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Cognitive Contributions to Anterior Cruciate Ligament Injury Risk

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COGNITIVE CONTRIBUTIONS TO
ANTERIOR CRUCIATE LIGAMENT INJURY RISK

by

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ABSTRACT

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by

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The purpose of this dissertation was to explore how cognitive factors contribute to non-contact anterior cruciate ligament (ACL) injury risk in young females. We specifically wanted to develop a better understanding of how the movement patterns of females with varying cognitive attributes/abilities are influenced as the cognitive demands associated with a task progress (Chapter 2). We also wanted to explore how task-related cognitive demands influence movement. We altered the cognitive demands associated with a movement task by requiring participants to execute a maneuver while attending to a simulated teammate (Chapter 3) or to a ball overhead (Chapters 4 & 5). In addition, we also imposed temporal constraints on decision-making (i.e. movement selection) by requiring participants to maneuver in response to an external stimulus (Chapters 4 & 5).

To investigate the influence of individual cognitive attributes, we utilized a computer-based clinical test to assess cognitive function for a group of 45 uninjured young females. The cohort was delineated into groups based on their performance on the reaction time component of the cognitive test (slow reaction times vs. fast reaction times). Both groups also performed a lateral cutting task in two conditions (un-planned, pre-planned). For the un-planned condition,

participants initiated a trial and then reacted to a stimulus that dictated the movement they were to perform (land, jump, or cut), which imposed temporal constraints on decision-making. During the pre-planned condition, participants knew to perform the cut prior to initiating a trial. We expected that the mechanics of the participants with slower reaction times would be influenced to a greater extent when there were temporal constraints on decision-making. Interestingly, this was not the case. In fact, we found that the participants with slower reaction times landed with greater forces regardless of the cognitive demands associated with the task. It appears that cognitive function plays a prominent role in an individual's ability to control their movement, even when there are not additional cognitive demands imposed.

Our assessment of the impact of additional task-related cognitive demands on movement included 20 uninjured young females with basketball experience. In our first analysis, we found that requiring participants to perform a basketball chest pass immediately after landing from a cut altered their mechanics in a manner that may increase ACL injury risk in comparison to trials performed without the pass. We also performed an analysis where participants performed a drop vertical jump task with and without additional cognitive demands. When temporal constraints were imposed on decision-making, participants demonstrated landing mechanics that may increase their ACL injury risk compared to baseline (i.e. trials performed without additional cognitive demands). We found similar results when participants were required to attend to a ball suspended overhead during execution of the drop vertical jump. Our findings indicate that additional task-related cognitive demands have a prominent influence on movement.

The results of this dissertation highlight how cognitive factors (individual and task-related) may contribute to non-contact ACL injury risk. Failure to incorporate cognitive factors could limit the effectiveness of ACL injury risk screening and prevention.

I dedicate this work to my wife Sarah and daughter Grace
I love you both very much

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

Introduction

As many as 250,000 people injure their anterior cruciate ligament (ACL) in the United States each year (Griffin et al., 2006). The majority of ACL injuries occur in young female athletes involved in sports such as basketball and soccer. Unfortunately, many athletes will not return to competitive sports participation following an ACL injury (Ardern, Webster, Taylor, & Feller, 2011). A variety of factors may explain why athletes frequently do not return-to-sport (e.g. physical impairments, fear of re-injury, etc.). Regardless, it is concerning as these athletes will not experience the positive health-related benefits that are associated with sports participation (Pate, Trost, Levin, & Dowda, 2000). In addition, there may also be long-term consequences in regard to joint health, even when an athlete undergoes a successful ACL reconstruction procedure (Harris, Driban, Sitler, Cattano, & Balasubramanian, 2015). For instance, one study found that more than half of former female soccer players that have suffered an ACL injury demonstrate radiographic evidence of knee osteoarthritis within 12 years of their initial injury, despite undergoing an ACL reconstruction (Lohmander, Ostenberg, Englund, & Roos, 2004). In addition, 75% of these athletes reported knee-related symptoms that negatively impacted their quality of life. In light of the high incidence of ACL injury, the negative effect on sports participation, and the potential long-term consequences in regard to joint health, developing effective ACL injury risk screening and prevention programs is of the utmost importance. The success of this endeavor is dependent on a thorough understanding of the underlying risk factors for injury (Bahr & Krosshaug, 2005; McLean, 2008).

