The presented p-values from the statistical evaluations have been already corrected to control for the assumptions of sphericity and to maintain a study-wise Type I error rate of 5%. Therefore, these p-values can be compared directly to the disciplinary standard alpha value of 0.05.

Performance measures

In jumps medial to the investigated limb (Table 4.1), the stance time between jumps significantly differed between cue conditions ($p < 0.001$). Late reactive and late predisposed conditions similarly ($p = 0.12$) demonstrated the longest stance time, followed by stepwise significant reductions to preplanned ($p < 0.005$), early reactive ($p < 0.046$), and finally early predisposed conditions ($p < 0.046$). Exit velocity also significantly differed between conditions ($p < 0.001$). The preplanned, early reactive, and early predisposed conditions demonstrated similar velocities ($p > 0.41$), which were significantly faster than the late reactive and late predisposed conditions ($p < 0.001$). The late predisposed condition was also significantly slower than the late reactive condition ($p = 0.015$).

Table 4.1: Mean (standard error) of kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across preplanned, reactive, and predisposed conditions in jumps medial to the investigated limb.

	Preplanned	Early Reactive	Late Reactive	Early Predisposed	Late Predisposed
Kinematics					
Knee flexion (°)	29.8 (1.9)	27.4 (2.2)	28.2 (1.9)	29.0 (1.9)	29.4 (1.9)
Knee valgus (°)	4.8 (1.1)$^{\mathbf{A}}$	5.7 (1.1)$^{\mathbf{A}}$	4.0 (1.1)$^{\mathbf{B}}$	5.9 (1.0)$^{\mathbf{A}}$	4.2 (1.1)$^{\mathbf{B}}$
Hip/Knee Ratio (%)	0.27 (0.03)$^{\mathbf{A}}$	0.18 (0.05)$^{\mathbf{B}}$	0.30 (0.04)$^{\mathbf{A}}$	0.25 (0.04)$^{\mathbf{AB}}$	0.27 (0.04)$^{\mathbf{A}}$
Knee kinetics					
Flexion (Nm/kg)	1.20 (0.13)$^{\mathbf{AB}}$	1.36 (0.14)$^{\mathbf{A}}$	1.05 (0.09)$^{\mathbf{B}}$	1.46 (0.16)$^{\mathbf{A}}$	1.23 (0.11)$^{\mathbf{AB}}$
Valgus (Nm/kg)	0.54 (0.08)$^{\mathbf{B}}$	0.78 (0.09)$^{\mathbf{A}}$	0.66 (0.07)$^{\mathbf{B}}$	0.81 (0.1)$^{\mathbf{A}}$	0.57 (0.07)$^{\mathbf{B}}$
Stiffness (Nm/kg/°)	19.4 (2)	24.3 (2.6)	21.4 (4.2)	22.2 (3.2)	20.8 (2.6)
Performance					
Stance Time (ms)	488 (23)$^{\mathbf{B}}$	431 (27)$^{\mathbf{C}}$	670 (27)$^{\mathbf{A}}$	392 (18)$^{\mathbf{D}}$	619 (26)$^{\mathbf{A}}$
Exit Velocity (m/s)	2.6 (0.1)$^{\mathbf{A}}$	2.6 (0.1)$^{\mathbf{A}}$	2.4 (0.1)$^{\mathbf{B}}$	2.6 (0.1)$^{\mathbf{A}}$	2.2 (0.1)$^{\mathbf{C}}$

Statistically significant differences indicated as A>B>C>D at false discovery rate-adjusted Type I error no more than 5%.

Lateral jumps demonstrated similar performance responses to medial jumps, as seen in Table 4.2. Stance time significantly differed between conditions ($p < 0.001$), remaining the longest in the preplanned, late reactive, and late predisposed conditions (which did not significantly differ; $p > 0.24$). The early reactive condition was significantly shorter than the preplanned and late reactive conditions ($p < 0.017$) but did not differ from the late predisposed condition ($p = 0.24$). The early predisposed condition again demonstrated the shortest stance time, significantly differing from all other conditions ($p < 0.017$). Exit velocity differed in a similar manner between conditions, with preplanned, early reactive, and early predisposed conditions maintaining a similar ($p > 0.06$), higher velocity ($p < 0.008$) than late reactive and predisposed conditions (which did not significantly differ; $p = 0.16$).

Injury risk factors

In medial jumps (Table 4.1), knee flexion angles at PPGRF did not significantly differ across cue conditions ($p = 0.25$), but knee valgus angles did demonstrate a significant main effect ($p < 0.001$). Valgus angles were significantly larger ($p < 0.05$) in preplanned, early reactive, and early predisposed conditions (which did not differ from one another; $p > 0.10$) than late reactive and late predisposed conditions (which did not significantly differ; $p = 0.70$). The ratio between hip velocity and knee velocity in the sagittal plane at PPGRF also significantly changed across the tested conditions ($p < 0.004$). The early reactive condition demonstrated a lower ratio, indicating less stiffness, than all other conditions ($p < 0.045$) but the early predisposed condition ($p = 0.24$); these other conditions did not significantly differ from one another $p > 0.15$).

External knee flexion moments significantly differed among conditions ($p = 0.029$) in medial jumps as well: The late reactive condition exhibited significantly reduced flexion moments than the early reactive and early predisposed conditions ($p < 0.047$). All other conditions did not significantly differ ($p > 0.25$). External knee valgus moments also presented a significant main effect ($p = 0.002$); early reactive and early predisposed conditions were similar ($p = 0.72$), but significantly larger ($p < 0.048$) than the other conditions (which did not significantly differ; $p > 0.09$). Knee joint stiffness did not significantly differ between conditions ($p = 0.62$).

Table 4.2: Mean (standard error) of kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across preplanned, reactive, and predisposed conditions in jumps lateral to the investigated limb.

	Preplanned	Early Reactive	Late Reactive	Early Predisposed	Late Predisposed
Kinematics					
Knee flexion (°)	31.9 (1.8)^{B}	36.2 (2.2)^{A}	27.7 (1.7)^{C}	37.0 (2.4)^{A}	29.8 (2.0)^{BC}
Knee valgus (°)	3.9 (1.2)^{AB}	2.4 (1.5)^{C}	3.6 (1.1)^{BC}	2.3 (1.4)^{C}	4.3 (1.1)^{A}
Hip/Knee Ratio (%)	0.32 (0.04)	0.36 (0.04)	0.30 (0.03)	0.35 (0.04)	0.30 (0.04)
Knee kinetics					
Flexion (Nm/kg)	1.18 (0.12)	1.09 (0.11)	0.99 (0.1)	0.97 (0.11)	1.24 (0.13)
Valgus (Nm/kg)	0.59 (0.07)^{A}	0.47 (0.06)^{B}	0.59 (0.07)^{A}	0.42 (0.06)^{B}	0.61 (0.07)^{A}
Stiffness (Nm/kg/°)	18.7 (2.0)	17.9 (2.0)	19.4 (2.4)	18.6 (2.3)	19.5 (2.3)
Performance					
Stance Time (ms)	534 (26)^{A}	472 (21)^{B}	570 (30)^{A}	447 (17)^{C}	505 (29)^{AB}
Exit Velocity (m/s)	2.1 (0.1)^{A}	2.2 (0.1)^{A}	1.3 (0.1)^{B}	2.3 (0.1)^{A}	1.6 (0.1)^{B}

Statistically significant differences indicated as A>B>C at false discovery rate-adjusted Type I error no more than 5%.

In contrast to medial jumps, knee flexion angles at PPGRF did significantly differ between conditions in lateral jumps (Table 4.2; $p < 0.001$). Early reactive and early predisposed conditions similarly demonstrated ($p = 0.49$) the largest knee flexion angles and were significantly reduced ($p < 0.03$) in the preplanned and late predisposed conditions (which did not significantly differ; $p = 0.11$). The late reactive condition demonstrated the smallest knee flexion angle compared to other conditions ($p < 0.001$) except when compared to the late predisposed condition ($p = 0.11$). Knee valgus angles presented more nuanced, significant changes across conditions ($p = 0.015$). The preplanned and late predisposed conditions demonstrated the largest valgus angles (but these conditions did not significantly differ from one another; $p = 0.25$) compared to the other conditions ($p < 0.047$) with the exception of the preplanned and late reactive conditions ($p = 0.47$). The early reactive and early predisposed conditions (themselves not significantly different; $p = 0.92$) demonstrated significant reductions in knee valgus angles compared to the preplanned and late predisposed conditions ($p < 0.047$), but not the late reactive condition ($p > 0.14$). The ratio of hip flexion velocity to knee flexion velocity at PPGRF was not significantly different after correcting for the false discovery rate ($p > 0.10$).

