THE EFFECTS OF TASK COMPLEXITY ON KNEE MECHANICS AND JOINT COORDINATION VARIABILITY DURING A SIDE-STEP CUTTING TASK

by

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ABSTRACT

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Injury to the anterior cruciate ligament (ACL) is a very common and debilitating injury suffered by athletes of all ages, genders, and abilities. Practitioners attempt to minimize risks by implementing ACL prevention programs designed to physically prepare athletes for the demands of sport, however, the success of these programs is very inconsistent. The majority of past ACL prevention programs prioritize constrained run and cut activities, the removal of motor variability - attempting to "idealize" mechanics - and limited task complexity. Due to the inherent complexities that exist within sport, it is possible that more task complexity and motor variability is necessary for the transference of training, preparation of athletes, and minimization of ACL injury risk. Therefore, the purpose of this study was to investigate the effects of a lower limb dual motor task and reactivity on joint coordination variability, knee joint mechanics, and knee joint variability during a side-step cutting task. 15 soccer athletes (7 males, 8 females; age 21.3 ± 1.8 years; mass: 70.1 ±14.4 kg; height: 1.7 ± .1 m), high school or higher level, were recruited to complete a run-to-cut task in three different conditions (CUT, KICK, and RXN). The CUT condition required subjects to perform a simple 45 degree run-to-cut. The KICK condition required subjects to do the same, but immediately pass a stationary soccer ball into a goal following the cut. The RXN condition required participants to pass a moving soccer ball into a goal. The soccer ball would be passed or faked to the subjects on random trials within this third condition. Three-dimensional kinematics were collected during the cutting stride. Initial contact (IC) angles and deceleration range of motions (ROM) were reported in all three planes at the hip, knee, and ankle. Vector coding was utilized to measure joint coordination variability. Repeated measure ANOVAs were run for all variables of interest to determine significant differences across conditions ($p < .05$). The CUT condition caused significantly different IC angles, relative to the KICK and RXN conditions, including greater hip flexion and greater hip internal rotation. Further, there was significantly greater knee sagittal plane and ankle frontal plane ROM during the deceleration phase. The KICK and RXN conditions produced significantly greater joint coordination variability, relative to the CUT condition, in two of the seven joint couplings tested. These two included 1) sagittal plane hip with frontal plane knee and 2) transverse plane hip with frontal plane knee. In general, motor behaviors emerged in the KICK and RXN conditions that were more in-line with those seen as mechanistic for ACL injury. Greater joint coordination variability in the KICK and RXN conditions could be due to the heightened complexity of the task, the external focus of attention the task elicited, and/or the greater perceptual-action demands. In conclusion, our findings indicate that motor behaviors become more consistent with ACL stress, and greater joint coordination variability is created within certain joint couplings, when shifting attentional focus externally. The addition of reactivity to an external focus of attention, as well as the lower limb dual task relative to past studies exploring upper limb dual tasks, did not change motor behaviors.

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Chapter 1: Introduction

Injury to the anterior cruciate ligament (ACL) is a very common, costly, and debilitating injury suffered by athletes (Griffin et al., 2006). Of the ~250,000 ACL injuries that occur annually in the United States, between 72% and 95% are non-contact in nature (Boden et al., 2000; Krosshaug et al., 2007; Olsen et al., 2004). Coaches and practitioners implement physical preparation programs in the attempts to minimize the risks of obtaining ACL injuries. While some ACL prevention programs have shown significant decreases in the likelihood of obtaining an injury (Al Attar et al., 2022; Mandelbaum et al., 2005), others have shown no changes (Gilchrist et al., 2008; LaBella et al., 2011). There appears to still be room for improvement regarding the physical preparation of athletes.

These prevention programs often involve neuromuscular training, balance exercises, muscular strength training, plyometric training, and change of direction activities (Gilchrist et al., 2008; LaBella et al., 2011; Mandelbaum et al., 2005). In most cases, plyometric and change of direction activity is limited to constrained, non-representative tasks such as vertical jumping, broad jumping, or pre-planned change of direction drills (Al Attar et al., 2022). These constrained tasks are neither fully representative of the athlete-environment relationship that is used to create motor solutions in sport, nor addresses the fact that risk factors for ACL injury include the relationship between an athlete's neuromotor and musculoskeletal system (Bolt et al., 2021; Krosshaug et al., 2007; McPherson et al., 2020; O'Connor et al., 2009; Olsen et al., 2004; Renshaw et al., 2010; Swanik et al., 2007). For example, Mandelbaum et al. (2005) had athletes perform lateral and forward hops as well as pre-planned diagonal runs. O'Connor et al. (2009) showed that pre-planned lateral and forward jumping tasks are unrepresentative of an unanticipated run-to-cut task, which may be more synonymous with motor behaviors seen in athletic competitions. Besier et al. (2001) and several others (Almonroeder, 2017; Weir et al., 2019) have shown significant changes in joint kinematics when a side-step cutting task becomes reactionary, as opposed to pre-planned. This could lead us to the notion that pre-planned change of direction drills, such as those performed in past ACL prevention research, may not be fully representative and therefore preparatory for athletes. Greater amounts of task complexity may be needed in training to prepare athletes and mitigate the presence of ACL injury in sport.

To address some of the limitations of past prevention programs and injury prevention research, some studies have attempted to add task complexity to relatively simple and constrained athletic motor behaviors within the laboratory setting. This has been accomplished by shifting a performer's attentional focus (Almonroeder, 2017; Almonroeder et al., 2018; Comyns et al., 2019; Fedie et al., 2010; Gokeler et al., 2015; Norte et al., 2020), utilizing a functional dual motor task (Chaudhari et al., 2005; Dai et al., 2018; Heidarnia et al., 2022; Norte et al., 2020), or adding an element of reactivity (Almonroeder, 2017; Almonroeder et al., 2018; Besier et al., 2001; Kim et al., 2014, 2016; O’Connor et al., 2009; Weir et al., 2019). In order to shift an athlete’s attentional focus, nearly all studies have added reaching or upper limb focused constraints to the various motor tasks studied. For instance, while completing a sidestep cutting task, Almonroeder et al. (2017) had individuals perform a basketball chest pass, Heidarnia et al. (2022) had athletes reach for an interception, and Norte et al. (2020) had athletes catch a pass. However, no studies, to our knowledge, have attempted to shift a performer’s attentional focus to an external stimuli involving the lower limb, as commonly seen in a sport like soccer. Soccer players most often navigate environments and solve functional tasks within their sport by organizing components of the lower limb. Therefore, the transferability and ecological validity of past studies that look solely at upper limb dual tasks may not be fully representative.

Most often, injury risk studies analyze single joint mechanics, such as the knee (Besier et al., 2001; Kim et al., 2014, 2016; Weinhandl et al., 2013). However, this reductionist method of analysis may fail to take into account the adaptability and complexity of the human body to function as a coordinated, connected unit (Bolt et al., 2021). A central problem facing athletes while performing is the ability to coordinate and organize the many degrees of freedom present at any point in time (Edelman & Gally, 2001; Kelso, 2014). The manner that an athlete organizes one degree of freedom will have an effect on other degrees of freedom. Solely looking at one joint fails to understand the complex coordinative nature of the human body that integrates as one unit in order to organize into functional motor solutions. A statistical model that simultaneously looks at multiple joints, and their relationship to one another, may provide a better representation of an athlete's motor behavior.

ACL prevention programs oftentimes attempt to "idealize" mechanics by promoting techniques that eliminate positions commonly thought of as mechanistic for ACL injury - thereby promoting a decrease in motor variability (Gilchrist et al., 2008; Krosshaug et al., 2007; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2004). However, past research often discovers greater levels of variability within contexts shaped by greater task complexity (Weir et al., 2019; Heidarnia et al., 2022). A disconnect appears to exist between the role of variability in past prevention programs as compared to the one it presents within sport. Although past theories of variability think of it as noise and a negative characteristic of motor behavior, a more modern viewpoint, the dynamic systems theory, views variability as not only beneficial but necessary in order to create consistent outcomes amongst dynamic environments (Hamill et al., 1999; Kelso, 1997). It's possible that variability discovered amongst greater task complexity is a necessary and functional component of movement. In which case, prevention programs may be more effective by incorporating greater levels of complexity, chaos, and variability to prepare athletes for the dynamic nature of sport. Further understanding how joint coordination variability is affected by changing task dynamics, is the first step towards guiding practitioners regarding the ideal role it should play in their injury prevention programs.

Statement of Purpose

Therefore, the purpose of this study was to investigate the effects of a lower limb dual motor task and reactivity on joint coordination variability and knee joint mechanics during a side-step cutting task. Subjects performed an anticipated cutting task under three conditions: First, without a dual motor task or reactivity. Secondly, with a dual motor task without reactivity (passing a stationary soccer ball at a target). Thirdly, with a dual motor task and reactivity (receiving a passed soccer ball and passing it towards a target).

Hypotheses

1. By adding a dual motor task, we hypothesized that knee mechanics will change to be more in line with those discussed in past literature as mechanisms of ACL injury. Specifically, by adding a dual motor task, it was anticipated that greater knee valgus and less knee flexion at impact would be present, relative to the single motor task condition.

Further, three-dimensional knee ranges of motion would be greater within the dual motor task condition. It was also anticipated three-dimensional coordination patterns between the hip, knee, and ankle would become more variable with the addition of the dual task. Finally, we expected the position of the knee joint, specifically at impact, to be more variable within the dual motor task condition.

2. By adding reactivity to the dual motor task, we expected to see more pronounced changes in both the discrete knee mechanics variables and joint coordination variability.

Delimitations of the Study

1. Recruited participants were young adults in the greater Milwaukee area.
2. Participants must have had advanced soccer experience (have played high school soccer or beyond for a minimum of three years).
3. Participants could not participate in this study if there is an existing condition(s) that interferes/prevents the individual from performing the study's activities.

Assumptions of the Study

1. All lower body segments are rigid bodies.
2. All equipment was calibrated appropriately before each testing session.
3. All retro-reflective markers were placed accurately on the appropriate anatomical landmarks.
4. Participants were running and cutting as they normally would within their sport.
5. Participants recruited from local, midwestern populations reflect motor behavior of other soccer athletes globally.

Significance of the Study

Limiting the risk of injury to the ACL requires improving the physical preparation of athletes. Investigating the effects of task complexity on motor behavior may help explain how sport competition, which is inherently chaotic and complex, increases the likelihood of sustaining an injury to the ACL. By better understanding motor behaviors, in relation to increasing task complexity, we can be more equipped to create physical preparation programs that work to eliminate ACL injuries from sport. Finally, a more complete understanding of joint coordination variability, and its changing role amongst shifting task dynamics, may help illuminate its functional purpose within our motor behavior and our physical preparation programs.