More than 70% of ACL injuries are characterized as non-contact, as they are not the result of a collision with a teammate or opponent (Boden, Dean, Feagin, & Garrett, 2000; Krosshaug, Nakamae, et al., 2007). Three distinct categories typically describe risk factors for non-contact ACL injury: anatomical risk factors, hormonal risk factors, and biomechanical risk factors (Griffin et al., 2006). However, cognitive factors may also play an important role, as it has been previously reported that athletes that sustain non-contact ACL injuries demonstrate poorer baseline performance on a clinical test of cognitive function in comparison to uninjured athletes (Swanik, Covassin, Stearne, & Schatz, 2007). The test utilized in this study was comprised of four main components that assess verbal memory, visual memory, visuomotor processing speed, and reaction time. The athletes that went on to sustain a non-contact ACL injury performed worse on each component. While this finding is certainly interesting, our understanding of the factors that underlie the relationship between cognitive function and ACL injury risk is limited. In fact, the most recent consensus statement from the ACL Research Retreat included a call for studies to improve the understanding of the relationship between central processes (e.g. reaction time, decision-making, attention, etc.) and ACL injury risk in order to, 'unravel the brain's role in maintaining joint stability' (Shultz et al., 2015). Developing this understanding has the potential to improve our ability to identify athletes that are at risk for injury and effectively intervene.

The unpredictable and constantly evolving sports environment presents athletes with a myriad of stimuli across different mediums (e.g. visual, auditory, somatosensory) (Schmidt & Lee, 2014). Unfortunately, attentional capacity is limited and an athlete must differentiate between stimuli which are relevant to the task and those that can be neglected (Marois & Ivanoff, 2005; Miller & Clapp, 2011). They must then integrate all relevant information and select a motor response that will promote the accomplishment of a sport-related task (e.g. evade a defender), and then execute the corresponding movement. Ideally, this process will result in the intended outcome without injury. However, it appears that achievement of this objective is inconsistent in light of the high incidence of acute injury during sports participation (Hootman, Dick, & Agel, 2007; Powell & Barber-Foss, 1999). Since the performance of complex athletic maneuvers within the dynamic sports environment routinely imposes a high cognitive load, participation in sports without injury likely requires a high level of cognitive function. As a result, the link between cognitive function and ACL injury risk may be related to an athlete's ability to perform the complex cognitive processing required to maneuver within the sports environment.

As highlighted, athletes performing in the sports environment must execute complex movements under a high cognitive load. In addition, significant temporal constraints are placed on the cognitive processes involved in the selection of a movement ('decision-making') (Besier, Lloyd, Ackland, & Cochrane, 2001; Miller & Clapp, 2011). Sports performed within an open environment such as basketball and soccer are dynamic in nature. Athletes participating in these sports must respond to a multitude of external stimuli (e.g. teammates, opponents, the ball), without the opportunity to pre-plan their movement. Most studies investigating ACL injury risk from a biomechanical perspective utilize tasks that allow for pre-planning of a movement prior to the initiation of a trial (Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010; Pollard, Sigward, & Powers, 2007; Sigward & Powers, 2006). Not surprisingly, the ecological validity of this approach has been questioned (Besier et al., 2001). In an attempt to simulate the demands of sports, some have begun to implement tasks that do not allow for pre-planning by presenting the stimulus which guides the direction of the movement after the athlete has initiated the trial