External flexion moments were also not significantly different between conditions in lateral jumps after Greenhouse-Geisser corrections ($p = 0.08$). In contrast, knee valgus moments did significantly differ ($p = 0.003$). Valgus moments were highest in the preplanned, late reactive, and late predisposed conditions (each did not differ from one another; $p > 0.72$), and significantly reduced ($p < 0.04$) in the early reactive and early predisposed conditions (which did not differ; $p = 0.33$). Stiffness, again, did not significantly differ between conditions ($p = 0.84$).

Discussion

This investigation was implemented to explore the effects of erroneous directional movement predisposition in reactive jump landings. This was designed to emulate late reversals in the decision-making process in response to a potentially deceptive opponent. As it was expected participants may implement this directional reversal via trunk inclination after the lower extremity was weight-bearing, it was expected these predisposed conditions would increase knee valgus moments and peak angles. This surprising directional change was also expected to increase sagittal plane knee joint stiffness. These injury risk factors and measures associated with performance are explored below.

Injury risk factors

Similar to our previous investigation, knee kinematics and kinetics generally changed in patterns recognized to indicate reduced neuromuscular control as the available time to react to the directional cue decreased to the instant of landing (Stephenson et al., 2018). Importantly, factors associated with ACL injury were altered depending on the direction of the subsequent jump. As this investigation only assessed the dominant limb, right and left jumps are more pertinently visualized as lateral and medial jumps to the limb of interest, respectively. In reactive conditions, ACL injury risk factors (Boden, Torg, Knowles, & Hewett, 2009; Koga et al., 2010; Krosshaug et al., 2007) generally decreased from early to late reactive conditions for medial jumps: Peak valgus angles decreased, and external flexion and valgus moments decreased. There was a significant increase in hip to knee flexion ratio, however, which may indicate increased injury risk given the same knee flexion angles (Hashemi et al., 2011). Lateral jumps demonstrated reduced knee flexion at PPGRF and an increase in external valgus moments, both potential indications of increased ACL injury risk (Hashemi et al., 2011; Owusu-Akyaw et al., 2018; Withrow, Huston, Wojtys, & Ashton-Miller, 2006). In a broad sense, these kinematic and kinetic results are comparable to our previous investigation (Stephenson et al., 2018).

A notable exception is found in the preplanned condition, however. In this investigation, results suggest the preplanned condition injury risk factors are more similar to late reactive conditions than early, a functional reversal compared to our previous research (Stephenson et al., 2018) and a corpus of literature comparing anticipated and unanticipated directional changes without stringent temporal controls (Almonroeder et al., 2015; Brown et al., 2014). We expect this is due to the inclusion of the predisposed conditions, which were initially indistinguishable from the preplanned condition at the start of the trial. This forced participants to delay their action in response to the directional cue until it was confirmed that it would not reverse; as the late predisposed condition reversed direction at landing from the initial jump forward, this effectively eliminated the preparatory value of the entire flight time in the initial anterior jump.

The increase in knee valgus collapse and external valgus moments in lateral jumps with late directional stimuli is likely due to the aforementioned latent lateral trunk inclination. As the direction in these conditions (and confirmation of the correct direction in the preplanned condition) occurs only once the lower extremity is loaded, this directional change is likely instigated via the trunk (Patla et al., 1999). From the perspective of the right lower extremity, trunk inclination to the right is likely to increase frontal plane knee joint loading as the center of mass proceeds laterally to the knee (Hewett & Myer, 2011). The opposite is also most likely true: In jumps to the left, the center of mass is likely to move further medial to the right knee, reducing external valgus moments. Exploration of trunk kinematic data from this and previous (Stephenson & Gillette, 2017; Stephenson et al., 2018) datasets appears to confirm this mechanism.

The primary concerns of the current investigation are the potential differences from the reactive to the predisposed conditions, however. In both lateral and medial jumps, kinematics and kinetics associated with ACL injury risk largely did not change between paired early and late reactive and predisposed conditions. Exceptionally, peak valgus angles did increase from late reactive to late predisposed conditions in lateral jumps, but this did not result in a paired increase in valgus moments. The trunk inclination mechanism described above therefore likely occurred in both late reactive and late predisposed conditions. Subsequent exploratory analysis indicated that some kinematic changes existed later during the landing phase, but as these are well outside of the critical time range immediately following landing (Dai et al., 2015; Koga et al., 2010), they are not expected to play a role in changing injury risk. As such, it appears that our hypothesis was not supported. It is possible that these later changes played a role in the alterations to performance measures between conditions in this study, however.

Performance measures

The identified change in performance measures between conditions also generally reflected our previous investigation's results (Stephenson et al., 2018). In both jump directions, delayed indications of the jump direction generally increased stance time. This likely represents a delay in requisite information processing and choice decision making in lieu of new or corrected directional cues (Miller & Clapp, 2011; Swanik, 2015). Interestingly in this investigation, the early predisposed condition often demonstrated the quickest stance time. This result may indicate that, unlike in the preplanned or late predisposed conditions, participants were given an early confirmation of the correct movement direction and could subsequently plan earlier for a faster movement. As the LED directional stimulus did not reverse twice in a trial, participants were effectively cued to the correct direction at the initiation of flight in the first jump. Even if a psychological refractory period did slow decision making (Broadbent & Gregory, 1967), it is possible that the flight time in the initial anterior jump was long enough to still allow adequate preparation for landing and subsequent performance.

Exit velocity off the ground between jumps was slower in the late reactive and late predisposed conditions compared to all others. Interestingly, medial jump exit velocity was lowest in the late predisposed condition. As the initial velocity in a jump is a dominating factor in jump performance (Komi & Bosco, 1978), these reductions in exit velocity suggest that erroneous movement direction predisposition may hinder an athlete's sports performance capability (Fujii, Yamashita, et al., 2014). In a pressing situation, this may be implemented by deceptive body movements intentionally to reduce an opponent’s performance and supersede their control of the field.

Implications

Multiple previous investigations have suggested that rapid opponent interactions on the field commonly result in ACL injury (Brophy et al., 2015; Waldén et al., 2015). These interactions, bound by rules of the particular game, often employ kinematic subterfuge (Brault, Bideau, Kulpa, & Craig, 2012; Smeeton & Williams, 2012; Wright & Jackson, 2014) that may result in an athlete erroneously assuming a movement direction close to loading from a forward bound or jump landing. We assumed late identification of the proper movement direction would play a role in increasing injury risk in this context, but it appears that this is not the case. Instead, all changes in ACL injury risk factors were associated only with the delay in the correct movement direction indication, whether this indication emerged from previous movement direction predisposition or not. A previous investigation analyzed pressing situations similar to that described above and concluded similarly: While injury often occurs in pressing situations, the source of this injury isn’t the athlete interaction itself but dangerous biomechanics that may or may not occur during pressing (Sasaki et al., 2018).

Results from the current investigation suggest that the increases in injury risk arise primarily from the delay in the presentation of the correct movement direction, which can potentially occur within and without close opponent interactions. It is possible that this places a novice sports player at increased injury risk, however (Fujii, Shinya, Yamashita, Oda, & Kouzaki, 2014). This delay may not only increase ACL injury risk in jumps lateral to the limb of interest but may also decrease immediate subsequent performance (Fujii, Yoshioka, et al., 2015). Undoubtedly the latter effect is beneficial for the opponent’s success and may be amplified in effective deceiving directional movements that require a movement correction medially.

These implications should not be accepted without caution, however. The movement and directional stimuli used in this investigation are contrived at best. Normal game situations may allow many alternative movement directions and strategies, as well as continuous sensory information utilized to reevaluate and plan potential movement alterations (Miller & Clapp, 2011). The overt, Boolean visual stimulus used in this investigation is potentially much less cognitively demanding and intentionally disables the capability of the participants from predicting directions. Other investigations have employed video directional stimuli of opponents that participants were required to react to with a directional change (Cortes, Blount, Ringleb, & Onate, 2011; Lee, Lloyd, Lay, Bourke, & Alderson, 2013), but the temporal control of this stimuli is questionable. As milliseconds may alter ACL injury risk factors (Stephenson, Zhu, & Dai, 2016), further research that better controls these information-rich visual stimuli is suggested.