Chapter 2: Literature Review

ACL Injuries

Injury to the anterior cruciate ligament is physically debilitating and can be costly on our healthcare system as well as the injured athlete. In the United States alone there are over 250,000 ACL ruptures annually (Griffin et al., 2006), and since 1990, there has been minimal-to-no improvement in the rate of injury (Sanders et al., 2016). Of these cases, between 72% and 95% are non-contact in nature, (Boden et al., 2000; Krosshaug et al., 2007; Olsen et al., 2004) meaning that the ACL injury is not caused by a direct, external force created by a player-to-player interaction. Females are 2 to 4 times as likely as males to sustain an ACL injury (Arendt & Dick, 1995).

Of non-contact ACL injuries, injury typically occurs when an athlete is attempting to decelerate, pivot, or land (Boden et al., 2000; Olsen et al., 2004). It is crucial that we consider that even in non-contact injury cases, opponents play an important role in the creation of motor patterns. Even if players are not in direct contact with one another, they still help shape one another's motor patterns as well as the functional solutions each is attempting to execute. Krosshaug found that out of 39 cases of ACL injury in basketball athletes, 29 occurred while attacking the basket and 5 occurred while defending an opponent (Krosshaug et al., 2007). Olsen et al. (2004) found a large majority (95%) of ACL injuries to occur amongst an offensive scoring attack. When an offensive player attacks the basket, or a defensive player attempts to guard an opponent, there is much more complexity to the development of motor behavior that resides outside of strict biomechanics. Because ACL injuries appear to most commonly occur within these situations (attacking or defending), we must consider the external demands being placed on the athlete including reaction, cognitive and attentional demand, emotional stress, as well as technical and tactical awareness.

ACL Injury Prevention Strategies and Past Literature

Attempts have been made to create training programs that minimize the risks of obtaining an ACL injury, with mixed results. These programs have typically included combinations of neuromuscular training/control, muscular strength training, plyometric and jump training, and education and feedback regarding “ideal” mechanics (Al Attar et al., 2022; Gilchrist et al., 2008; Mandelbaum et al., 2005; Renstrom et al., 2008). Mandelbaum et al. (2005) studied the effects of a neuromuscular training program on female soccer athletes that included stretching, strength training, as well as constrained plyometrics and change of direction activities. They discovered a significant decrease in the presence of ACL injuries within the intervention group, relative to a control group of age matched individuals.

In a similarly designed prevention program and study, Gilchrist et al. (2008) utilized the PEP (Prevent Injury and Enhance Performance) Program, which has many similarities to the exercise programs utilized by other researchers (Mandelbaum et al., 2005). They found no significant changes to the likelihood of ACL injury (Gilchrist et al., 2008). Similarly, Labella et al. (2011) found no significant changes to the likelihood of ACL injury in their prevention program study which had experimental groups complete a 20 minute neuromuscular warm-up before every practice. Within this warm-up, athletes complete plyometric, strength training, balance, and agility exercises with an emphasis on “proper” form.

When looking at the usage of plyometrics training, Hewett et al. (1999) concluded that the incidence of serious knee injury was 2.4 to 3.6 times greater in the untrained group than in the plyometric trained group. Furthermore, a recent 2022 review concluded, “prevention programs that included plyometric exercises reduced ACL injury rate by 60% per 1,000 hours of exposure” (Al Attar et al., 2022).

A small amount of literature has attempted to uncover the benefits of balance training on minimizing the risk of ACL injury, with mixed results. Söderman et al. (2001) showed no significant differences in injury rates amongst athletes that completed a balance board training program, and those that did not. Other studies have shown success in minimizing injury after the completion of a balance specific training program (Myklebust et al., 2003; Wedderkopp et al., 1999).

Lastly, the overwhelming majority of research surrounding ACL prevention strategies includes a component of “idealizing” mechanics. In nearly all studies, a component of intervention involves shifting mechanics towards those inconsistent with ACL injury. For example, most studies sought to eliminate knee valgus, large amounts of knee extension upon changing directions or landing, as well as promoting “soft landings” to minimize ground reaction forces. Some studies accomplished this through showing videos of “proper” technique (Gilchrist et al., 2008; Mandelbaum et al., 2005; Myklebust et al., 2003), while others is through more direct coaching and teaching (Hewett et al., 1999; LaBella et al., 2011). The effectiveness and results from this coaching and motor learning strategy is unclear.

The validity and efficacy of “idealizing” mechanics within a constrained training setting has been questioned as of late. O’Connor et al. (2009) showed that constrained jump and cut tasks are unrepresentative of unanticipated run and cut tasks, especially in the frontal plane. A large amount of literature indicates that kinematics and kinetics significantly change when athletes are placed under novel stressors such as reactivity, or increased cognitive and attentional demand (Almonroeder, 2017; Almonroeder et al., 2018; Chaudhari et al., 2005; Gokeler et al., 2015; Heidarnia et al., 2022; Weir et al., 2019).

Mechanisms of ACL Injury

Mechanisms of ACL injury include, but are not limited to, environmental factors, anatomical factors, hormonal factors, biomechanical factors, and neuromuscular factors. Anatomically, ACL risk factors include increased joint laxity, Q-angle, excessive tibial torsion, and excessive foot pronation (Griffin et al., 2000). Joint laxity, which is a combination of hypermobility and musculotendinous flexibility, appears to be more common in females, but the research is unclear as to whether this is a significant risk factor for injury (Söderman et al., 2001; Uhorchak et al., 2003). Söderman et al. (2001) investigated the risk of injury in female soccer players and discovered that an increased generalized joint laxity and knee hyperextension led to an increased risk of lower limb injury (not specific to ACL). Uhorchak et al. (2003) studied US Military Academy cadets within a 4 year prospective cohort study and found that general joint laxity as well as a decreased femoral notch width were amongst the top risk factors of ACL injury. Opposedly, Moretz et al. (1982) found no correlation between knee injury and ligamentous laxity testing in collegiate football players. However, it should be noted that the “laxity” testing completed by Moretz was simply general flexibility tests such as a toe touch test, an upper body rotation test, a lotus position test, a knee hyperextension test and a lower extremity rotation test. The ability of these passive stretching tests to detect joint laxity could be debated.

The Q-Angle is the angle created between two lines, one formed from the anterior-superior iliac spine to the central patella and one formed from the central patella to the tibial tuberosity. Past literature is unclear as to the prominence of this risk factor as a predictive measure for ACL injury. A greater Q-Angle is theorized to lead to greater foot eversion and hip internal rotation, however, Heiderscheit et al. (2000) found significant differences in Q-Angle amongst young-adult male and female runners, but insignificant indirect differences in tibial rotation and foot eversion as a result of this increased Q-Angle. They did find that a high Q-Angle group achieved maximum tibial internal rotation later in the stance phase as compared to the low-Q-Angle group, however this could be indicative of creating a less vulnerable motor system due to the time the individuals are allowing for force absorption.

Notch width and ACL size have also been reported as anatomical risk factors for ACL injury, but it is unclear the extent of their predictive validity (Uhorchak et al., 2003). As we know, females are 2-to-4 times as likely as males to sustain an ACL injury (Arendt & Dick, 1995). Chandrashekar et al. (2005) reported that females have ACLs that are smaller in length, cross sectional area, and mass relative to males, which could contribute to this dramatic difference in injury prominence. This same study reported no difference in notch geometry, which is in disagreement with Uhorchak et al. (2003).

The neuromuscular system is responsible for generating movement, most often via unconscious muscular activation, which, when dysfunctional, could play a role in the development of injury such as an ACL rupture. During deceleration, as the knee moves into flexion, it is the role of the quadriceps muscle group to eccentrically contract, absorbing force. However, the quadriceps muscle group is also responsible for anterior translation of the tibia under the femur, which is a central mechanism of ACL loading and injury (Boden et al., 2000). Because of this, ACL strain appears to be maximized amongst large quadricep activation while the knee is close to full extension (Fleming et al., 2003). Simultaneous co-contraction of the hamstring muscle group amongst large loading placed on the quadricep muscle group, often during a landing or deceleration task, can increase the stability of the knee joint and place less strain on the ACL (Withrow et al., 2008). Maintaining a healthy relationship of quadricep to hamstring muscular strength could be important for improving the function and health of the knee joint.

Biomechanically, many lower limb positions and moments have been detected as risk factors for ACL injury. Kinematically, these include increased knee extension at impact of a deceleration maneuver (James et al., 2004; Krosshaug et al., 2007; Olsen et al., 2004; Yu et al., 2006) as well as increased knee valgus angle (Hughes et al., 2008; Krosshaug et al., 2007; Olsen et al., 2004; Pappas et al., 2007). In a review of recorded ACL injuries, one paper determined that ACL injuries occur most often in sport when an athlete creates a forceful valgus and experiences simultaneous internal rotation of the tibia on the femur, amongst a fully extended knee (Olsen et al., 2004). Kinetically, increased ground reaction forces at impact of a deceleration maneuver have been linked to greater ACL stress (Decker et al., 2003; James et al., 2004).

Comparing the biomechanics of males and females can potentially give us some insights into mechanisms of ACL injury. Numerous studies have studied sagittal plane mechanics during landing and cutting maneuvers comparing males and females noting that females tend to display greater knee and hip extension at impact (Decker et al., 2003; James et al., 2004; Salci et al., 2004). These mechanics could be associated with a “stiffer” lower limb during deceleration and a more vulnerable knee position for injury. Salci et al. (2004) studied the landing mechanics of male and female collegiate volleyball players noting that females tended to land with increased knee extension and significantly greater normalized ground reaction forces - both of which are risk factors for ACL injury. James et al., (2004) found similar gender differences in high school and collegiate basketball athletes during a rapid run-to-cut task, noting that females landed with 5.8 less degrees of knee extension at impact. Looking at the frontal plane, Hughes et al. (2008) studied collegiate volleyball players during a block jump landing. He noted that both females and males landed in valgus, but males quickly moved into varus after initial ground contact while females moved further into valgus. The initial valgus angle was not significantly different, but the range of frontal plane knee motion and maximum knee valgus angle were significantly different between the genders. Taken together, the mechanics utilized by females appear to be significantly different than males, which could be playing a role in the higher prominence of ACL injuries within the female population.

Neurocognitive Influence to ACL Injury

Some evidence points to neurocognitive influences playing a significant role in musculoskeletal injuries, and more specifically ACL injuries (Swanik et al., 2007, McPherson et al., 2019, McPherson et al., 2020). Effective motor control is, at least in part, driven by a highly functioning central nervous system, which is placed under large demands within the context of sport. These higher cognitive demands could contribute to the greater risk of injury seen within sporting competition (Olsen et al., 2004). Swanik et al. (2007) found high negative correlations between the presence of non-contact ACL injuries and neurocognitive test scores in a collegiate athlete population. In a 2019 meta-analysis, McPherson and colleagues (2019) discovered that athletes that suffered a past concussion have 1.6 greater odds at sustaining a future ACL injury compared to those without a previous concussion.

Furthermore, within the laboratory setting, many researchers have attempted to add cognitive demand to athletic movements in order to study changing motor patterns. In general, kinematics and kinetics associated with ACL injury tend to be more present amongst greater cognitive demand, relative to more constrained tasks (Almonroeder, 2017; Almonroeder et al., 2018; Besier et al., 2001; Dai et al., 2018; Ford et al., 2005; Heidarnia et al., 2022; Houck et al., 2006; O’Connor et al., 2009; Weir et al., 2019; Wilke et al., 2021).