(Almonroeder, Garcia, & Kurt, 2015). Interestingly, multiple studies have reported that incorporating this type of ‘decision-making’ into testing often results in lower extremity mechanics that may increase ACL loading (e.g. reduced hip and knee flexion, increased frontal plane knee loading) (Besier et al., 2001; Brown, Palmieri-Smith, & McLean, 2009; Collins, Almonroeder, Ebersole, & O'Connor, 2016; Cortes, Blount, Ringleb, & Onate, 2011; Kipp, Brown, McLean, & Palmieri-Smith, 2013; Lee, Lloyd, Lay, Bourke, & Alderson, 2013; Mornieux, Gehring, Furst, & Gollhofer, 2014; Park, Lee, Ryue, Sohn, & Lee, 2011; Weinhandl et al., 2013). The results of these studies indicate that imposing temporal constraints on the cognitive processes involved in decision-making may have a prominent influence on movement. This may help to explain why athletes with slower baseline reaction times and visuomotor processing speeds may be at greater risk for sustaining a non-contact ACL injury (Swanik et al., 2007). An athlete that is challenged to consistently meet the demands of this environment may be unable to maneuver in a manner that allows for successful performance without injury.

While the athletic environment itself imposes significant cognitive demands, this is not the only challenge presented to athletes. Sports such as basketball and soccer also require an athlete to simultaneously allocate attentional resources to additional tasks (e.g. dribbling, passing, etc.) while moving. The influence of additional task demands is often analyzed using a dual-task paradigm, where individuals divide their attention between a primary task and an additional secondary task they are performing simultaneously (Magill & Anderson, 2014). The decrement in performance on the primary task typically serves as an indicator of the attentional demands associated with the secondary task. Surprisingly, very few studies have incorporated secondary tasks into their testing protocols when analyzing the performance of a sports-related maneuver. However, preliminary results indicate that subtle alterations in a testing protocol to incorporate additional sport-related tasks may have a prominent influence on an athlete's movement. For instance, one study required a group of female basketball players to perform a 45° run-and-cut task in two conditions; one in which they simply performed the cut and another in which they performed the cut while also dribbling a basketball (Chan, Huang, Chang, & Kernozek, 2009). The athletes demonstrated increased frontal plane knee loading for the trials that included the additional dribbling task. It is likely that the effect of the additional dribbling task on knee mechanics was the result of the athlete having less attentional resources available to allocate to performing the run-and-cut task. However, the effects of the additional dribbling task could also be the result of constraining the upper extremities. A previous study reported that constraining the upper extremities by having individuals carry a football or a lacrosse stick when performing a run-and-cut task also results in increased loading of the knee in the frontal plane (Chaudhari, Hearn, & Andriacchi, 2005).

Improving our understanding of the role in which the focus of attention plays in regard to lower extremity mechanics during cutting could help to explain the underlying reason for a curious observation from video taken at the time of ACL injury. Video analysis has consistently indicated that the vast majority of ACL injuries in team sports, such as basketball and handball, occur when an athlete is on offense and is in control of the ball (Boden, Torg, Knowles, & Hewett, 2009; Krosshaug, Nakamae, et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). For instance, one study that analyzed non-contact ACL injuries in female handball players reported that each of the 19 injuries assessed occurred while the athlete was on offense and was handling the ball (Olsen et al., 2004). This finding may be due to the mechanical constraints imposed on the upper extremities; however, it is also possible that the increased risk of ACL injury when an athlete is in possession of the ball is due to the relatively high cognitive load they are experiencing at this time. An athlete in possession of the ball must allocate attentional resources to manipulating the ball and must also be aware of the location of their opponents, teammates, and the goal in order to make decisions within a dynamic environment (e.g. shoot vs. pass).