This investigation only recruited female participants with sports experience that include rapid, reactive directional changes to increase the homogeneity of the recorded biomechanics. As female athletes are more likely to suffer from ACL injuries (Agel et al., 2005; Hootman et al., 2007) and are chronically underrepresented in injury prevention literature (Brookshire, 2016; Costello, Bieuzen, & Bleakley, 2014), we suggest that *starting* with female participants is a wise strategy. As such, we suggest that the potential effects of erroneous predisposition next be explored in male participants next, as the results of the current study may not generalize across the sexes, particularly given a potentially different injury pattern (Quatman & Hewett, 2009).

Conclusion

Previous assessments suggested that ACL injury risk may be amplified in rapid, reactive interactions with opponents in team sports. It has been well-established that these conditions are critical for sports performance, and deception is often employed to circumnavigate the opponent. Our investigation identified that erroneous directional movement predisposition itself, such that could occur from opponent deception, likely does not increase factors associated with ACL injury. Instead the simple delay in pertinent directional cues likely plays the dominant role. As such, if deception delays directional action closer to a loading event such as a jump landing, injury risk may increase. A decrease in movement performance parallels this effect. We suggest that this potential phenomenon be investigated with more complex visual stimuli that allows prediction that is less guaranteed to better represent on-field sports experience.

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CHAPTER 5. THE TIMING OF DIRECTIONAL CUE DIFFERENTIATION DETERMINES JUMP LANDING SAFETY AND PERFORMANCE WHEN UTILIZING CONTINUOUS VISUAL STIMULI

Abstract: The potential use of deception to mask an athlete's intended movements from their opponents in team sports has previously been associated with increased anterior cruciate ligament (ACL) injury risk. Visual sensory stimuli provide a wealth of directional cues that athletes can use to predict movement requirements, but previous research attempts to implement reactive directional changes simplify directional cues to simple, Boolean indications at a discrete point in time. This research compared this effect to a pseudo-continuous visual stimulus consisting of an array of directional cues, altering the probability of a movement direction during the performance itself. Results suggest that this complex cue does alter lower extremity control and performance, predominantly due to the change in timing of the differentiating cue. Similar to previous investigations, as participants were provided less time to react to the directional cue, their jump landing control and performance was altered. New evidence from this investigation also suggests that if the directional cue is reversed later in the movement that this may further alter frontal plane biomechanics associated with ACL injury. The directional cues in this investigation were still drastically simplified in comparison to available sensory cues; the potential ambiguity or conflicting cues may amplify this potential effect by further delaying correct identification. Further research is suggested, utilizing continuous directional cues that include more sensory information that are still precisely temporally controlled.

Introduction

Team sports often offer a diverse on-field experience as strategically-placed players advance and defend portions of the field or court in preparation and reaction to opponents (Fujii, Isaka, Kouzaki, & Yamamoto, 2015). Often these tactics demand rapid decision making that becomes complicated by deceptive cues from opponent body postures, footwork, and gaze (Smeeton & Williams, 2012; Wright & Jackson, 2014). In these contexts, the successful evaluation of the opponent determines an athlete's success in the play or game (Fujii, Shinya, Yamashita, Oda, & Kouzaki, 2014a; Fujii, Yamashita, Kimura, Isaka, & Kouzaki, 2015). Feature-rich visual information can provide a wealth of pertinent and potentially distracting information (Miller & Clapp, 2011).

Previous researchers have suggested that these reactive interactions between players may play a role in anterior cruciate ligament (ACL) injury risk (Almonroeder, Garcia, & Kurt, 2015). Video analysis demonstrated that pressing and defending situations in multiple sports increases factors associated with ACL injury (Brophy, Stepan, Silvers, & Mandelbaum, 2015; Waldén et al., 2015). As ACL injury is a prevailing epidemic (Agel, Rockwood, & Klossner, 2016; Beck, Lawrence, Nordin, DeFor, & Tompkins, 2017) that often causes long-term musculoskeletal complications in athletes (Lohmander, Englund, Dahl, & Roos, 2007), further investigation of injury risk in this reactive context is well-warranted.

These player-on-player contexts demand rapid decision-making that has previously been associated with increased injury risk (Almonroeder et al., 2015; S. R. Brown, Brughelli, & Hume, 2014). Our own investigations demonstrated that the precise timing of directional cues play a role in the specific injury risk, whereas less available time to react before lower extremity loading from a jump landing undermines neurocognitive control and increases risk

(Stephenson & Gillette, 2018; Stephenson et al., 2018; Stephenson, Zhu, & Dai, 2016). The vast majority of this reactive task literature, including our own, employed simplistic directional cues such as lights and arrows to indicate movement directional changes at discrete points in time (Almonroeder et al., 2015; S. R. Brown et al., 2014). This methodology is simple to implement and control in lab-based contexts, but previous research has demonstrated that it may alter the estimation of ACL injury risk factors compared to video-based cues from a recorded opponent (Lee, Lloyd, Lay, Bourke, & Alderson, 2013).

Some previous research employed video directional cues in rapid, reactive directional change investigations of ACL injury risk. The general results, if not the specific magnitudes of the measured factors, agree with more simplistic visual cues: Reactive conditions that demand some level of choice decision making increases injury risk (Cortes, Blount, Ringleb, & Onate, 2011; Lee et al., 2013; Lee, Lloyd, Lay, Bourke, & Alderson, 2019). But the particular injury factors did not change in a systematic way between these video directional cues and other simplified implementations. In fact, across the body of reactive ACL injury literature, there is some ambiguity to the precise effects of reactive conditions on ACL injury risk factors (Almonroeder et al., 2015): Many results partially or entirely conflict. Many of these investigations explored these reactive effects in slightly different populations with different methodological approaches. We proposed that much of the ambiguity in this body of literature is due to the lack of precise timing of the directional cues within a critical reaction time window (Stephenson et al., 2018, 2016): Our previous results demonstrated that milliseconds of change in the presentation of the directional cue, particularly within the requisite choice reaction time period before landing from a jump (Hick, 1952; Stephenson et al., 2016), can significantly alter ACL injury risk factors (Stephenson et al., 2018).

Simplified directional cues, such as lights and arrows can be relatively easily temporally controlled, but video cues may be more difficult to quantify, as the presentation and evaluation of these cues is dependent on the recorded "opponent" and the participant's perceptual capabilities (Fujii, Shinya, Yamashita, Oda, et al., 2014a; Miller & Clapp, 2011). The latter alone can delay effective cue identification by 360 ms (Fujii, Shinya, Yamashita, Oda, et al., 2014a), which may significantly alter ACL injury risk factors (Stephenson et al., 2018). Yet these video directional cues offer participants two affordances that simplified cues generally do not: A degree of ambiguity in the probability of the directional cue indicating a movement direction, and a capability of the participant using early sensory information to predict later directional cues (Abernethy, 1990; Fujii, Shinya, Yamashita, Kouzaki, & Oda, 2014; Fujii, Shinya, Yamashita, Oda, et al., 2014a; Miller & Clapp, 2011). If pertinent directional cues, or precursor indications of these cues, are perceived earlier in an injury-prone directional movement, this may alleviate the risk of injury compared to situations where these cues are perceived later and closer to lower extremity musculoskeletal loading (Stephenson et al., 2018). Our previous investigation (Chapter 4) demonstrated that cues simplified to a discrete, Boolean representation may not be perceived as valuable predictors if there was a probability of the cues being incorrect.

In order to elucidate whether more informationally-rich directional cues do significantly alter ACL injury risk factors, precise temporal controls of the directional cues are necessary. This investigation sought to explore this potential effect in a controlled manner with simplified, pseudo-continuous visual cues (Figures 5.1-4) that were precisely temporally controlled. These cues were designed to provide early or late differentiation of the requisite movement direction and were compared to discrete reactive conditions found in previous literature. As our previous investigation indicated that the timing of the correct directional cue instead of whether that cue was initially correct played a dominant role in ACL injury risk factors (Chapter 4 of this dissertation), we hypothesized that the timing of when these pseudo-continuous cues could be differentiated would play a similar role. Notably, if the cues could not be differentiated until later in the movement (Figures 5.2-3, referred to as the 2nd and 3rd patterns) as the participant neared the instant of lower extremity loading, this would compromise the safety of landing and subsequent neuromuscular control. This would, in effect, increase factors associated with ACL injury risk and decrease movement performance.

Methodology

This investigation relied on a within-participants, repeated measures design to explore the potential effects of pseudo-continuous directional cues as an analog to continuous evaluation of sensory data in an estimation and prediction of subsequent directional movement in team sport settings. The methodological approach was intentionally designed to provide partial overlap with previous studies in the tested conditions to provide basic validation and comparison capabilities. Data were collected in the Biomechanics Lab of the Kinesiology Department at Iowa State University. To comply with Federal and institutional requirements, the university's Institutional Review Board approved this investigation before data collection began (see Appendix).