Ecological Validity of Past Research

There are multiple pressing issues that allow us to question the ecological validity of traditional research as it relates to assessing injury risk. First, the laboratory setting fails to preserve the athlete-environment relationship (Bolt et al., 2021). An athlete's motor patterns are never isolated from the context in which they are performed. Athletes perform within a context that is shaped by three central constraints: Task constraints, environmental constraints, and individual constraints (Renshaw et al., 2010). As noted above, ACL injuries most often take place within sport amongst complex attacking or defending plays (Krosshaug et al., 2007; Olsen et al., 2004). The environment, and informational stimuli it is providing to the athlete, plays a role in the creation of motor behavior by athletes and therefore any injuries sustained. The laboratory setting removes the complex environmental stimulus that provides athletes information regarding the creation of motor patterns and motor solutions.

Secondly, injury risk studies are often strictly biomechanical in nature and potentially overlook the importance of other variables such as opposing player or teammate motor behavior, attentional focus, cognitive demand, or the surrounding environment (Bolt et al., 2021). Studying motor patterns without consideration for the context they are performed in fails to fully understand the motor behavior the athlete and the injury mechanisms present. For example, O'Connor et al. (2009) demonstrated how various constrained jump-to-cut tasks are not representative of an unanticipated run-to-cut task, especially when looking at frontal plane knee mechanics.

Third, injury risk studies often analyze single joint mechanics, such as the knee, which is a reductionist method of analysis, failing to take into account the adaptability and complexity of the human body to function as a coordinated, connected body (Bolt et al., 2021). A central problem facing athletes while performing is the ability to coordinate and organize the many degrees of freedom present at any singular point in time (Edelman & Gally, 2001; Kelso, 2014). The manner that an athlete organizes one degree of freedom will have an effect on other degrees of freedom. Solely looking at one joint fails to understand the complex coordinative nature of the human body that functions as one unit to organize into functional motor solutions. To account for these shortcomings, recent papers have attempted to shift the way we research and analyze injury risk, bringing into account additional variables such as attentional focus, cognitive demand, and task complexity.

Attentional Focus Research

Considerable research has been conducted to study differences in performance and motor strategy across changing attentional foci. An internal focus of attention would occur when a coach has their athlete place their attention on the coordination of body movement (Wulf et al., 1998). For example, if a coach was teaching somebody to play golf, they may direct the athletes attention to their trailing elbow by saying “think about keeping the trailing elbow tucked to your ribs.” This would be an example of an internal focus of attention. An external focus of attention would occur when the athlete places their attention on the effects of their actions on the environment (Wulf et al., 1998). For example, a golf coach may say to the athlete “During this next swing I want you to think only about that red flag we are aiming at." This would be an external focus of attention.

There has been an overwhelming amount of research that demonstrates an external focus of attention appears to create higher levels of performance as well as changes in the kinematics utilized to achieve it (Almonroeder, 2017; Almonroeder et al., 2018; Comyns et al., 2019; Dai et al., 2018; Fedie et al., 2010). Gokeler et al. (2015) had individuals with a prior ACL reconstruction complete single leg broad jumps amongst both an internal and external focus of attention. They found that when utilizing an external focus of attention, the performers showcased "safer" biomechanics, that is those that theoretically would place less stress on the ACL such as greater knee flexion, range of motion, and time to peak knee flexion. This is in disagreement with other papers that found when placing an individual into an external focus of attention, mechanics shift to be more "dangerous" yet often higher performing (Almonroeder et al., 2018; Comyns et al., 2019; Fedie et al., 2010). The most likely explanation for disagreement is the specific motor task being executed as well as the manner in which an external focus of attention is implemented by the researchers, both of which vary drastically across studies.

Researchers have taken on various strategies to implement an external focus of attention within the laboratory setting. One unique way that makes the laboratory environment more sport-like is by having the performer attend to an external stimulus or task. For example, in his dissertation work Almonroeder had individuals complete a basketball chest pass during a side-step cutting action (Almonroeder, 2017). This required the performer to take their attention away from the cutting task being executed and instead place it on the target that they were trying to pass the ball to. Fedie et al. (2010) as well as Heidarnia et al., (2022) had performers attempt to intercept a pass between researchers immediately following the completion of a cutting task. Similarly, this forced the performer to take their attention away from the completion of the cutting task and towards the ball being intercepted.

Cognitive Demand Research

Several research studies have attempted to challenge a motor task by increasing the cognitive demand placed on the performer. This has been done by requiring performers to count by specified intervals during the completion of a landing task (Dai et al., 2018), recall a visual image during a landing task (Wilke et al., 2021), reacting off of a simulated defender (Heidarnia et al., 2022) or adding a reactionary component to the motor task (Almonroeder, 2017; Almonroeder et al., 2018; Besier et al., 2001; Houck et al., 2006; O'Connor et al., 2009; Weir et al., 2019).

Besier et al. (2001) were amongst the first to study the inclusion of reactivity during a side-step cutting task. They had 11 individuals complete a side step cutting task in four different directions in both an anticipated and unanticipated condition. These four directions included a 60 degree cut, 30 degree cut, straight ahead run, and a crossover 30 degree cut. Significant differences in lower limb mechanics were found when the researchers included an element of reaction. These differences included increases in varus/valgus moments, increases in internal/external rotation moments, and decreases in knee flexion angle at peak push off.

Many follow up studies have since been completed and have identified similar changes in lower limb kinematics amongst the inclusion of reactivity (Almonroeder, 2017; Almonroeder et al., 2018; Houck et al., 2006; Kim et al., 2014, 2016; Meinerz et al., 2015; O'Connor et al., 2009; Weinhandl et al., 2013; Weir et al., 2019). Weir et al. (2019) studied kinematic and coordinative variability differences during the completion of a planned side-step cutting task and an unplanned one, concluding that "anticipated and unanticipated sidestepping are not the same task."

While most studies agree that unanticipated movement, relative to anticipated, pre-planned movement, creates motor behavior more in-line with "risky" positions, or those more associated with ACL injury, Meinerz et al. (2015) found that female soccer players actually shifted their mechanics to a more hip dominant strategy amongst the inclusion of a land-to-cut task. A hip-dominant strategy would potentially take loading off of the ACL, creating a "safer" motor behavior. However, as opposed to most studies that utilize a run-to-cut task, their study had individuals complete a land-to-cut task off of a box. Individuals started elevated onto a box and proceeded to land on a force plate and react to a light stimulus. This motor task may have caused an increase in hip strategy due to the angle of energy that needed to be absorbed, as compared to a run-to-cut task which requires both a horizontal and vertical force absorption. O'Connor et al. (2009) found constrained land and cut tasks to be unrepresentative of unanticipated run-to-cut tasks, especially regarding frontal plane mechanics. This may be a central reason for the disagreement between Meinerz' findings and those of similar studies.

Task Complexity

Many research studies have increased the complexity of motor tasks within the laboratory setting in the attempts of maintaining the athlete-environment relationship, as well as to study the effects of complexity on motor patterns.

Norte et al. (2020) asked individuals to complete a constrained 45 degree cutting task amongst reactivity and increasing task complexity. Increased complexity was created through the presence of the researcher passing a ball to the performer immediately after completion of the cutting task. There was also a fake pass condition, as well as a no pass condition. Further, there was an unanticipated and an anticipated condition to add an element of reactivity, increasing the cognitive demand of the performer. In total, 6 different conditions were present. Differences in mechanics were mostly found at the trunk, which was more vertical during conditions in which a ball was present. Minimal differences were found at the knee or hip across tasks and changing complexity. However, because the researchers did not study joint coordination relationships, it is possible that the coordination strategy, or the manner in which performers were organizing into the joint mechanics differed across tasks.

Almonroder (2018) had individuals perform a basketball chest pass immediately following a cutting task. In the same study the researcher had individuals simply carry a basketball during a run and cut task as well as perform a standard run and cut with no ball present. Individuals demonstrated significantly less hip flexion at IC within the passing condition, relative to the carrying condition. Peak knee flexion was also much less in the landing limb within a passing condition, relative to the carrying condition. Finally, peak knee abduction was significantly greater in the passing condition relative to the carrying condition. Very few differences were found when comparing the carrying condition and the standard cutting condition. This is in disagreement with Chaudari et al. (2005) who found greater frontal plane knee loading when carrying a football in the arm on the side of the plant limb or while carrying a lacrosse stick in both hands. One proposed reason for this is that Alomonroeder used subjects that were more familiar with the task complexity being added while Chaudari's subjects were very unfamiliar with the task additions.

Few studies noted above looked beyond single-joint biomechanical analysis. While the behavior of a single joint is important, we should additionally be studying various joint relationships (Bolt et al., 2021). Within sport, athletes are required to organize many degrees of freedom into functional action (Edelman & Gally, 2001; Kelso, 2014). The organization of one degree of freedom can have dramatic implications on degrees of freedom that exist throughout the kinematic chain. Meaning, instead of considering joints and muscles to be controlled independently of one another, it is necessary that we consider them functionally linked to one another so as to form coordinative structures (Kelso, 2014). By understanding the functional linkage between joints, or the coordination strategies they employ in unison, we may be better equipped to understand the resulting motor strategies performers make use of amongst varying motor tasks and constraints.

As an example, Weir et al. (2019) studied lower limb coordination strategies during an anticipated and unanticipated run-and-cut motor task. They concluded that unanticipated, and therefore increasing cognitive demand, led to an increase in coordination variability between the trunk-hip as well as the hip-knee relationships. This increase in variability, they concluded, is likely seen as a result of utilizing more degrees of freedom to solve the more complex task.

Hamill et al. (1999) utilized a statistical analysis method known as continuous relative phasing to measure the relative phasing of joints throughout the entirety of a motor task. By doing so, they could further understand the coupling relationship between joints as well as the variability in their coordination patterns. Within their study they identified specific instances of increased coordination variability within a healthy population of runners as compared to a group experiencing patellofemoral pain. Heiderscheit et al. (2002) found opposite results in their study of runners, that is, runners with patellofemoral pain demonstrated greater thigh rotation-leg rotation coupling variability on their injured limb as compared to their uninjured limb. Overall, the functional role of variability within our motor behavior is still very much unknown and disagreed upon.

Dynamic Systems

A central contributor to injury is the complexity and dynamic nature that exists within sport as well as the human movement system independent of external forces. One way to understand movement is by utilizing a dynamical systems approach. Within all human movement systems, a central motor problem that needs to be overcome is the organization of the many degrees of freedom present (Edelman & Gally, 2001; Kelso, 2014). To solve a motor task, such as the many presented by sport, the athlete is responsible for organizing their many degrees of freedom to create a functioning motor behavior. The manner in which an athlete goes about doing so is very much still unclear, but various theories of motor control exist.