Despite the development of a link between cognitive function and ACL injury risk by Swanik et al. (2007), ACL injury risk screening typically relies solely on the assessment of biomechanical factors. Unfortunately, this approach has demonstrated limited success (Goetschius et al., 2012; Krosshaug et al., 2016; Smith, Johnson, et al., 2012). The reluctance to incorporate cognitive factors may be the result of a poor understanding of the underlying reason(s) for the link between cognitive function and ACL injury risk. For instance, the relationship between an individual's cognitive attributes (e.g. reaction time) and their ability to maneuver within the sports environment is currently unknown. Understanding how an individual's risk of ACL injury is influenced by their cognitive attributes would help to optimize risk screening and prevention programs. There is also a need to develop the understanding of how task-related cognitive demands (e.g. decision-making, focus of attention) influence an individual's movement. Despite encouraging progress to improve the ecological validity of biomechanics testing protocols by incorporating a decision-making component, or integrating sports-relevant secondary tasks, this is still a limited body of literature. Understanding how cognitive factors (individual cognitive attributes, task-related cognitive demands) influence lower extremity mechanics could potentially have a profound influence on ACL injury risk screening and prevention.

Statement of Purpose

The purpose of this dissertation was to improve the understanding of how cognitive factors (individual cognitive attributes, task-related cognitive demands) influence an individual's lower extremity mechanics during the execution of sports-related maneuvers (i.e. cutting, landing, jumping). This will assist in the development of ACL injury risk screening and prevention programs that incorporate cognitive factors related to injury.

Specific Aims & Hypotheses

Aim #1: Investigate the extent to which individual cognitive attributes influence movement.
<u>Working hypothesis:</u> The movement of females with relatively low cognitive function will be affected to a greater extent when there are temporal constraints on decision-making in comparison to females with relatively high cognitive function.

Aim #2: Determine the extent to which altering the focus of attention influences movement.
<u>Working hypothesis:</u> Requiring individuals to focus their attention on an additional sports-related task will affect their lower extremity mechanics during a land-and-cut maneuver.

Aim #3a: Evaluate how additional cognitive task demands influence an individual's movement.
<u>Working hypothesis:</u> Incorporating additional cognitive demands (related to decision-making and/or the focus of attention), during the execution of a task that assesses ACL injury risk from a biomechanical perspective (drop vertical jump), will influence lower extremity mechanics.

Aim #3b: Investigate the extent to which additional cognitive task demands influence the results of an ACL injury risk screening measure.

Working hypothesis: Incorporating additional cognitive demands (related to decision-making and/or the focus of attention), will influence the results of a commonly utilized two-dimensional measure to assess ACL injury risk during a drop vertical jump task.

Delimitations

1. The lower extremity mechanics of females without a history of ACL injury will be analyzed. As a result, it is possible that these individuals may not be reflective of a population that is at risk for ACL injury.
2. Despite a significant effort to replicate the demands of the sports environment, the testing protocols utilized in this study are still far less demanding than what an athlete will experience while participating in sports such as basketball and soccer.
3. The focus of this dissertation is to understand how cognitive factors influence an individual's lower extremity mechanics during the execution of sports-related maneuvers. However, it is likely that an athlete's risk of sustaining an ACL injury is dependent on a combination of anatomical, hormonal, biomechanical, and cognitive factors.

Assumptions

1. The individuals will conduct the cognitive testing to the best of their ability.
2. The biomechanical model will adequately represent lower extremity mechanics.
3. The demands of the sports environment will be reflected by the laboratory testing protocol.
4. The sample of females included in this study will reflect the population of interest.

Significance

An improved understanding of the role of cognitive factors (individual cognitive attributes, task-related cognitive demands) in relation to ACL injury may be critical to the development of more effective risk screening protocols. Currently, ACL injury risk screening typically does not integrate tasks that are challenging from a cognitive perspective. For instance, one of the most common tasks used to assess ACL injury risk involves the analysis of lower extremity mechanics as athletes perform a vertical jump after dropping from a box (drop vertical jump task). However, a recent study conducted a three-dimensional motion analysis for over 600 female athletes as they executed this task and reported that the mechanics of the lower extremity during landing were not significant predictors of subsequent non-contact ACL injury (Krosshaug et al., 2016). The limited predictive validity of ACL injury risk screening protocols of this nature may be due to the fact that they solely assess the capacity of the musculoskeletal system and do not impose any type of cognitive demand. As a result, individuals that are at risk for ACL injury due to cognitive factors may not be identified.