Participants

In accordance with the hypothesized results, the specific pseudo-continuous conditions investigated in this study were expected to create similar effects in lower extremity kinematics and kinetics that were found in early and late reactive conditions previously explored by other research (Stephenson et al., 2018). The moderate effect sizes in these investigations (Stephenson & Gillette, 2018; Stephenson et al., 2018) suggested a minimum of 19 female participants would be necessary to explore these potential effects while maintaining statistical power of 80% with a Type I error rate of 5%. As such, 13 participants were recruited (mean ± standard deviation: 20.2 ± 1.4 years; 64.1 ± 9.7 kg; 1.64 ± 0.08 m) as part of this ongoing study. Participants were required to be free of recent musculoskeletal injury or concussion and participate in a minimum of 150 minutes of moderate or 75 minutes of intense physical activity per week. Furthermore, this activity was required to include sports participation that included rapid directional changes in an open, reactive environment, such as is demonstrated in soccer, basketball, volleyball, tennis, etc.

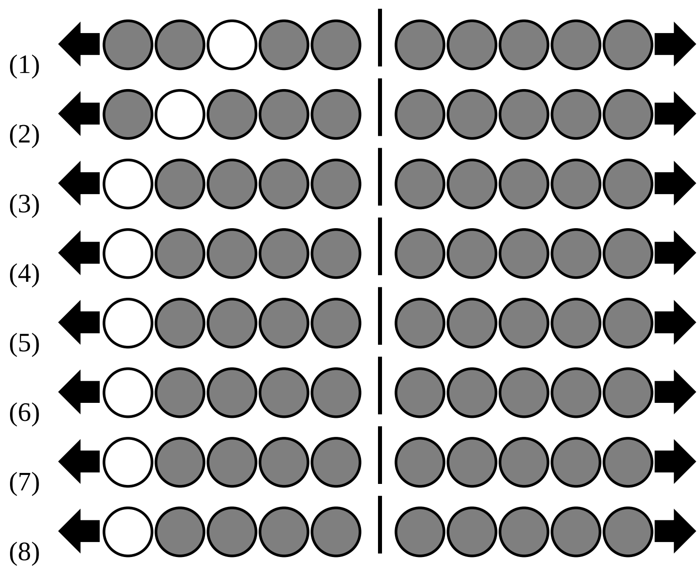


Figure 5.1*: Continuous 1. Example of serial (phases 1-8) LED display utilized as a pseudo-continuous directional cue, with one illuminated LED indicating to jump to the left (medial to the right knee). This pattern decreases probability of directional change early in the maneuver by "moving" away from the centerline and holding this position throughout the flight of the initial anterior jump.*

Protocol

During a single data collection session, participants completed a standardized warmup and performed the following protocol after multiple practice bouts. Utilizing a similar jump-landing task to other investigations (Stephenson et al., 2018), participants stood on a 30 cm tall block instrumented with a force platform (Advanced Mechanical Technologies, Inc. Watertown, MA, USA). Once the participant was ready, they jumped anteriorly a distance equal to 50% of their body height, landing on force platforms mounted flush with the ground. Prioritizing both the speed of the movement and the jump distance of the subsequent jump, they then jumped to the left or right at an angle marked on the ground 60° lateral to the anterior.

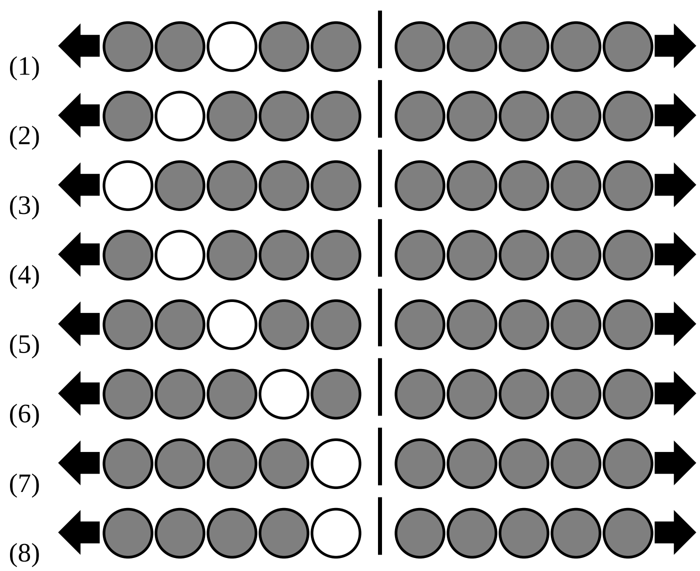


Figure 5.2*: Continuous 2. Example of serial (phases 1-8) LED display utilized as a pseudo-continuous directional cue, with one illuminated LED indicating to jump to the left (medial to the right knee). This pattern decreases probability of directional change early in the maneuver by "moving" away from the centerline and then increases the subsequent probability later without changing direction.*

The direction of the second jump was indicated to the participant by light-emitting diodes (LEDs) mounted in an array in front of the jumping area indicating the respective jump direction during the initial jump forward. The array consisted of ten identical LEDs mounted in a horizontal line, with a 5 cm gap between the left and right five LEDs. This visual stimulus was controlled by an Arduino Mega 2560 Rev3 board that monitored the vertical analog signals from the in-ground and block force platforms to estimate the discrete time periods of takeoff and landing of the initial anterior jump. Pilot and simulation data indicated the system was temporally accurate within 1 ms of any event and illuminated the LED stimuli within a subsequent millisecond.

Two discrete visual cueing conditions were tested, similar to previous investigations (Stephenson et al., 2018). In the **early reactive condition**, a single LED was illuminated in the middle of the five LEDs on the respective intended jump direction side of the LED array at the instant the participant left the 30 cm tall block. Similarly, a single LED was illuminated at the instant the participant landed on the in-ground force platforms in the **late reactive condition**. These discrete conditions contrasted to the pseudo-continuous cueing tested in the remaining four conditions. In these conditions, the same middle LED on one side of the array was illuminated. This LED was extinguished, and the next immediate neighboring LED was illuminated; in this way, a pattern of "movement" was simulated on the LED array.

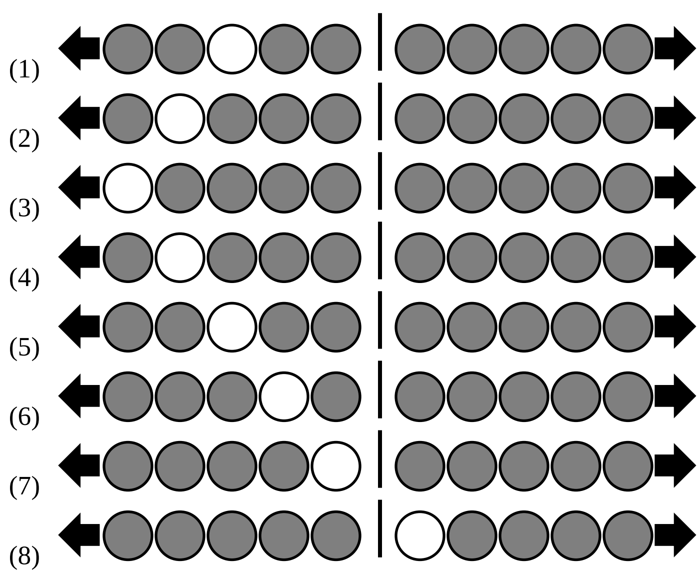


Figure 5.3*: Continuous 3. Example of serial (phases 1-8) LED display utilized as a pseudo-continuous directional cue, with one illuminated LED indicating to jump to the right (lateral to the right knee). This pattern decreases probability of directional change early in the maneuver by "moving" away from the centerline and then increases the subsequent probability later and ultimately reverses the direction indicated by crossing the centerline.*

The transition rate between LEDs in the **four pseudo-continuous conditions** was fixed at 12.5% of the estimated flight time of the initial jump forward. A weighted average of the previous pseudo-continuous conditions was used to estimate flight time; practice trials were used to seed this estimation for the initial trials (Stephenson et al., 2018). It should be noted that these pseudo-continuous conditions (Figures 5.1-4) were constrained in two explicit fashions: The direction of "travel" could not reverse more than once, and "movement" would not start again after it was halted. With these constraints and constant "velocity" participants were potentially capable of estimating the terminally-indicated jump direction with early pattern recognition. The 4th pattern was designed to be easily differentiated from the other conditions by 12.5% of the flight time, while patterns 2 and 3 were designed to undermine this capability by differentiating the terminal movement direction near the instant of landing (87.5% of flight time). The first pattern initiated similarly to the 2nd and 3rd, but was easily differentiable by 37.5% of the flight time. Nonetheless, participants were expected to jump in the *last* indicated jump direction independent of the displayed pseudo-continuous pattern. It was suggested to all participants that waiting for this late indication would inhibit the requisite performance and was therefore not recommended.