The more traditional theory of motor control, the Generalized Motor Program Theory, believes that a central controller is in charge of organizing the movement patterns we create (Chow et al., 2015; Shumway-Cook & Woollacott, 2007). A more modern approach to motor control, the dynamical systems theory, believes that our motor patterns self-organize into functioning patterns based on our perception of the environment, the task we are trying to complete, and the current state of the individual mover (Chow et al., 2015; Davids et al., 1999; Kelso, 1997; Newell & Vaillancourt, 2001). With these differing viewpoints of motor control arises differences in the way motor variability is viewed. Under the traditional approach, variability is thought of as noise and sought to be eliminated. Within the dynamical systems framework, variability is a necessary element of our motor system in order to navigate the dynamic environments and tasks that individuals find themselves completing (Kelso, 1997). Dynamic theorists would argue that because the environment and tasks being completed within sport are dynamic in nature, meaning they are constantly changing, it's impossible to utilize a consistent motor solution. In his book chapter titled "Dynamic Patterns" Kelso says:

> Biological systems like ourselves, for example, are multifunctional; we can use the same set of anatomical components for different behavioral functions… or different components to perform the same function… Moreover, how a given pattern persists under various environmental conditions and how it adjusts to changing internal and external conditions have to be accounted for (Kelso, 1997).

Therefore, under a dynamical systems framework, variability is essential in inducing a coordination change or establishing a combination of motor stability and flexibility or adaptability, within our motor patterns (Hamill et al., 1999). Degeneracy is often the term used to describe the ability of complex biological systems to achieve the same or different outcomes in varying situations, with structurally different components of the musculoskeletal system (Chow et al., 2015; Edelman & Gally, 2001).

Variability and Injury Risk

Research attempting to uncover the functionality of variability within human motor behavior is unclear and quite limited. Few studies have attempted to outline the functional significance of variability as it relates to injury risk, and the studies that have, show mixed results (Edwards et al., 2017; Hamill et al., 1999; Heidarnia et al., 2022; Nordin & Dufek, 2017b, 2017a; Pollard et al., 2005). There appears to be two central distinctions within the injury risk, variability research; studies that investigate overuse injuries and studies that investigate traumatic injuries.

Hamill et al. (1999) studied variability amongst long distance runners, who often sustain overuse type of injuries. He and his colleagues compared runners with and without the presence of patellofemoral pain, uncovering a slightly greater degree of variability amongst healthy runners. These findings point towards variability being a functional advantage for the runners not experiencing pain. Greater variability allows them to explore their degrees of freedom, in search for the most optimal and functional motor solution. It also potentially has an injury mitigating mechanism that disperses loads and stresses on the tissues of the knee, limiting degeneration and wear.

ACL injuries are traumatic in nature and often occur amongst rapid changing direction or landing, and usually are paired with an intense sporting maneuver such as attacking a scoring opportunity or defending an opponent (Krosshaug et al., 2007; Olsen et al., 2004). Therefore, studies that look at sporting maneuvers such as side step cutting may be more representative and informative regarding variability's functional role in minimizing or attenuating injury.

Heidernia et al., (2022) studied individuals completing a side-step cutting task amongst placing their attentional focus on a dual interception task. The researchers studied the continuous relative phase of healthy individuals versus those with a past ACL reconstruction. They found significantly increased variability in joint coordination strategy within the ACL reconstructed individuals only amongst more cognitively demanding tasks. These findings could be indicative of the ACL reconstructed athletes attempting to explore their newly available degrees of freedom as caused by the injury, or be attempting to explore novel patterns working around the additional motor constraints created during the injury and recovery process. It also could be indicative of a lack of stability within the newly repaired joint, causing lesser motor control and heightening the reinjury risk.

Edwards et al. (2017) studied joint kinematic and kinetic variability during the completion of an unanticipated side-step cutting task within individuals with and without groin pain. Utilizing a simplified method of studying variability, coefficient of variation, they discovered that athletes with a history of groin pain displayed greater hip and lower lumbar joint kinematic variability but less lower ankle, knee, and T12-L1 kinematic variability. These differences are suggestive of a difference in motor strategy executed to complete the unanticipated cutting task.

Nordin et al., (2017a) studied kinematic and kinetic variability amongst the various height drop landings and discovered that the variability of the knee joint far exceeded both the variability present at the hip and ankle. Joint moment variability appeared to decrease as the landing height increased. The researchers concluded that a great landing height created a more constrained solution space among the lower extremity joints, leading to less variability in the way force was absorbed. However, it should be noted that this study utilized a simplified standard deviation and coefficient of variation model to investigate variability as opposed to the more detailed models discussed below such as PCA, Vector Coding, or Continuous Relative Phasing.

In a separate study by Nordin et al. (2017b) investigating movement variability in single-leg landing amongst increasing loading and increasing landing height. Utilizing principal components analysis, they discovered that greater task demands such as increasing load or increasing the landing height led to similar decreases in variability.

Finally, Pollard et al. (2005) studied gender differences during an unanticipated cutting task. To study variability, they utilized a strategy known as Vector Coding to analyze the coordination patterns between lower extremity joints. They discovered that women display less coordinative variability, which they concluded to be due to “less flexible coordination patterns,” indicative of potentially less adaptability. This could be a contributing factor as to the far greater prominence of ACL injury in women relative to men.

Joint Coordination Analysis

In order to study the joint coordination strategy utilized by performers within a motor task, several methods have been outlined within the literature with the primary methods being Principal Components Analysis (PCA), vector coding and Continuous Relative Phasing (CRP).

PCA has been utilized to analyze data in several biomechanical research studies (Landry et al., 2007; O'Connor et al., 2009). PCA can be summarized as an orthogonal transformation of the original waveform data into a new data set that allows waveform features such as magnitudes, phase shifts, and amplitudes to be identified based on the variability in the data set (Landry et al., 2007).

Vector coding and CRP are similar in that they assess coordination between two structures by quantifying phase plane trajectories. However, where they differ is that the vector coding phase plane contains only positional data while CRP utilizes both positional and velocity data to provide spatio-temporal information (Miller et al., 2010). Both vector coding (B. Heiderscheit et al., 2002; Pollard et al., 2005) and CRP (Hamill et al., 1999) have been used successfully in biomechanical research to understand joint coordination variability and study multi-joint relationships during a singular motor task.

Our purpose in utilizing these statistical analysis techniques is to understand the joint coordination variability present as motor task complexity increases. Due to the fact that the joint coordinations that will be studied are non-sinusoidal, the use of continuous relative phase may produce inaccurate results (Heiderscheit et al., 2002).

Chapter 3: Methods

The purpose of this study was to measure kinematic and joint coordination variability changes to a side-step cutting task amongst the addition of task complexity. Participants completed a 45° run-to-cut task in varying conditions. Three-dimensional motion capture was utilized to evaluate differences in motor behavior amongst changing task dynamics.

Participants

Fifteen male and female experienced soccer individuals were recruited for this study. A sample size estimation based on knee valgus during a lateral cutting task estimated that 15 total participants would be adequate based on an effect size of 0.5, power of .8 and an alpha of .05 (Alenezi et al., 2016). Participants were recruited from the undergraduate population at the University of Wisconsin-Milwaukee as well as the surrounding universities and communities. Participants were required to have 3 or more years of competitive soccer experience (high school or beyond) and be between 18 and 25 years old. Participants were sent an online questionnaire to complete upon expressing interest. Ineligible factors that the questionnaire screened for were conditions that prevent/interfere with the individual's ability to perform the study's tasks, pregnancy, inadequate experience. Furthermore, individuals with current significant musculoskeletal injuries, past ACL reconstruction surgery or other past significant lower limb injuries were excluded from the study. Individuals with diagnosed concussions in the past three years were also excluded from the study.

Table 1: Participant demographic information

Code	Gender	Age	Mass (kg)	Height (m)
01	M	19	81.75	1.803
02	M	20	69.22	1.753
03	F	19	44.14	1.524
04	M	25	80.33	1.803
05	M	22	59.43	1.727
06	F	21	77.98	1.803
07	F	22	73.29	1.753
08	M	20	100.2	1.829
09	M	22	51.48	1.778
10	F	21	64.02	1.727
11	F	20	61.67	1.702
12	F	22	55.66	1.702
13	F	21	71.97	1.676
14	F	21	76.55	1.753
15	M	25	83.08	1.803
Mean		21.3	70.1	1.7
SD		1.8	14.4	0.1

Instrumentation and Equipment

A ten-camera Motion Analysis Eagle System (Motion Analysis Corp., Santa Rosa, CA, USA) was used to obtain lower extremity kinematics by tracking the trajectories of retroreflective markers at 200 Hz. Kinetic variables were obtained using one Bertec force plate (Bertec, Inc., Columbus, OH, USA) at 1000 Hz. These two systems collected data synchronously. Participants wore comfortable, athletic clothing of their choice. A standard sized soccer ball was utilized within the external focus experimental conditions. Visual 3D v2022 (C-Motion Inc, Boyds, MD, USA) was used for data processing, and Matlab (MathWorks Inc., Natick, MA, USA) was used to extract dependent variables.

Experimental Protocol

The participant's sex, weight, and height were collected prior to data collection. Participants were asked to warm up for 10 minutes before completion of the cutting tasks by lightly jogging on a treadmill, stretching, or doing any other activities they may normally do prior to physical activity. Retroreflective markers and cluster sets were applied to the subject's right lower extremity and pelvis. Extra adhesive strips were used to secure the markers. The individual markers were placed on the anterior superior and posterior superior iliac spines, iliac crests, and greater trochanters. Markers were also placed on the right lateral and medial femoral epicondyles, lateral and medial malleoli, and the heads of the first and fifth metatarsals. The clusters were strapped onto the right lateral thighs and shank, roughly at mid-length. After a brief standing calibration, the markers on the iliac crests, greater trochanters, femoral epicondyles, and malleoli were removed.

Participants performed five side-step cutting tasks in three different conditions. Amongst all conditions, the participants began by starting approximately eight meters from the cutting point. They accelerated towards the cutting point and reached a speed between 3.5 - 4.5 m/s. This approach speed was monitored through two timing gates 1.75 m apart positioned along the runway. Participants planted their right foot on the force plate and proceeded to cut at a 45° angle. The first condition was a pre-planned side-step cutting task (CUT). The second condition was a pre-planned cut with a dual motor task (KICK). Within this condition, the participants were required to pass a stationary soccer ball into a soccer goal immediately following the completion of a 45° side-step cut (Figure 1). Prior to completion, the participants were told to “pass the soccer ball with as much accuracy as possible, while still maintaining appropriate speed.” The third condition was a pre-planned cut with a reactive dual motor task (RXN). Within this condition, the participants were required to redirect a moving soccer ball, passed to them by the researcher, into a goal immediately following the completion of a 45° side-step cut. Within this third and final condition, the ball was kicked to the individual only half of the time (chosen randomly), creating the reactionary effect (Figure 2). Therefore, more than five trials of the third condition were completed and collected with only the five passing trials analyzed. These five trials of each condition will be completed together, and the order of the three conditions were randomized. A two-minute break was provided between conditions. A successful trial was completed when the participant reached a speed within the necessary range, accurately hit the cutting point so that the entirety of their foot is on the force plate and completed the functional task (where applicable).