ACL injury prevention programs would also undoubtedly benefit from a more thorough understanding of how cognitive factors influence an athlete's risk of injury. A recent systematic review was conducted to assess the extent to which current prevention programs reduce the incidence of non-contact ACL injury in young female athletes (Noyes & Barber-Westin, 2014). The authors of this review included eight programs in their analysis. Fortunately, three of these programs resulted in a significant reduction in the incidence of ACL injury. However, the potential for any of these programs to have a prominent effect on ACL injury rates is certainly questionable, as even the most effective program would require 70 athletes to participate in training in order to prevent a single ACL injury. Considering the time and cost associated with administering these programs it is difficult to justify their wide-scale implementation, limiting their potential influence from an epidemiological perspective. The authors of this systematic review also commented on the striking degree of variability among the training components included in the programs they analyzed. Programs often included balance training, targeted strengthening, or movement training in isolation or in some combination. This variability is likely the result of an incomplete understanding of the factors that contribute to injury risk. Interestingly, none of the programs they analyzed incorporated training designed to target cognitive factors. This may be a key omission which contributes to the limited effectiveness of previously utilized injury prevention programs.

The results of this dissertation will assist sports medicine professionals in identifying athletes that are at risk for ACL injury due to cognitive factors and will also provide important insight to those interested in developing more comprehensive prevention programs. Each of these contributions is necessary in order to have a meaningful influence on the rate of non-contact ACL injury in female athletes.

Chapter 2

Poorer Performance on a Clinical Test of Reaction Time is

Associated with Higher Landing Forces During Lateral Cutting

Introduction

As many as 250,000 people injure their anterior cruciate ligament (ACL) in the United States each year (Griffin et al., 2006). The majority of these injuries occur in young female athletes participating in sports such as basketball and soccer (Hootman et al., 2007; Powell & Barber-Foss, 1999). Many female athletes will not return-to-sport following an ACL injury (Ardern et al., 2011) and those that do are at a significantly greater risk of sustaining a second ACL injury after they resume competition (Wiggins et al., 2016). As a result, there is an urgent need to develop programs to identify young females that are at risk for ACL injury and effectively intervene. The success of this endeavor is dependent on a thorough understanding of the underlying injury risk factors (Bahr & Krosshaug, 2005; McLean, 2008).

The vast majority (>70%) of ACL injuries are characterized as 'non-contact', as they are not the result of a collision with a teammate or opponent (Boden et al., 2000; Krosshaug, Nakamae, et al., 2007). Anatomical (Domzalski, Grzelak, & Gabos, 2010; Zeng et al., 2014), hormonal (Shultz, Sander, Kirk, & Perrin, 2005), and biomechanical factors (Hewett et al., 2005) have been studied extensively and may all influence an individual's risk of sustaining a non-contact ACL injury. In addition, cognitive factors may also play a prominent role (Swanik et al., 2007). Swanik et al. (2007) found that athletes that sustain non-contact ACL injuries demonstrate poorer baseline performance on a clinical test of cognitive function in comparison to uninjured athletes. The test utilized by these authors was the Immediate Post-Concussion Assessment and

Cognitive Testing (ImPACT) protocol, which is a computer-based program specifically designed to help clinicians determine when it is appropriate for an athlete to return-to-sport following a concussion (Elbin, Schatz, & Covassin, 2011; Schatz, 2010; Schatz & Sandel, 2013). ImPACT has four main composite measures: reaction time, visuomotor speed, visual memory, and verbal memory. In the study by Swanik et al. (2007), individuals that went on to sustain a non-contact ACL injury performed worse on each ImPACT measure, regardless of concussion history. While this finding is certainly interesting, the factor(s) that underlie the relationship between cognitive function and ACL injury risk are poorly understood (Shultz et al., 2015).