Participants completed three trials of each condition for each jump direction, totaling 36 successful trials. The displayed patterns in the pseudo-continuous conditions were mirrored for the other jump direction. Approximately three "catch" trials were randomly inserted into the tested conditions, whereas no LED was illuminated, or all LEDs were extinguished, during the performance and the participant was expected to not initiate the second, lateral jump. All trials were separated by a minimum of 30 seconds rest (Oliveira et al., 2019). The order of testing was double-blind randomized by the Arduino Mega 2560 using a Durstenfeld shuffle (Durstenfeld, 1964). In cases where a trial was performed erroneously, the condition in question was randomly re-inserted into the remaining trials. If this occurred near the end of the data collection, a random additional condition was additionally randomized into the remaining trials to preserve unpredictability.

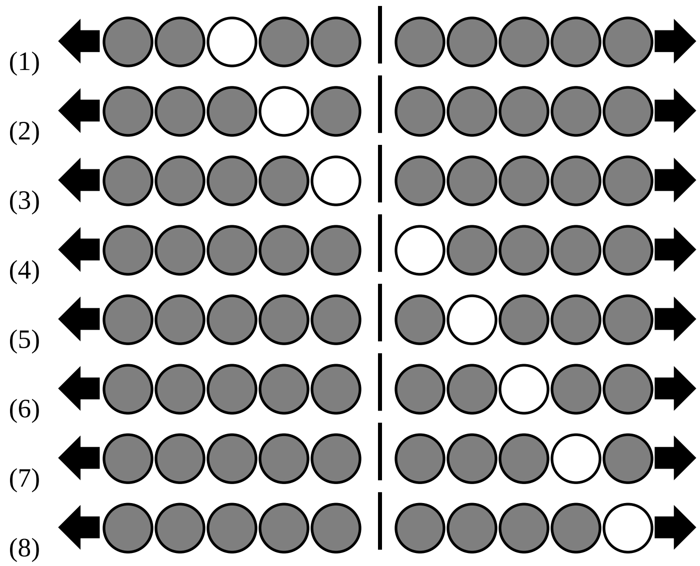


Figure 5.4*: Continuous 4. Example of serial (phases 1-8) LED display utilized as a pseudo-continuous directional cue, with one illuminated LED indicating to jump to the right (lateral to the right knee). This pattern increases the probability of directional change early in the maneuver by "moving" towards the centerline and then decreases the subsequent probability by moving away from the centerline on the opposite side. Its distinguishable start was implemented to contrast to the other conditions, which utilized identical initial phases.*

Trial performance was monitored kinematically via 19 retroreflective markers placed on the pelvis and dominant foot, shank, and leg. Eight Vicon cameras (Vicon Motion Systems Ltd, Oxford, UK) recorded the three-dimensional locations of these markers at 160 Hz. Ground reaction forces during the landing between jumps were recorded via the in-ground force platforms at 1600 Hz. These kinematic and kinetic data were synchronized and recorded with Vicon Nexus 1.8.5 on a personal computer.

Analysis

Post processing was performed with a custom Matlab script (R2019a, Mathworks, Inc. Natick, MA, USA). Data were filtered with a 4^{th}-order recursive Butterworth lowpass filter at 15 Hz for kinematic data and 200 Hz for kinetic data (Yu, Gabriel, Noble, & An, 1999). Anatomical segment positions were used to estimate joint angles in the lower extremity; baseline angles calculated from a static, standing posture were used to estimate neutral for each participant. Cardan joint angles were calculated using a sagittal, frontal, and then transverse rotation order (Grood & Suntay, 1983). These data were then combined with anthropometric measurements to estimate the three dimensional inertial and center of mass kinematics (de Leva, 1996). Finally, these estimations were utilized, in combination with the ground reaction kinetics, to calculate lower extremity joint moments via a bottom-up inverse dynamics technique.

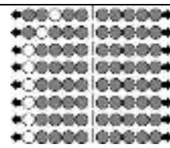
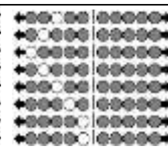
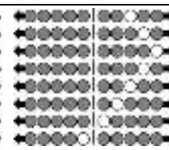
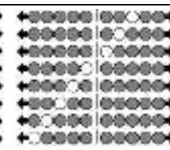
To reflect both potential changes in ACL injury risk factors and performance variables, multiple kinematic and kinetic measures were analyzed. Previous research indicated that ACL injury often occurs within the first 50 ms of landing from a jump (Dai, Mao, Garrett, & Yu, 2015; Koga et al., 2010); a peak in the posterior ground reaction force (PPGRF) generally occurs in this time range and is associated with anterior translation of the proximal tibia from the femur and subsequent ACL loading (Lin et al., 2009; Sell et al., 2007; Yu, Lin, & Garrett, 2006). Further literature suggests that ACL loading occurs in landings with relatively little knee flexion and a stiff knee joint with incompatible hip and knee flexion velocities (Hashemi et al., 2011; Owusu-Akyaw et al., 2018). When this occurs, valgus collapse may follow, further increasing ACL injury risk (Dai et al., 2015; Hashemi et al., 2011; Koga et al., 2010; Krosshaug et al., 2007). As such, knee flexion angles and external flexion moments were identified at the instant of PPGRF, as well as the ratio of hip joint flexion velocity to knee joint flexion velocity. Knee joint stiffness was calculated as the change in internal extension moments divided by the change in knee flexion angle from the instant of landing until PPGRF. Peak valgus angles and external valgus moments were then identified within 50 ms after PPGRF. Stance time on the ground between jumps, as well as the resultant velocity of the mean of the five pelvis markers at the instant the participants left the force platforms for the second jump were assessed to reflect changes in movement performance (Dai et al., 2019).

These dependent measures were statistically explored via a 6x1 repeated measures analysis of variance for each jump direction. The assumption of sphericity was verified with Mauchly's test; in situations where this assumption was violated, Greenhouse-Geisser corrections were performed. After potential corrections, significant ($p < 0.05$) main effects were then explored with pairwise t-tests; study wise significance levels were corrected with the false discovery rate methodology (Benjamini & Hochberg, 1995).

Results

Results within this section are reported as means (standard error) for each variable and condition. Where appropriate, Greenhouse-Geisser and false discovery rate corrections have already been applied to the presented p-values, facilitating direct comparison with the Type I error rate cutoff of 0.05. As the timing of the presented signals was forward estimated from previous performances and flight time between participants and between trials could hypothetically vary, there is some temporal error in the timing of relevant visual cues used to differentiate the continuous patterns. These temporal errors are summarized in Table 5.1 below. No differences in timing were statistically significant ($p > 0.64$) between any conditions.

Table 5.1: Mean (standard error) of flight time, relevant cue times from landing, and estimation errors per condition for both combined jump directions.

	Early Reactive	Late Reactive	 Continuous 1	 Continuous 2	 Continuous 3	 Continuous 4
Flight time (ms)	352 (5.6)	353 (5.4)	347 (5.5)	348 (5.6)	349 (5.6)	352 (5.6)
Cue Time (ms)						
12.5 % Flight	N/A	N/A	304 (5.5)	304 (5.6)	306 (5.6)	308 (5.6)
37.5 % Flight	N/A	N/A	217 (5.5)	217 (5.6)	219 (5.6)	220 (5.6)
87.5% Flight	N/A	N/A	43 (5.5)	43 (5.6)	44 (5.6)	44 (5.6)
Error (ms)	N/A	N/A	-1.8 (1.1)	0.1 (0.9)	-1.8 (0.9)	-7.7 (1.2)

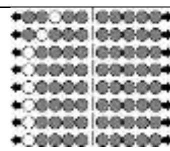
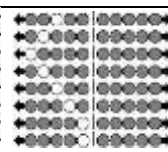
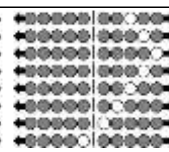
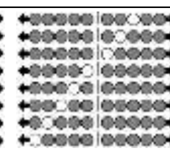
Injury risk factors

Jumps medial to the dominant limb did not demonstrate significant main effects for knee flexion angles at PPGRF ($p = 0.37$) but did for peak valgus angles ($p = 0.03$). The PPGRF occurred an average of 17 (3) ms after initial contact with the ground; this timing did not significantly differ between jump conditions or directions ($p > 0.4$). As seen in Table 5.2, the early reactive condition resulted in the largest knee valgus angles, which did not significantly differ from the 2nd or 4th continuous patterns ($p > 0.66$); the late reactive, as well as the 1st and 3rd continuous patterns resulted in significant reductions in valgus angle, however ($p < 0.043$). The late reactive, 1st, 2nd, and 4th continuous patterns did not significantly differ ($p > 0.09$), but the 3rd continuous pattern was significantly lower than all others ($p < 0.047$). The ratio of hip flexion angular velocity to knee flexion angular velocity did not significantly differ between conditions, ($p = 0.061$).