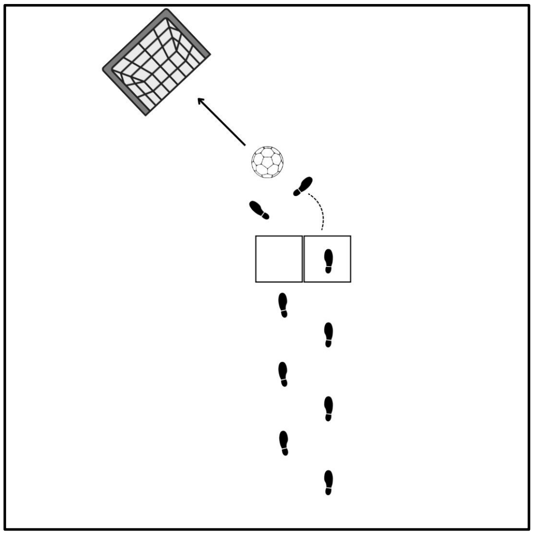


Figure 1. A depiction of the KICK experimental, dual task condition.

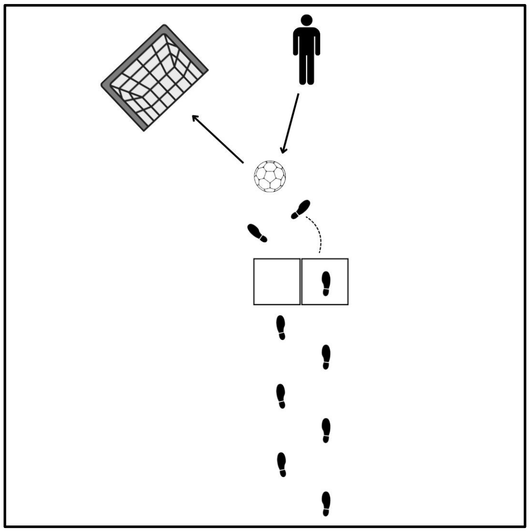


Figure 2. A depiction of the RXN experimental, dual task and unanticipated condition.

Data Reduction

Three-dimensional joint positions and ground reaction forces (GRF) were collected from the impact of the cutting limb on the force plate, until complete push off of the cutting limb. The kinematic and kinetic data was filtered using a 4^{th} order, zero-lag, low pass Butterworth filter with a cut-off frequency of 12 Hz and 50 Hz, respectively. Thigh, shank, and foot coordinate systems were established from the standing calibration trial. The X-axis is orientated mediolaterally, the Y-axis is orientated anteroposteriorly, and the Z-axis is orientated inferosuperiorly. Joint angles were calculated using the joint coordinate system approach (Grood & Suntay, 1983). This was done for hip, knee, and ankle kinematics. Hip, knee, and ankle abduction/adduction or eversion/inversion is motion along the Y-axis in the frontal plane. Hip, knee, and ankle flexion/extension or dorsiflexion/plantarflexion is motion along the X-axis in the sagittal plane.

Joint kinematics and GRF were extracted from initial contact (IC) until completion of the stance phase. Stance phase was defined when vertical ground reaction force is greater than or equal to 10 N. Three dimensional joint angles at the knee, ankle, and hip are reported at IC and range of motion. Joint range of motion (ROM) is defined as the difference between the joint angle at IC and that after 15% of the stance phase, which was determined to be consistently in line with peak vertical deceleration ground reaction force.

Vector coding, as described by Heiderscheit (2002), was utilized to analyze joint coordination variability within the weight acceptance/deceleration phase of the side-step cut, as described by Besier (2001). To do so, angle-angle plots across the deceleration phase (first 15% of stance phase), as outlined above, were created for the following joint relationships:

- Hip Sagittal + Knee Sagittal (HSKS)
- Hip Frontal + Knee Sagittal (HFKS)
- Hip Transverse + Knee Sagittal (HTKS)
- Hip Sagittal + Knee Frontal (HTKF)
- Hip Frontal + Knee Frontal (HFKF)
- Hip Transverse + Knee Frontal (HTKF)
- Knee Frontal + Ankle Frontal (KFAF)

The standard deviation of the coupling angles was calculated and reported as a measure of joint coordination variability across the first 15% of the stance phase.

Statistical Design and Analysis

The primary dependent variables for this study are initial contact and range of motion knee joint kinematics as well as joint coordination variability for the couplings identified above. Repeated-measure ANOVAs with three levels for the three experimental conditions (CUT, KICK, RXN) were utilized to identify significant differences (alpha = .05) in the dependent variables. Tukey's post hoc tests were performed to identify pairwise differences.

Chapter 4: Results

Kinematic Data

Participants showed similar patterns of joint kinematics at the hip, knee, and ankle in all three planes across the three task conditions (Figure 3), with multiple significant differences between the three task conditions tested.

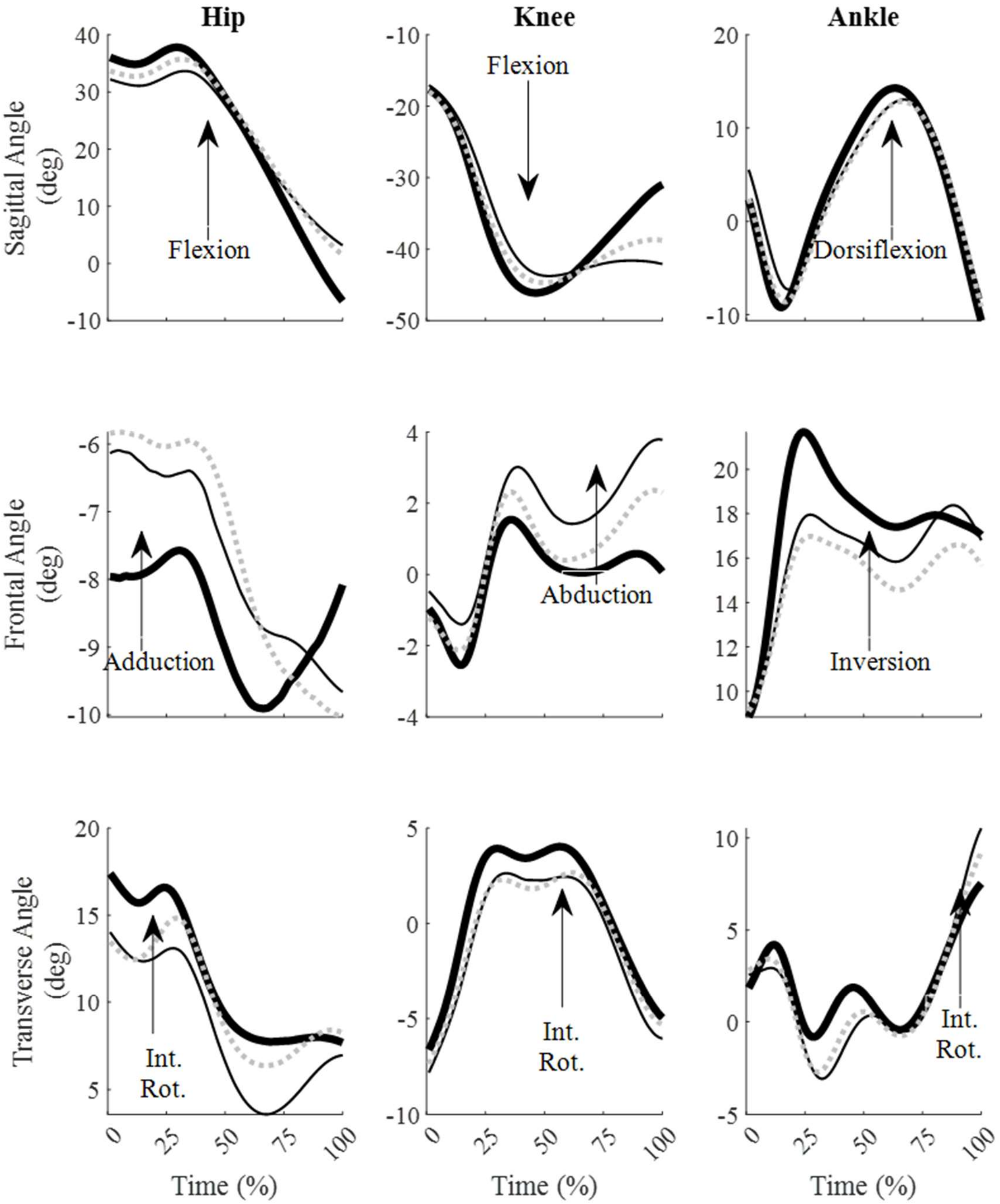
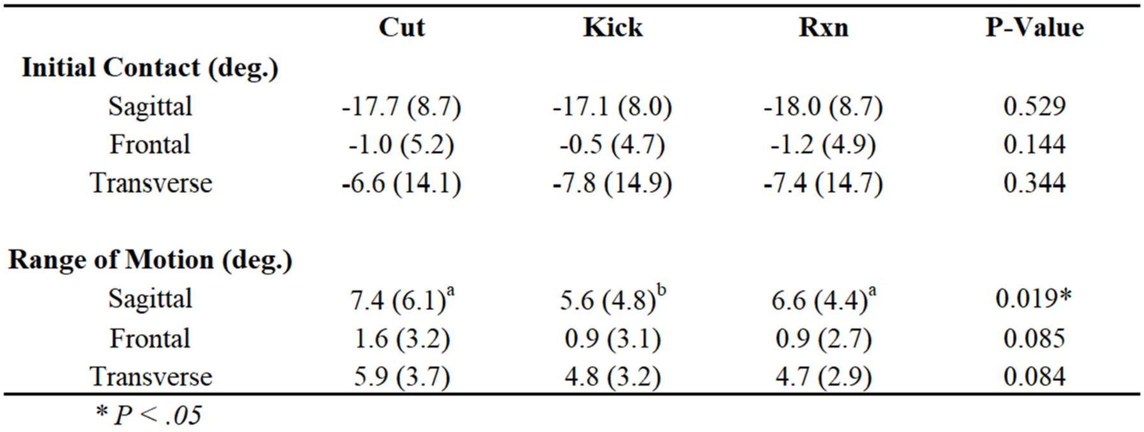


Figure 3. Joint kinematic data across 100% of the cut task. Thick line = CUT, thin line = KICK, dotted line = RXN.

Knee Joint Discrete Variables

At IC, there was no significant difference between knee joint angles across the three conditions tested in any plane (Table 2). ROM at the knee was significantly different in the sagittal plane. The CUT condition produced a significantly larger ROM than the KICK condition.

Table 2. Mean (SD) knee joint discrete variables during the three conditions. For variables with a significant p-value, like letters indicate values that are not different.