The cognitive processing involved in motor control is often characterized using a three phase model where individuals initially identify relevant stimuli from their environment, then select a motor response ('decision-making'), and finally organize the motor system to execute this response (Schmidt & Lee, 2014). Cognition plays a major role in all stages of goal-directed movement, but none more than the decision-making component. A challenge associated with sports participation is that significant temporal constraints are placed on decision-making, as athletes are often afforded only milliseconds for response selection (Miller & Clapp, 2011; Nakamoto & Mori, 2008). In general, not allowing athletes to pre-plan/select the maneuver they will perform prior to initiating a trial often results in mechanics that are likely to increase ACL loading (Almonroeder et al., 2015; Brown, Brughelli, & Hume, 2014). This supports the potential role temporal constraints on decision-making may play with respect to non-contact ACL injury. It is possible that individuals with slower reaction times may be challenged to a greater extent by the temporal constraints that are imposed on decision-making during sports participation, leading to altered lower extremity mechanics which may increase ACL loading. This may explain why athletes that demonstrate slower reaction times are at greater risk for ACL injury (Swanik et al., 2007). However, to our knowledge, there has not been an attempt to relate an individual's reaction times to their response to temporal constraints on decision-making during the execution of an athletic maneuver.

The purpose of this study was to compare how individuals that demonstrate relatively slow reaction times (Slow RT) on a clinical test of cognitive function respond to temporal constraints on decision-making during lateral cutting in comparison to individuals that demonstrate faster reaction times (Fast RT). We hypothesized that the mechanics of individuals in the Slow RT group would be affected to a greater extent when temporal constraints were imposed on decision-making in comparison to individuals in the Fast RT group. The results of this analysis provide additional insight into potential reasons why individuals with poorer cognitive ability, as measured by overall reaction time, may by at greater risk for non-contact ACL injury.

Methods

Participants

This study included 45 females between the ages of 18 to 25 years old. Participants all had experience (current and/or previous) competing in sports that involve landing and cutting. We used a previously described classification system to differentiate sports based on the amount of landing and cutting involved (Daniel et al., 1994); participants in this study were currently participating, or had previously participated, in either level I (e.g. basketball, soccer, etc.) or level II (e.g. tennis) sports. In addition, participants were required to be at least recreationally active at the time of the study (Tegner Activity Level Scale score greater than 4/10) (Tegner & Lysholm, 1985). Exclusion criteria included: 1) any medical condition that limited physical activity, 2) a previous history of lower extremity surgery, or 3) a lower extremity injury in the previous six months that limited training.

Testing Protocol

All of the testing associated with this study took place during a single session. Participants were first required to complete the ImPACT protocol (ImPACT Applications Inc., Pittsburgh, PA, USA). Testing was conducted in accordance with the instructions provided by the ImPACT developers and was led by an individual that had successfully completed the recommended training for administering baseline testing. Participants were encouraged not to partake in strenuous physical activity in the three hours prior to their scheduled session.

After completion of the ImPACT protocol, biomechanics testing was initiated. Participants were provided with standard laboratory footwear that was worn throughout testing (Saucony Jazz, Lexington MA, USA). Retro-reflective calibration markers were placed bilaterally on the anterior-superior iliac spines, posterior-superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. In addition to the calibration markers, four tracking markers attached to a rigid shell (marker cluster) were applied bilaterally to the thigh and shank to track the motion of these segments during the movement trials. An additional marker cluster was applied to the heel counter of each shoe to track the motion of the foot. The three-dimensional position of the retro-reflective markers was recorded at 200 Hz with a ten-camera Eagle system (Motion Analysis Inc., Santa Rosa, CA, USA), while two adjacent Bertec force plates (Bertec Corp., FP4060-NC, Columbus, OH, USA) collected ground reaction forces at 1000 Hz. An initial three-second standing calibration trial was conducted with both the calibration and tracking markers applied.