External knee flexion moments did not significantly differ ($p = 0.39$) between conditions in lateral jumps, but external valgus moments did ($p < 0.001$). The early reactive condition demonstrated similarly large ($p > 0.09$) valgus moments to the 1st, 2nd, and 4th

continuous pattern conditions, and were significantly larger ($p < 0.04$) than the moments in the late reactive and 3rd pattern conditions. The late reactive condition did not significantly differ ($p > 0.272$) from any continuous condition, but the 1st, 2nd, and 4th patterns were significantly larger ($p < 0.048$) than the 3rd. Knee joint stiffness also significantly differed ($p = 0.019$) across conditions: The early reactive condition demonstrated a significantly higher stiffness ($p < 0.046$) than all conditions except the 4th continuous pattern ($p = 0.203$). The 4th pattern did not significantly differ from the other conditions, which were also not significantly different from one another ($p > 0.202$).

Table 5.2: Mean (standard error) of kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across reactive and pseudo-continuous conditions in jumps medial to the dominant limb.

	Early Reactive	Late Reactive	 Continuous 1	 Continuous 2	 Continuous 3	 Continuous 4
Kinematics						
Flexion (°)	25.6 (2.1)	27.9 (2)	29.0 (2.7)	26.5 (2.1)	30.1 (2.2)	28.7 (3.4)
Valgus (°)	11.1 (1.7)^{A}	9.0 (1.8)^{B}	9.7 (1.6)^{B}	10.8 (1.9)^{AB}	7.7 (1.7)^{C}	10.9 (1.7)^{AB}
Hip/Knee Ratio (%)	0.20 (0.08)	0.32 (0.06)	0.29 (0.06)	0.23 (0.05)	0.32 (0.05)	0.25 (0.07)
Kinetics						
Flexion (Nm/kg)	1.36 (0.22)	1.27 (0.21)	1.34 (0.26)	1.15 (0.21)	1.29 (0.24)	1.50 (0.24)
Valgus (Nm/kg)	0.87 (0.17)^{A}	0.59 (0.17)^{BC}	0.74 (0.21)^{AB}	0.84 (0.16)^{AB}	0.51 (0.21)^{C}	0.73 (0.21)^{AB}
Stiffness (Nm/kg/°)	27.6 (5.4)^{A}	16.0 (2.6)^{B}	15.9 (2.4)^{B}	17.9 (3.4)^{B}	16.8 (3)^{B}	18.2 (3.6)^{AB}
Performance						
Stance Time (ms)	410 (33)^{C}	624 (39)^{A}	446 (35)^{C}	568 (42)^{AB}	538 (30)^{B}	430 (32)^{C}
Velocity (m/s)	2.2 (0.2)^{A}	2.0 (0.2)^{B}	2.2 (0.1)^{A}	1.9 (0.2)^{B}	1.9 (0.2)^{B}	2.2 (0.1)^{A}

Statistically significant differences indicated as A>B>C at false discovery rate-adjusted Type I error no more than 5%.

In lateral jumps, knee flexion angles also did not significantly differ between conditions ($p = 0.86$), but valgus angles again did ($p < 0.010$). Results are presented in Table 5.3. The 3rd pattern demonstrated the largest valgus angles compared to other conditions ($p < 0.0372$), excepting the 4th pattern condition ($p = 0.219$). The 4th pattern was not statistically significantly different than any condition ($p > 0.107$) except the early reactive condition ($p = 0.046$). While the late reactive condition demonstrated significantly larger knee valgus angles than the early reactive condition ($p = 0.046$), the 1st and 2nd patterns did not ($p > 0.180$). The ratio between hip and knee flexion velocities did not significantly differ between conditions ($p = 0.22$).

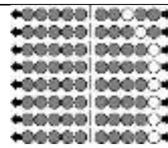
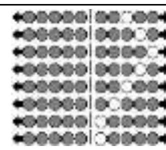
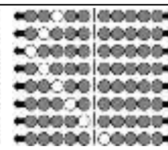
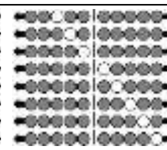
Similar to medial jumps, lateral jump external knee flexion moments did not significantly differ between conditions ($p = 0.30$), but external knee valgus moments did ($p = 0.003$). Valgus moments were similarly high ($p > 0.103$) between all conditions except early reactive, which was significantly less ($p < 0.043$) than the late reactive, 1st, 3rd, and 4th continuous patterns but not different from the 2nd pattern ($p = 0.174$). Unlike medial jumps, knee joint stiffness did not significantly differ between conditions ($p = 0.768$) in jumps lateral to the dominant limb.

Performance measures

Performance measures changed relative to the condition in both jump directions. In medial jumps (presented in Table 5.2), stance time was fastest in the early reactive, 1st, and 4th continuous patterns (these conditions did not significantly differ; $p > 0.21$) compared to all others ($p < 0.008$). The late reactive condition demonstrated the slowest stance time, similar to the 2nd continuous pattern ($p = 0.15$), but significantly slower than all others ($p < 0.02$). The 3rd continuous pattern did not significantly differ from the 2nd ($p = 0.51$) but was significantly different than all others ($p < 0.02$). Exit velocity also demonstrated a significant main effect ($p < 0.002$), whereas the early reactive, 1st, and 4th patterns demonstrated similarly ($p > 0.17$) significantly faster velocities ($p < 0.045$) than the late reactive, 2nd, and 3rd patterns (which were similar; $p > 0.90$).

Interestingly, stance time did not significantly differ for jumps lateral to the tested limb ($p = 0.156$). Exit velocity did significantly differ ($p < 0.001$), following a similar pattern of change as the medial jumps: The early reactive, 1st, and 4th patterns were not significantly different ($p > 0.180$), but were significantly faster ($p < 0.042$) than the late reactive, 2nd, and 3rd patterns (which did not significantly differ ($p > 0.121$). These results are presented in Table 5.3.

Table 5.3: Mean (standard error) of kinematic and kinetic variables associated with ACL injury risk, as well as performance factors across reactive and pseudo-continuous conditions in jumps lateral to the dominant limb.

	Early Reactive	Late Reactive	 Continuous 1	 Continuous 2	 Continuous 3	 Continuous 4
Kinematics						
Flexion (°)	27.9 (2.4)	25.8 (2.0)	26.3 (1.0)	27.6 (1.7)	25.6 (2.2)	27.5 (1.6)
Valgus (°)	6.1 (2.1)^{C}	7.9 (2.0)^{B}	6.4 (1.6)^{BC}	7.6 (1.9)^{BC}	9.6 (1.7)^{A}	8.2 (2.2)^{AB}
Hip/Knee Ratio (%)	0.29 (0.05)	0.28 (0.06)	0.24 (0.06)	0.30 (0.05)	0.23 (0.04)	0.29 (0.05)
Kinetics						
Flexion (Nm/kg)	0.86 (0.09)	1.19 (0.16)	1.02 (0.20)	1.21 (0.17)	1.06 (0.18)	0.93 (0.11)
Valgus (Nm/kg)	0.48 (0.16)^{B}	0.69 (0.18)^{A}	0.61 (0.17)^{A}	0.59 (0.19)^{AB}	0.69 (0.17)^{A}	0.61 (0.18)^{A}
Stiffness (Nm/kg/°)	19.2 (2.6)	17.0 (2.7)	20.0 (2.0)	16.7 (3.3)	17.2 (2.9)	16.9 (2.7)
Performance						
Stance Time (ms)	434 (37)	507 (45)	436 (41)	436 (41)	459 (42)	436 (41)
Velocity (m/s)	1.8 (0.2)^{A}	1.3 (0.2)^{B}	1.7 (0.2)^{A}	1.1 (0.3)^{B}	1.4 (0.2)^{B}	1.7 (0.3)^{A}

Statistically significant differences indicated as A>B>C>D at false discovery rate-adjusted Type I error no more than 5%.