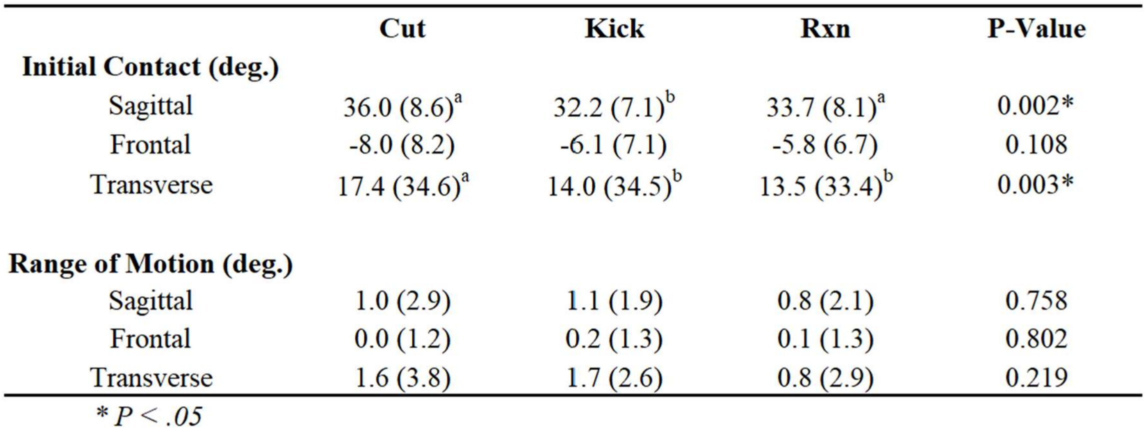
	Cut	Kick	Rxn	P-Value
Initial Contact (deg.)				
Sagittal	-17.7 (8.7)	-17.1 (8.0)	-18.0 (8.7)	0.529
Frontal	-1.0 (5.2)	-0.5 (4.7)	-1.2 (4.9)	0.144
Transverse	-6.6 (14.1)	-7.8 (14.9)	-7.4 (14.7)	0.344
Range of Motion (deg.)				
Sagittal	7.4 (6.1)^a	5.6 (4.8)^b	6.6 (4.4)^a	0.019*
Frontal	1.6 (3.2)	0.9 (3.1)	0.9 (2.7)	0.085
Transverse	5.9 (3.7)	4.8 (3.2)	4.7 (2.9)	0.084

* *P < .05*

Hip Joint Discrete Variables

Significant differences were identified at the hip joint at IC in the sagittal and transverse planes (Table 3). In the sagittal plane the hip joint was significantly more flexed at impact during the CUT condition, relative to the KICK condition. In the transverse plane, the hip joint was significantly more internally rotated in the CUT condition, relative to both the KICK and RXN conditions. Range of motion at the hip joint was not significantly different in any plane.

Table 3. Mean (SD) hip joint discrete variables during the three conditions. For variables with a significant p-value, like letters indicate values that are not different.



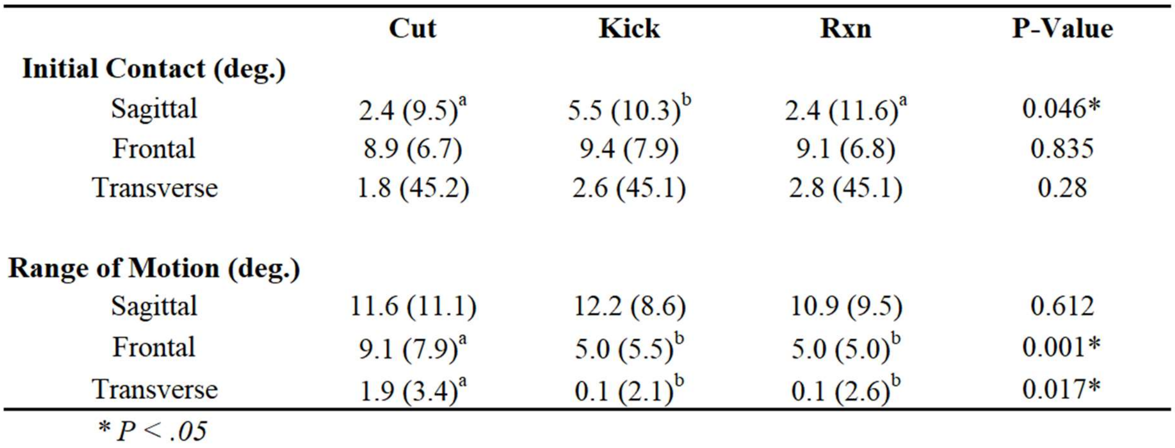
	Cut	Kick	Rxn	P-Value
Initial Contact (deg.)				
Sagittal	36.0 (8.6)^{a}	32.2 (7.1)^{b}	33.7 (8.1)^{a}	0.002*
Frontal	-8.0 (8.2)	-6.1 (7.1)	-5.8 (6.7)	0.108
Transverse	17.4 (34.6)^{a}	14.0 (34.5)^{b}	13.5 (33.4)^{b}	0.003*
Range of Motion (deg.)				
Sagittal	1.0 (2.9)	1.1 (1.9)	0.8 (2.1)	0.758
Frontal	0.0 (1.2)	0.2 (1.3)	0.1 (1.3)	0.802
Transverse	1.6 (3.8)	1.7 (2.6)	0.8 (2.9)	0.219

* $P < .05$

Ankle Joint Discrete Variables

At the ankle joint, there was a significant difference in impact position between the KICK and RXN conditions, with the KICK condition showing 3.1° more of dorsiflexion at IC (Table 4). In the frontal and transverse planes, the ankle joint moved through a significantly larger ROM in the CUT condition, relative to both the KICK and RXN condition. This could be due to the changing nature of the cutting task and the functional requirements of the KICK and RXN tasks.

Table 4. Mean (SD) ankle joint discrete variables during the three conditions. For variables with a significant p-value, like letters indicate values that are not different.



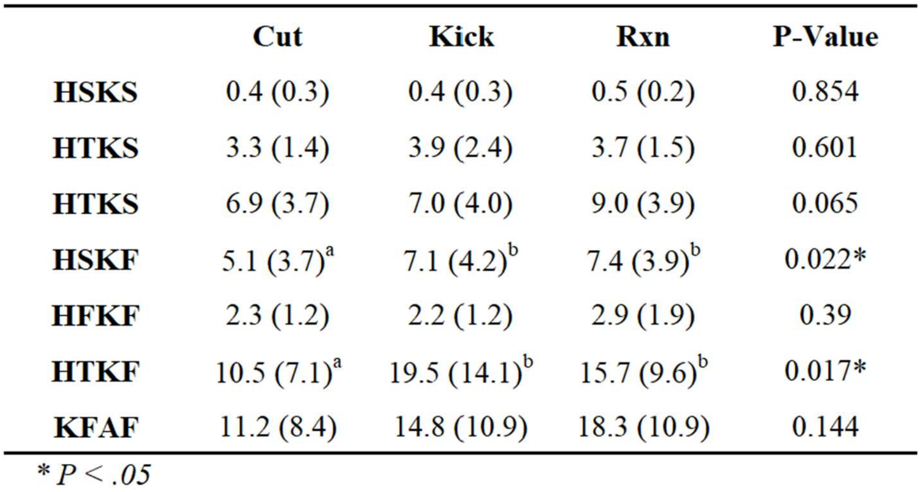
	Cut	**Kick**	**Rxn**	**P-Value**
Initial Contact (deg.)				
Sagittal	2.4 (9.5)[a]	5.5 (10.3)[b]	2.4 (11.6)[a]	0.046*
Frontal	8.9 (6.7)	9.4 (7.9)	9.1 (6.8)	0.835
Transverse	1.8 (45.2)	2.6 (45.1)	2.8 (45.1)	0.28
Range of Motion (deg.)				
Sagittal	11.6 (11.1)	12.2 (8.6)	10.9 (9.5)	0.612
Frontal	9.1 (7.9)[a]	5.0 (5.5)[b]	5.0 (5.0)[b]	0.001*
Transverse	1.9 (3.4)[a]	0.1 (2.1)[b]	0.1 (2.6)[b]	0.017*

* *P* < .05

Joint Coordination Variability

When comparing variability between various joint couplings (Table 5, Figure 4), significant differences in variability were found within two couplings involving the hip and the knee frontal plane (HSKF and HTKF). For both couplings, joint coordination variability was significantly less for the CUT task compared to the other two.

Table 5. Mean variability (SD) of joint coupling vector coding angles during the three conditions. For variables with a significant p-value, like letters indicate values that are not different.



	Cut	**Kick**	**Rxn**	**P-Value**
HSKS	0.4 (0.3)	0.4 (0.3)	0.5 (0.2)	0.854
HTKS	3.3 (1.4)	3.9 (2.4)	3.7 (1.5)	0.601
HTKS	6.9 (3.7)	7.0 (4.0)	9.0 (3.9)	0.065
HSKF	5.1 (3.7)^{a}	7.1 (4.2)^{b}	7.4 (3.9)^{b}	0.022*
HFKF	2.3 (1.2)	2.2 (1.2)	2.9 (1.9)	0.39
HTKF	10.5 (7.1)^{a}	19.5 (14.1)^{b}	15.7 (9.6)^{b}	0.017*
KFAF	11.2 (8.4)	14.8 (10.9)	18.3 (10.9)	0.144