All calibration markers were removed following the standing trial with the exception of the markers placed on the anterior-superior and posterior-superior iliac spines. These markers were used to track the motion of the pelvis during the movement trials.

Following the completion of the standing calibration trial, participants performed a standardized warm-up program consisting of bilateral squats (2 sets, 8 repetitions) and vertical jumps (2 sets, 5 repetitions) (Dingenen et al., 2015; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2011). After the warm-up was complete, we explained/demonstrated the testing protocol to the participant and had them perform five successful practice trials in each condition. Once the practice trials were complete, we began data collection. Movement trials were conducted in two conditions: 1) pre-planned (PP) and 2) un-planned (UN). For both conditions, the participants initiated each trial with a forward jump from a standing position 1.5 m from the center of the force plates. For the UN trials, participants performed one of three maneuvers: 1) a lateral cut off of their non-dominant limb, 2) a single-leg landing on their non-dominant limb without a subsequent cut, or 3) a bilateral landing and vertical jump. They were unaware of the maneuver they would perform until after they had initiated the trial. The illumination of one of three different stimuli on a screen positioned 1.0 m in front of the force plates, slightly below eye level, dictated the specific movement they were to perform. As a result, the participant was unable to pre-plan/select their movement prior to the trial, which imposed temporal constraints on decision-making. For the PP trials the participant was aware that only the lateral cut stimulus would illuminate (i.e. they were able to pre-plan/select their movement). For both conditions (PP, UN), the illumination of the stimulus was triggered using a Tapeswitch signal mat (Tapeswitch Corp., CVP, Farmingdale, NY, USA), which was interfaced with a custom LabView program (National Instruments Corporation, Austin, TX, USA) (Meinerz, Malloy, Geiser, & Kipp, 2015). The illumination of the stimulus occurred approximately 350 ms prior to contact with the force plate (Kipp et al., 2013). Only the lateral cut trials were included in our analysis. The single-leg landings and vertical jumps were included for the UN condition so that the participants could not pre-plan/select the maneuver. We chose to analyze a lateral cutting task because non-contact ACL injuries are common during single-leg cutting in female athletes (Olsen et al., 2004).

For the lateral cut trials, the participants were required to land with their non-dominant limb and immediately cut in the opposite direction (i.e. a participant that landed on their left limb would cut to the right). For the purpose of this study, we considered the non-dominant limb to be contralateral to the limb that the participant reported they would use to kick a ball as far as possible (Borotikar, Newcomer, Koppes, & McLean, 2008; Hewett et al., 2005). In order to ensure consistency among the cutting trials, participants were required to cut from the force plate that was located on the same side as their stance limb (i.e. landing on the left limb occurred on the left force plate with respect to the participant) and needed to land within a pre-designated area following the cut. This area was consistent across all trials, conditions, and participants. A diagram of the testing setup is included in Figure 1. Participants continued conducting UN trials until five successful lateral cuts had been collected. Five lateral cut trials were also collected for the PP condition. The order of the conditions was randomized across participants to distribute any possible fatigue or practice effects among conditions.

Data Processing

The raw three-dimensional marker and force data were filtered using a 4th-order, zero lag, recursive Butterworth filter with a cutoff frequency of 20 Hz. The force and marker data were filtered at the same cutoff frequency based on the recommendations of previous authors (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Right-handed Cartesian local coordinate systems were defined to describe the position and orientation of the pelvis, thighs, legs, and feet. The midpoint between the medial and lateral femoral epicondyles and the medial and lateral malleoli were used to estimate the knee and ankle joint centers, respectively. The hip joint centers were estimated based on previously described regression equations (Bell, Pedersen, & Brand, 1989, 1990). We calculated joint angles using a joint coordinate system approach (Grood & Suntay, 1983) and net joint moments using a Newton-Euler approach with previously estimated body segment parameters (Dempster, 1955). Joint moments were resolved into the local coordinate system of the distal segment and normalized to the participant's body mass (Nm/kg). The moments reported are 'external' net joint moments. Visual3D software (C-Motion Inc., Rockville, MD, USA) was used to process the biomechanics data.