Discussion

The current investigation sought to explore the potential effects of pseudo-continuous visual cues on lower extremity control and ACL injury risk in rapid jump landing motions. As these patterned responses could potentially provide earlier cues that participants could use to predict the subsequent movement direction, it was expected that the continuous conditions with early differentiable cues (notably the 4th and subsequently the 1st pattern conditions) would exhibit reduced ACL injury risk factors in comparison with continuous conditions that were only differentiable later in the movement (the 2nd and 3rd pattern conditions). Assessment of the temporal estimation of flight times, and the subsequent timing of distinctive phases between the pseudo-continuous cues illustrate an acceptable level of temporal precision that did not differ between conditions (Table 5.1).

Injury risk factors

The early and late reactive conditions included in this investigation are similarly implemented in our previous study (Stephenson et al., 2018). Like this investigation, reducing the available time to react to the directional cue before the instant of landing created different results depending on the jump direction of interest. When jumping laterally to the limb of interest, peak valgus angles effectively increased; medial jumps resulted in a functional decrease in peak valgus angles. Similarly, jumping lateral to the dominant limb increased external valgus moments in the late reactive condition and jumping medially created the opposite effect. These results can be interpreted as effectively increasing and decreasing ACL injury risk, respectively (Koga et al., 2010; Krosshaug et al., 2007; Quatman & Hewett, 2009). This frontal plane alteration may be caused by a latent trunk inclination to initiate movement directional changes after the lower extremity is weight-bearing (Fujii, Shinya, Yamashita, Kouzaki, et al., 2014; Hewett & Myer, 2011; Patla, Adkin, & Ballard, 1999). A previous investigation that utilized video cueing identified a similar effect (Lee et al., 2013).

Unlike our previous investigation, the current results did not identify significant changes in knee flexion angles or external flexion moments between conditions. One of the few other investigations to manipulate the presentation timing of directional cues also did not identify a significant change in the sagittal plane (Brown, Palmieri-Smith, & McLean, 2009), but it should be noted that this may be due to the manipulation of the cues occurring outside of the pertinent range for the given task (Hick, 1952; Stephenson et al., 2016). Sagittal plane knee joint stiffness in medial jumps does appear to be reduced in later reactive conditions, however; this may have performance implications, discussed later in this section. A reduction in joint stiffness may reduce injury risk (Hashemi et al., 2011), and may be driven by an increase in knee flexion range of motion during the landing (Stephenson et al., 2018). This may have been caused by a “wait-and-see” approach by the participants, whereas they did not inhibit a deeper jump landing with more knee flexion until confirming the requisite movement direction (Cortes et al., 2011).

Unique to the current investigation, pseudo-continuous conditions created differing biomechanical responses. In medial jumps, the 3rd pattern significantly reduced peak knee valgus angles compared to the other conditions. This condition initially indicated an increased probability of a lateral jump and was not distinguishable from the 2nd pattern for lateral jumps until less than 50 ms before landing; it is likely that participants were not capable of enacting neuromuscular control in response to this cue within the first 50 ms of landing (Hick, 1952). A similar but opposite effect is seen in the 3rd pattern for lateral jumps; the peak knee valgus angle is more closely related to medial jumps instead of lateral. External knee valgus joint moments follow a similar response: The pseudo-continuous cues that are directionally differentiated from other cues later in the movement are akin to the other pseudo-continuous cues of the opposite movement direction. Overall, this may aggravate ACL injury risk in jumps lateral to the knee of interest (Krosshaug et al., 2007).

Performance measures

As the manipulation of the presentation of directional cueing by opponents is likely intended to mitigate the performance of an athlete instead of their injury risk, performance measures were also assessed across conditions. We previously identified that a reduction in the time between the directional cue and landing increased stance time between jumps (Stephenson et al., 2018); interestingly in this investigation, this only occurred in jumps medial to the dominant limb. This may be related to the reduction in joint stiffness for this jump direction. Stance time was also significantly reduced in the pseudo-continuous pattern conditions that cued the movement direction earlier in the movement (the 1st and 4th pattern). The exit velocity from the ground between jumps, otherwise viewed as the initial velocity in the second jump, is a defining component of the second jump's performance (Komi & Bosco, 1978). Similar to our previous analyses, performance effectively decreased as the directional cues were presented later; this was apparent in both jump directions for both discrete and pseudo-continuous cues. As the 2nd and 3rd patterns could only be differentiated within 50 ms of landing, performance was inhibited similarly to the late reactive condition. In all three conditions, this effect is likely due to a loss of plyometric capability in lieu of delayed information processing and decision making (Miller & Clapp, 2011). Similar to a previous investigation, our results suggest that the parsimonious consideration of early correct directional cue identification dominates performance capabilities instead of erroneous or mismatched assumptions altering performance (Fujii, Shinya, Yamashita, Oda, et al., 2014a).

Implications

The interactions of opposing athletes on sports fields is likely to include some level of deception (Fujii, Isaka, et al., 2015). Employed effectively, this delays the recognition of pertinent directional cues and likely decreases the performance of the opponent (Smeeton & Williams, 2012; Wright & Jackson, 2014). Our results from multiple investigations demonstrate that this may increase injury solely due to the delay in identifying an actionable directional cue (Stephenson & Gillette, 2018; Stephenson et al., 2018). These current results suggest a subsequent effect: Contexts where the directional cues reverse the necessary movement direction may further alter lower extremity control and the capability of the athlete to customize their movement to the demanded direction. This does not inherently amplify ACL injury risk factors over the effect of the delayed directional cue identification, however. As such, our hypothesis pertaining specifically to injury risk was effectively not supported.

Previous literature suggested that these athletic opponent interactions may increase ACL injury risk (Brophy et al., 2015; Waldén et al., 2015), as both injury and amplified injury risk factors are often identified in these contexts. This may not explicitly be the case (Sasaki, Koga, Krosshaug, Kaneko, & Fukubayashi, 2018). Instead, any mechanism or action that delays an athlete's identification of a movement direction may alter risk, and the continual evaluation of potential cues may only further impact these factors if the directional cue demands a relatively late movement direction reversal. Our results indicate this may only reduce risk in medial movements. This may suggest that athletes do not always perform a neutral, "default" movement until absolute confirmation of a correct directional cue (Stephenson et al., 2018; van Sonderen & Denier van der Gon, 1991), and instead may attempt to customize the preparatory movements to a probable movement direction (David, Mundt, Komnik, & Potthast, 2018; Fujii, Yamashita, et al., 2015).

These results suggest that any factor that may modify functional choice response time in the perception, decision making, or response execution phases of motor control may modulate ACL injury risk. Interestingly, athletes with ACL injuries often demonstrated delayed reaction time in simplified tests outside of sport contexts (Swanik, Covassin, Stearne, & Schatz, 2007). But simple neuromuscular fatigue can also increase reaction time and undermine cognitive attentional resources (Stephenson, Ostrander, Norasi, & Dorneich, 2019), which may impact this perception and action performance capability. Finally, the capability of athletes to perceive relevant directional cues may be a function of their specific sports experience (Abernethy, 1990; Fujii, Shinya, Yamashita, Oda, & Kouzaki, 2014b), which may provide athletes an opportunity to improve response time and reduce the risk of undermining lower extremity control.

Interestingly, the novel use of pseudo-continuous cues did identify different results than our previous attempts to explore erroneous movement direction predisposition with discrete cues (Chapter 4). The discrete cues effectively stimulated no significant differences in injury risk factors compared to the more simplistic temporal presentation manipulation. The results of the current investigation do suggest that this erroneous predisposition may impact frontal plane biomechanics, but only if continual visual cueing is evaluated. This may be indicative of the value of more complex visual stimuli that create both some ambiguity in the indicated requisite movement direction and some capability to utilize advance cues in prediction (Miller & Clapp, 2011). As kinematic and kinetic changes outside of the first 50 ms of jump landing is likely not pertinent to ACL injury risk (Dai et al., 2015; Koga et al., 2010), this investigation did not analyze these subsequent results. Preliminary exploration does suggest that other changes may occur later in the landing and may be of interest for other lower extremity injuries.