* *P* < *.05*

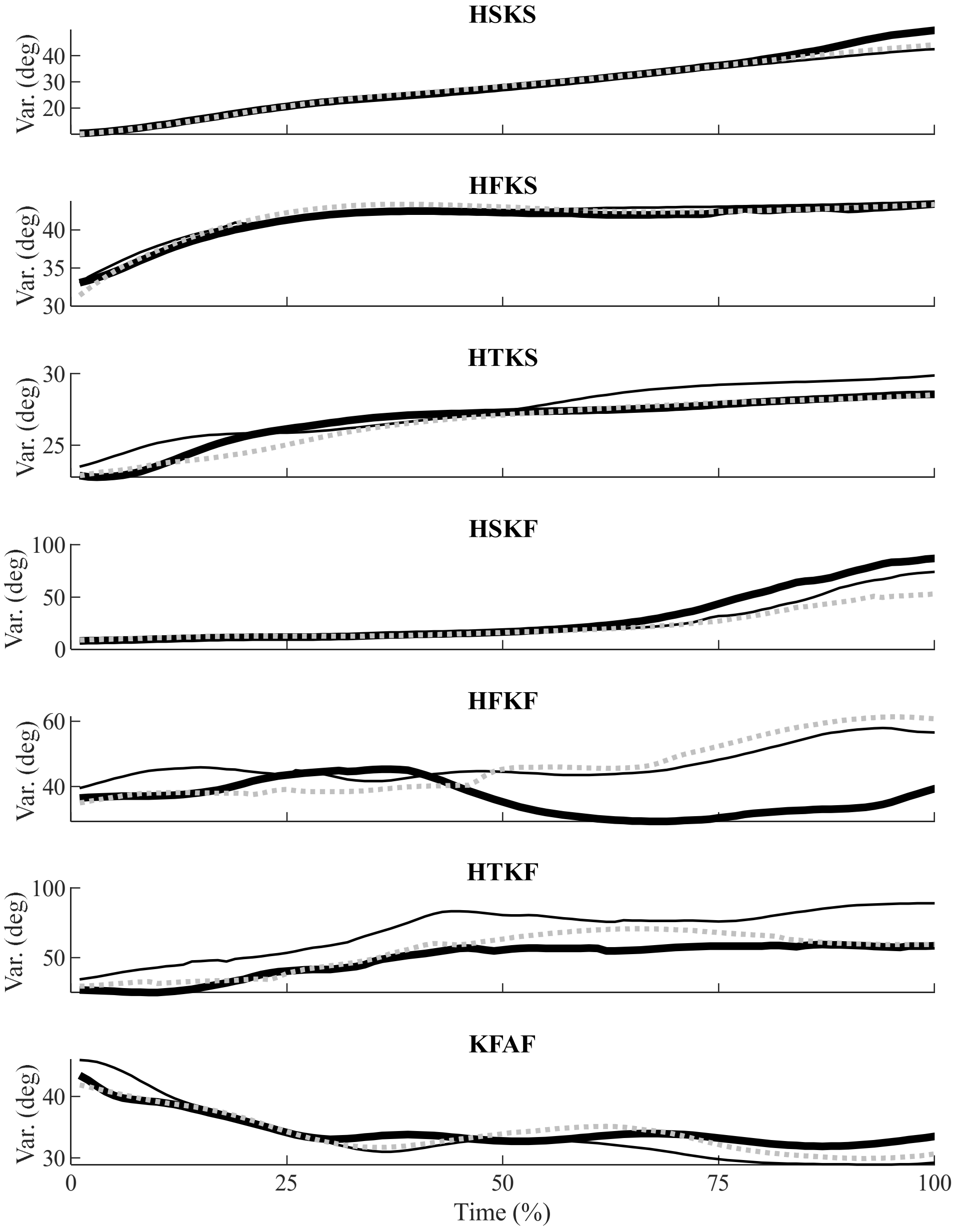


Figure 4. Vector coding variability for joint couplings across the entire stance phase. Thick line = CUT, thin line = KICK, dotted line = RXN.

Chapter 5: Discussion

The purpose of this study was to explore changes in lower limb mechanics and joint coordination variability amongst the addition of a dual motor task and reactivity to a run-to-cut motor task. The first hypothesis of this study was that, by adding a dual motor task to a run-to-cut task, knee joint mechanics would be more in line with those previously discussed as mechanistic for ACL injury, including, but not limited to, increased knee valgus and increased knee extension. The hypothesis also notes that by adding reactivity to the dual motor task, there would be more pronounced changes to kinematics. This hypothesis was partially supported. While changes in knee valgus and knee extension at initial contact were not identified, as hypothesized, other characteristics were present within the KICK and RXN conditions that indicate potentially greater risk to the ACL. The second hypothesis was that joint coordination variability would increase as we introduced a dual motor task and reactivity to the run-to-cut task. Heightened joint coordination variability was found to emerge within the KICK and RXN conditions, partially supporting our second hypothesis. Minimal differences were discovered between the KICK and RXN conditions, which tells us that while shifting to an external focus of attention will adjust motor behaviors, additional reactivity may not be necessary.

The current study uncovered a significantly greater ROM in the sagittal plane in the CUT condition, as compared to the KICK condition, potentially indicating a greater, active loading at the knee joint (Pollard et al., 2005) and a more effective, displaced energy absorption. Furthermore, greater hip flexion as well as internal rotation at initial contact of the CUT condition may similarly point to a greater ability to actively absorb energy, thereby limiting risk to passive structures such as the ACL. Greater dorsiflexion at initial contact in the KICK condition could point to a more rigid lower limb, indicating less effective energy absorption. In all kinematic variables tested, there were no significant differences between the KICK and the RXN conditions, indicating that the addition of reactivity, and a moving soccer ball that needs to be redirected, did not significantly change the motor behavior of subjects, relative to the stationary soccer ball pass.

Of the seven joint couplings explored, two exhibited significant differences in joint coordination variability: 1) Sagittal plane hip movement + Frontal plane knee movement and 2) Transverse plane hip movement + Frontal plane knee movement. Both significant differences showed the largest joint coordination variability in the RXN and KICK conditions, and both included the frontal plane knee. This fact could be revealing in that knee abduction is a common biomechanical risk factor for ACL injury. The pattern of greater joint coordination variability in the KICK and RXN conditions seemed to emerge in the majority of the couplings measured while only two met our threshold and were determined to be significantly different.

Along with being significantly more flexed at initial contact, the hip joint was also found to be significantly more internally rotated, relative to both the KICK and RXN condition. These changes in transverse plane hip kinematics were not present across other run-to-cut task studies (Besier et al., 2001; Hughes & Dai, 2021). It is possible that the increased internal rotation at the hip joint during the CUT condition was simply caused by the changing task itself. In order to pass a soccer ball with the inside of one’s foot, an athlete needs to externally rotate at the hip joint. Because both the KICK and RXN conditions required subjects to immediately pass a ball after cutting, it is likely that the function of the subsequent pass caused a change in the kinematics active during the cut. In this case, the change was a less internally rotated hip in preparation for the external rotation needed to pass the soccer ball. Further, greater internal rotation of the hip joint in the CUT condition could be further emergence of absorptive, less rigid, properties relative to the KICK and RXN conditions. Greater internal rotation of the hip in the CUT condition may take load off the ACL by minimizing internal rotation of the tibia relative to the femur.

At the ankle joint, significantly greater dorsiflexion existed at IC in the KICK condition, relative to the CUT condition. Furthermore, the CUT condition caused significantly greater ankle inversion range of motion during the deceleration phase. It is possible that greater ankle dorsiflexion at initial contact was caused by the changing task itself, similar to above. In order to pass a soccer ball with the inside of one’s foot, the ankle must move into a rigid, dorsiflexed position. During the KICK condition, subjects may have maintained a more rigid and dorsiflexed ankle in preparation for the upcoming kick activity, however, no differences were found between the RXN and CUT conditions, which could render this theory invalid. Regarding the greater ankle inversion range of motion during the deceleration phase, it appeared the athletes were able to complete the CUT condition at a slightly sharper angle, while in the KICK and RXN conditions subjects had to account for the swing of their kicking leg post-cut, resulting in a slightly more rounded cut. This was based strictly on observations made during testing, but it does coincide with the quantitative findings in the frontal plane at the ankle joint.

The kinematic data presented within the current study is in line with past research on run-to-cut activities (O'Connor et al., 2009; Weinhandl et al., 2013). O'Connor et al. (2009) showed touchdown knee angles of -16.4°, -1.4°, and -1.3° in the sagittal, frontal, and transverse planes. This compares to the current study's IC angles at the knee joint of -17.7°, -1.0°, and -6.6° in the sagittal, frontal, and transverse planes. The joint coordination variability data presented within this current study, calculated utilizing vector coding methods, appear to be in line with those shown in past research by Heidarnia et al. (2022) and Pollard et al. (2005). For instance, in Heidarnia's dual motor task they uncovered an HSKF joint coordination variability of 3.1° for a healthy population, and 5.1° for an ACL reconstructed population. This compares to our HSKF joint coordination variability of 5.1°, 7.1°, and 7.4° degrees for the CUT, KICK, and RXN conditions, respectively.

In general, differences uncovered in the current study point towards heightened task complexity creating motor behaviors that are more in-line with risk of sustaining an ACL injury. For example, significant elevation of joint coordination variability in the KICK and RXN conditions was always tied to frontal plane knee patterns (HSKF and HTKF). A greater variability in the way that the frontal plane knee coordinates with the sagittal and transverse plane hip could push athletes closer to a point of mechanical failure at passive structures that support the knee joint, such as the ACL. Furthermore, limited sagittal plane knee range of motion during the deceleration phase was also identified in the KICK condition. Less ROM within this condition could be due to a multitude of factors including greater comfort with the relatively simple, constrained CUT task. This increased comfort may have allowed subjects to actively absorb more of the deceleration loading via knee flexion and the elastic tissues that surround the joint, as opposed to relying on passive, more rigid structures. Secondly, by incorporating a kicking activity immediately after completion of the cutting task, the current study created an external focus of attention within the subjects. This external focus of attention may have taken away from the subject's ability to focus on the absorption of the cut as their attentional focus was placed on the immediately following kick activity. Past research has attempted to create an external focus of attention during a run-to-cut task by passing a basketball (Almonroeder, 2017), catching a basketball chest pass (Norte et al., 2020), attempting to intercept a passed basketball (Heidarnia et al., 2022), adding a reactionary stimulus (Besier et al., 2001), or carrying an object (Chaudhari et al., 2005). The majority of these studies report similar findings that shifting an athlete's attentional focus causes changes in kinematics and the manner that a task is performed. Chaudhari et al. (2005) showed that simply carrying a lacrosse stick while cutting led to increased valgus loading. Almonroeder (2017) found significantly less knee flexion within the dual-task conditions as well as significantly less hip flexion, both of which were found in the current study as well. And, in a review of the literature, Hughes et al. (2021) concluded that "decision making and dividing attention have been shown to influence a number of biomechanical risk factors for ACL injury" including "reduced knee flexion angle…"

All of these studies discussed in the preceding paragraph utilize an upper body or visual dual task to elicit the external focus of attention. For a sport like soccer where the lower body is responsible for both locomotion as well as the functional task and object manipulation, these studies may lack some ecological validity. The fact that similar motor behaviors appear to emerge when attentional focus is shifted using an upper limb task, visual task, or lower limb task, as in the current study, would lead us to believe that it’s less important how attentional focus is shifting, and more important that it simply is changing.

Throughout ACL prevention programs, variability is consistently seen as a negative characteristic of movement, or as noise that should be removed (Hamill et al., 1999; Kelso, 1997). This study found elevated joint coordination variability within certain joint couplings as task complexity increased which, as discussed above, could be seen as pushing athletes closer to a point of mechanical failure. However, instead of viewing that finding as indicative of injury creating, we can also view that finding as potentially injury mitigating. Past studies have shown that constrained jumping, landing, and cutting tasks may not be fully representative of a more unconstrained, reactive motor tasks, such as those sport may create (O’Connor et al., 2009; Weir et al., 2019). Sport is inherently complex. The goal of ACL prevention and physical preparation programs is to prepare athletes for the demands of sport. This study, when taken into consideration with results from other studies, shows that as task complexity increases, motor behaviors change. Being the case, ACL prevention programs may be improved, based on the principles of specificity, by incorporating more complexity, reactivity, and therefore, variability. If the goal is to prepare athletes for sport, we should be considering the motor behaviors, complexities, and demands of those sports. The motor behaviors athletes utilize to complete constrained tasks in training, and these past ACL prevention programs - that are only partially effective - may not be fully representative or preparatory for sport. Instead of considering variability to be “noise” within training programs, practitioners may be better suited to encourage variability, preparing athletes for the upcoming variability that sport and complexity promote.