It should be noted that the current investigation's implementation of pseudo-continuous directional stimuli is still appreciably bereft of information-rich visual cues that could be used to assess the probability of a particular movement direction. Under normal sport circumstances, an opponent is likely to provide multiple cues through their direction of gaze, body orientation, ball manipulation, and other kinetics; if these cues include deception, conflicting information may need to be evaluated (Brault, Bideau, Kulpa, & Craig, 2012; Smeeton & Williams, 2012; Wright & Jackson, 2014). An athlete can utilize these cues in combination with larger, field-level player positions to create a more accurate estimation of the movement direction. The visual cues of this study sacrificed information richness for the sake of temporal control, and this may undermine its veracity in sports performance. Notably, it may neutralize the value of expertise in differentiating movement direction earlier (Fujii, Shinya, Yamashita, Oda, et al., 2014a). The specific jump landing task employed in the current investigation may also have limited the participants' capability to customize their response to the stimuli (David et al., 2018; Dos'Santos, McBurnie, Thomas, Comfort, & Jones, 2019). Participants may have preferred alternative movement changes or foot placements incompatible with the constraints of the landing area due to the size of the force platforms. We qualitatively identified that participants performed more movement errors, notably by landing with their foot placed off the force platform and requiring the trial to be repeated, only in conditions with early presentation of the directional cue. It may be valuable to identify if force platform size inhibits preferred movement patterns in some conditions.

The current investigation only explored the potential effects of pseudo-continuous stimuli in female athletes with sports experience related to the reactive task. As male participants may demonstrate a different ACL injury mechanism dominated by sagittal plane factors (Quatman & Hewett, 2009) and have demonstrated differences in neurocognitive information processing that may be pertinent to this task (Laguë-Beauvais, Gagnon, Castonguay, & Bherer, 2013), we suggest that exploring this effect in males would also be valuable. Furthermore, it is possible that varying levels of sports experience may modulate perception and motor control capabilities (Abernethy, 1990; Fujii, Shinya, Yamashita, Oda, et al., 2014a; Savelsbergh, Williams, Van der Kamp, & Ward, 2002) in such a rapid environment; results from this sample of experienced athletes may not generalize well to novices or elite athletes.

Conclusion

Opponent interactions in sport require rapid decision-making and directional changes that have been associated with ACL injury. The rich sensory information provided by these interactions provide an athlete some capability to predict movement direction, but this predictive capability had not been explored in research that also provided strict temporal control of directional cues. Results indicate that injury risk is predominantly driven by the timing of the correct directional cue but may be further modulated by reversals in the predicted movement direction if the differentiation occurs late in the movement and close to lower extremity loading. This may alter lower extremity control and decrease performance. These results are preliminary, and data collection continues to confirm the potential magnitude of this effect. As the visual stimuli used in this investigationare still appreciably simplified compared to in sports environments, it is possible that athletes sometimes have stronger or weaker understanding of movement direction probability, which may further amplify this potential effect.

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CHAPTER 6. GENERAL CONCLUSIONS

As anterior cruciate ligament injuries continue at a high rate, research has shifted to exploring potential neurocognitive effects that may alter lower extremity control. Much of this body of literature concentrates on the potential effects of decision making during a rapid directional change, often contextualized as a response to a deceptive opponent in team sports. But biomechanical factors associated with ACL injury risk appear to respond inconsistently in reactive movements. Our previous investigation identified that this is likely due to the inconsistent presentation timing of the directional cues, as the precise timing before lower extremity loading, often within 350 ms, can significantly alter injury risk factors.

We noted that this change in ACL injury risk factors paralleled a reduction in subsequent jump performance that may not be acceptable in competitive social situations. The first investigation of this dissertation (Chapter 3) controlled performance, not allowing movement speed to decrease as the available time to react to directional cues was reduced. This did not appear to significantly impact ACL injury risk factors, however. But the increase in movement speed between jumps paralleled a potential decrease in subsequent jump performance in early cueing conditions, indicating a functional tradeoff that again may not be acceptable to athletes, depending on the specific task demands of the sport.

The first investigation again confirmed that the timing of the directional cue impacts ACL injury risk factors. These directional cues, often originating from an opponent on the field, include some elements of deception that may mislead athletes until late in the movement. It was expected that if this occurred once the lower extremity was loaded, redirection to the correct directional cue would aggravate ACL injury risk factors via a trunk inclination mechanism. Our second investigation (Chapter 4) explored this potential effect by reversing a directional cue early or late in the jump landing movement. In contrast to expectations, this erroneous directional predisposition did not significantly alter ACL injury risk factors in lateral movements. Instead, the timing of the correct directional cue precipitated the change, effectively aggravating ACL injury risk factors in lateral jumps and mitigating them in medial jumps. Similar to our previous investigations, late presentation of the correct directional cue undermined lower extremity control. It was possible that the initial cue was perceived as less valuable and subsequently ignored, undermining the effect of the erroneous predisposition. This suggests that participants may ignore directional cues that provide little probabilistic advantage in predicting movement directions.

The previous investigation that implemented erroneous directional predisposition utilized simplified, Boolean directional cues that were presented at a single, discrete point in time. This drastically contrasts to the continuous, feature-rich sensory information athletes rely on when making decisions about movement direction changes in team sport contexts. The limited attempts to use more complex visual stimuli to cue movement change relied on video of “opponents” that were not precisely temporally controlled. For the third investigation of this dissertation (Chapter 5), we implemented a pseudo-continuous visual stimulus as a directional cue that provided advance indication of a movement direction probability which changed during the movement. Similar to our previous investigations, the timing of pertinent changes in the pseudo-continuous stimuli that allowed differentiation between the presented patterns caused the largest changes in factors associated with ACL injury risk and changes in performance. These changes were again direction-specific; lateral jumps demonstrated changes that may increase injury risk as the time available to react to the directional cue before landing decreased, while medial jumps demonstrated the opposite. Both discrete and pseudo-continuous conditions resulted in similar effects to our previous investigations in this regard. It does appear that erroneous predisposition that is corrected late in the movement may amplify this effect, changing jump landing performance to more closely match kinematics and kinetics associated with the opposite movement direction. If this opposite movement creates an increased risk for ACL injury, this may effectively create a similar effect.

In summary, it appears that a dominating factor in lower extremity control in reactive conditions is related to the precise timing of the pertinent directional cue. If participants identify that the preceding cues may not be accurate, the timing of the relevant cue defines the available time to react before lower extremity loading occurs. In contexts where the preceding erroneous cue is perceived as valuable in predicting the movement direction, the subsequent revision may occur later than the short time period after landing that ACL injuries are likely to occur in. While this may impact subsequent performance, the changes to ACL injury risk factors are relatively minor. As such, it can be concluded that the timing of the perception of the directional cues in reactive movements is particularly relevant in ACL injury risk. Factors that impact this perceptual capability, such as neurocognitive function, experience, and fatigue may ultimately modify ACL injury risk. Training to identify the correct directional cues and to speed information processing are suggested to reduce injury risk across athletic populations. Further research is necessary in order to identify the most effective strategies to train this perception and action response time in sport contexts.

APPENDIX. INSTITUTIONAL REVIEW BOARD APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2207
515 294-4500
FAX 515 294-4267

Date:	6/21/2016		
To:	Mitchell Stephenson 283 Forker	**CC:**	Jason Gillette 245 Forker Bldg
From:	Office for Responsible Research		
Title:	Effects of controlled stance time in unanticipated jump landing tasks		
IRB ID:	16-286		
Approval Date:	6/17/2016	**Date for Continuing Review:**	6/16/2018
Submission Type:	New	**Review Type:**	Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, **including the recruitment materials and informed consent documents that have the IRB approval stamp.**
- **Retain signed informed consent documents for 3 years after the close of the study**, when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.
- **Complete a new continuing review form** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 6/6/2017

To: Mitchell Stephenson
283 Forker

CC: Dr. Jason Gillette
245 Forker Bldg

From: Office for Responsible Research

Title: Effects of movement predisposition in unanticipated jump landing tasks

IRB ID: 17-168

Approval Date:	6/5/2017	**Date for Continuing Review:**	6/4/2019
Submission Type:	New	**Review Type:**	Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, **including the recruitment materials and informed consent documents that have the IRB approval stamp.**
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Institutional Review Board
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Date:	04/02/2019		
To:	Mitchell Stephenson		Jason Gillette
From:	Office for Responsible Research		
Title:	**Effect of complex visual stimuli on lower extremity biomechanics**		
IRB ID:	**19-113**		
Submission Type: Initial Submission		**Review Type:** Expedited	
Approval Date: 04/02/2019		**Approval Expiration Date: N/A**	

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- Retain signed informed consent documents **for 3 years after the close of the study,** when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of