A limitation of this study is that the motor tasks being completed are still not fully representative of the sporting environment, or the athlete-environment relationship that exists within it (Bolt et al., 2021). A second limitation of this study is the fact that our subject sample did not allow us to compare gender differences. Based on previous studies comparing the motor behavior of males versus females, there does appear to exist significant differences that could affect ACL injury risk (Decker et al., 2003; Hughes et al., 2008; Pollard et al., 2005). The third central limitation of the current study is that an exclusion criteria included was previous ACL injury and surgery. Heidarnia et al. (2022) showed that normal subjects behave quite differently than those with a previous injury to the ACL. The current study therefore cannot be extrapolated to a population that includes those with previous ACL injury.

Future studies should attempt to measure motor behaviors within the actual sporting environment that they occur within. As our study shows, motor behaviors are quite easily changed by shifting task demands and environments. Being the case, the motor behaviors executed by athletes within contests needs to be measured and compared to those utilized within our training and prevention programs to further understand the transferability and applicability. Furthermore, future studies should compare joint coordination variability measures across genders as this could be a crucial piece of information regarding the higher likelihood of female ACL injuries, relative to males. Finally, while it was not a focus of this study, exploring changes in kinetics could provide insights into the joint loading patterns that are being created by shifting attentional foci, reactivity, and complexity.

In conclusion, implementing an external focus of attention causes athletes to utilize motor behaviors more in line with those mechanistic for ACL injuries. Additional reactivity, on top of shifting to an external focus of attention, may not be necessary to change motor behaviors. Past ACL prevention programs are inconsistent and lack some effectiveness. It is possible that more complex tasks - specifically those that elicit an external focus of attention - are necessary to transfer and prepare athletes for sport. Furthermore, a lower extremity dual task, like the one utilized within the current study, may not necessarily be better than an upper extremity dual task, even for soccer athletes, as changes in motor behaviors were similar. Practitioners should utilize the information found within the current study to help guide their programming, understanding that variability, complexity, and attentional foci are important considerations that will change an athlete's motor behaviors.

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APPENDIX A

Recruitment Flyer

Soccer Players Needed for a Research Study!

TITLE

The Effects of Task Complexity on Knee Mechanics and Joint Coordination Variability during a Side-Step Cutting Task

PURPOSE

We are attempting to compare mechanics and coordination strategies during a run-to-cut with and without the inclusion of a dual task - kicking a soccer ball.

WHERE WILL THIS TAKE PLACE?

UW-Milwaukee Enderis Hall - Room 132

WHO CAN PARTICIPATE?

- Young adults between ages 18-25
- Must have 3+ years of soccer experience (high school or beyond)
- Must be able to perform a run-to-cut task
- Must not have any current lower extremity injuries (within the last 6 months)
- Must not have a previous ACL injury or ACL reconstruction surgery
- Must not have a previous lower extremity surgery
- Must not be pregnant

WHAT DOES THIS STUDY INVOLVE?

- One testing session (~1.5 hours)
- Filling out screening and subject information questionnaire
- Perform run-to-cut task pre-planned
- Perform run-to-cut task into an immediate soccer ball pass
- Perform run-to-cut task into an immediate reactionary soccer ball pass

- Wearing tracking markers while performing the study

INTERESTED IN PARTICIPATING OR HAVE QUESTIONS?

Contact: Carter Schmitz

Email: schm2484@uwm.edu

Phone: 262-352-3848

APPENDIX B

Recruitment Script

Hi, my name is Carter and I am a student in the master's student in the Kinesiology program at UW-Milwaukee. I am conducting a research study examining cutting mechanics within a young adult population and I'd like to welcome you to participate in the study. The goal of the study is to understand the loading on the legs, specifically the knee, when completing a run-and-cut task within different conditions. I am looking for past soccer players (male or female) with at least three-years of soccer experience (high school or beyond).

Participation in this study is voluntary and will only take about two hours. During that time, you will be asked to perform a run-and-cut task while motion and force information are recorded. The goal is to record at least 5 successful trials in three different conditions. The first will be a simple pre-planned run-and-cut. The second will be a run-and-cut plus a soccer pass into the goal. Finally, the third condition will be a run-and-cut with a reactionary soccer pass into a goal.

If you are interested in participating, I will send you an eligibility screening questionnaire. A later email will be sent informing you if you are an eligible candidate or not. To be eligible, you must have at least 3 years of soccer experience (within the last 10 years), be recreationally active, and not have any lower extremity surgeries, conditions, or recent injuries that may interfere with the completion of a run-and-cut task, and must not be pregnant.

There will be no direct benefit to you or any subject compensation. However, your participation will benefit society and the athlete population by furthering the scientific literature and understanding of ACL injuries. The overall results will also be shared to you once the study is completed.

If you have questions or would like to participate, please email me (schm2484@uwm.edu) and I will be more than happy to provide further details.

APPENDIX C

Screening Questionnaire

1. What is your name?
2. Please provide a contact email.
3. Are you between the ages of 18 and 25?
4. Do you have 3 years of soccer experience (high school or beyond)?
5. Are you pregnant?
6. Have you had any lower extremity injuries within the last 6 months? If so, please provide further details.
7. Have you ever had any lower extremity surgeries? If so, please provide further details.
8. Do you have a current condition(s) that prevents/interferes with your ability to perform running or cutting tasks (e.g., running 15 meters and cutting at a 45 degree angle)? If so, please provide further details.
9. Do you have any hearing, vision, or mobility impairments?
10. Are you recreationally active (physically train, work out, or play a sport for a minimum of 2 hours per week)

APPENDIX D

Consent Form

Study title	The Effects of Task Complexity on Knee Mechanics and Joint Coordination Variability during a Side-Step Cutting Task
Researcher	Carter Schmitz, B.A., Master’s student in the Department of Kinesiology

We’re inviting you to participate in a research study. You are free to withdraw from the study at any time. If you agree to participate now, you can always change your mind later. There are no negative consequences, whatever you decide.

What is the purpose of this study?

We want to compare the effects of task complexity on knee mechanics and joint coordination variability during a run-to-cut motor task.

What will I do?

Before coming in:

- You’ll complete a screening questionnaire to determine your eligibility for this study. (5 minutes)
- We will ask you to wear/bring your athletic shoes and as minimal sports clothing as you are comfortable with for data collection (e.g., sports bra, spandex, tank top, running shorts) (2 minutes)

In our lab:

- You will be walked through the informed consent process, complete a questionnaire about your yourself, and have your height and weight measured (5 minutes)
- You will be asked to warm-up by jogging, stretching, doing jumping jacks, etc. (10 minutes)
- You will be asked to perform 3-5 practice run-to-cut tasks (5 minutes)
- We will place reflective markers on your skin and shoes. Markers will be placed on the lower back, hips, and right thigh, knee, shin, ankle, and shoe. Cameras will only record the positions of the markers while you perform the activities below. The cameras do not record your image. (10 minutes)
- You will be asked to perform the following three tasks in a random order. Five

successful trials of each task will be recorded. (45 minutes)

- Running and cutting
- Running, cutting, and kicking a stationary soccer ball into a goal
- Running, cutting, and kicking a passed soccer ball into a goal

Risks

Possible risks	**How we're minimizing these risks**
Breach of confidentiality (your data being seen by someone who shouldn't have access to it)	· All identifying information is removed and replaced with a study ID. · We'll store all electronic data on a password-protected, encrypted computer. · We'll store all paper data in a locked filing cabinet in a locked office.
Minor muscle soreness, muscle strain, or ligament strain (Unlikely)	· We will not ask you to perform activities beyond a typical low-impact training session. · Practice trials will be performed to allow you to become familiar with the protocol · Adequate and frequent rest periods will be given. · We'll provide first-aid medical treatment in the unlikely event of physical injury · Students will be referred to the Norris Health Center for follow-up care. Non-UWM students will be referred to their primary care physician and will be responsible for all expenses incurred.

Minor skin irritation from the reflective marker adhesives (Unlikely)	· If you feel any irritation while participating, please tell the investigators as soon as possible · Students will be referred to the Norris Health Center for follow-up care. Non-UWM students will be referred to their primary care physician and will be responsible for all expenses incurred.

There may be risks we don't know about yet. Throughout the study, we'll tell you if we learn anything that might affect your decision to participate.

What if I am harmed because I was in this study?

If you're harmed from being in this study, let us know. If it's an emergency, get help from 911 or your doctor right away and tell us afterward. We can help you find resources if you need psychological help. You or your insurance will have to pay for all costs of any treatment you may need.

Other Study Information

Possible benefits	· The athletic population will benefit from more research on the knee joint, working to improve coaches' and practitioners' ability to limit future ACL injuries · This study will increase the world's understanding of motor control, and more specifically, variability. · You may feel satisfaction or fulfillment from contributing to research! • Subjects will be compensated with a $20 Amazon gift card
Estimated number of participants	15 young adults (male and female; ages 18-25)
How long will it take?	1.5 Hours

Costs	On campus parking
Compensation	Subjects will be compensated with a $20 Amazon gift card
If I don’t want to be in this study, are there other options?	No.
Future research	Your data won’t be used or shared for any future research studies.

Data Security

What identifying information will be collected and why?	Your name and email address will be collected in order to share overall results when the study is completed.
How long will my data be kept?	Until August 31^{st}, 2025
How is data kept secure?	· Screening questionnaire data will be stored on a password protected account. Electronic data will be stored on a desktop computer in END 132, which will be password protected. Data collected on paper will be stored in a file cabinet in END 132, which will be locked.

Who might see my data and why?

The researchers	To conduct the study and analyze the data
The IRB (Institutional Review Board) at UWM The Office for Human Research Protections (OHRP) or other federal agencies	To ensure we’re following laws and ethical guidelines
Anyone (public)	We plan to share our findings in publications or presentations. You will not be identified by name.

Contact information:

For questions about the research, problems, or complaints	PI: Dr. Kristian O’Connor SPI: Carter Schmitz	414-251-5277 / krisocon@uwm.edu 262-352-33848 / schm2484@uwm.edu
For questions about your rights as a research participant, problems, or complaints	IRB (Institutional Review Board; provides ethics oversight)	414-662-3544 / irbinfo@uwm.edu

Signatures

If you have had all your questions answered and would like to participate in this study, sign on the lines below. Remember, your participation is completely voluntary, and you’re free to withdraw from the study at any time.

____

Name of Participant (print)

____ ____________

Signature of Participant Date

____

Name of Researcher obtaining Consent (print)

____ ____________

Signature of Researcher obtaining Consent Date

Remember, your participation is completely voluntary, and you’re free to withdraw from the study at any time. Do you have any questions about the study? Do you agree to participate?

APPENDIX E

Demographic, Injury History & Soccer Skill Level Questionnaire

For the Participant:

Please answer the following questions to the best of your ability.

Age: _____________

Gender: __________________

Height: _____________

Weight: ___________________

How many years of soccer experience do you have (high school and beyond)? ________

Comments/Notes:

____
____
____