Data Analysis

For the lateral cutting trials, we specifically analyzed the initial 100 ms after the participant made foot contact. Initial foot contact was defined as the time during the cutting trial when the vertical ground reaction force (vGRF) first exceeded 20 N. We chose to analyze the 100 ms after initial contact because ACL injuries appear to occur relatively early (within the initial 100 ms) after an athlete contacts the ground (Koga et al., 2010; Krosshaug, Nakamae, et al., 2007). The kinematic variables of interest were the hip flexion, knee flexion, and knee abduction initial contact angles and range of motion (ROM). We calculated the ROM as the difference between the peak angle and the angle at initial contact. The kinetic variables of interest were the peak knee abduction moments and the peak vGRFs. We normalized the vGRFs to the participant's bodyweight (BW). The variables of interest corresponded to either landing stiffness (hip and knee flexion angles, vGRF) or knee valgus (knee abduction angles/moments), which are two mechanisms that may be related to non-contact injury risk (Olsen et al., 2004). We also analyzed the time the foot was in contact with the force plate (stance time), as this may provide additional insight into the influence of temporal constraints on decision-making on motor control. For each participant, the five-trial average for the variables of interest was determined for both the PP and UN conditions.

Performance on the ImPACT reaction time measure was used to differentiate participants into groups. We chose to analyze the reaction time measure because we believed it best reflected the individual attribute(s) that we attempted to challenge with our UN task (i.e. cognitive processing speed). The ImPACT reaction time measure comprises an individual's performance on three sub-tests (Schatz, Pardini, Lovell, Collins, & Podell, 2006). For each subtest, the time it takes the individual to respond (only correct responses) is incorporated into the final composite value. We compared each participant's reaction time value to normative data provided by the ImPACT developers for 'university women' (ordinal categories: 'impaired'; 'borderline'; 'low average'; 'average'; 'high average'; 'superior'; 'very superior') (Iverson, Lovell, & Collins, 2003). Participants with reaction times ranging from 0.52-0.59 s ('average') were not included in our analysis. Participants with reaction times above 0.59 s ('low average', 'borderline', 'impaired') were included in our Slow RT group, while participants with reaction times less than 0.52 s ('high average', 'superior', 'very superior') were included in our Fast RT group. Our Slow RT and Fast RT groups consisted of 15 and 13 participants, respectively. Figure 2 illustrates the number of participants in each ordinal category. We compared the group's reaction times, age, mass, height, and activity level using independent t-tests. The effect size for these measures was calculated by dividing the difference between the group means by the average of the groups standard deviations (Cohen's d). Activity level was quantified using the Tegner Activity Level Scale (Tegner & Lysholm, 1985).

For each biomechanical variable of interest, we conducted a mixed-model ANOVA to determine if there was a group (Slow RT, Fast RT) by condition (PP, UN) interaction. Effect sizes were reported as partial eta squared statistics (η^2). An alpha of .05 was used for all tests of statistical significance. We conducted all statistical testing using SPSS software (IBM Corp., Version 22.0, Armonk, NY, USA). A sample size estimate indicated that 12 participants per group would be adequate to detect a medium-large effect (η^2= 0.08) using an alpha of .05, a beta of .20, and a within-factor correlation of 0.8. The within-factor correlation used for our sample size estimation was based on reliability data reported for lateral cutting (Alenezi, Herrington, Jones, & Jones, 2016). We used G*Power software to perform the sample size estimation (Faul, Erdfelder, Lang, & Buchner, 2007).

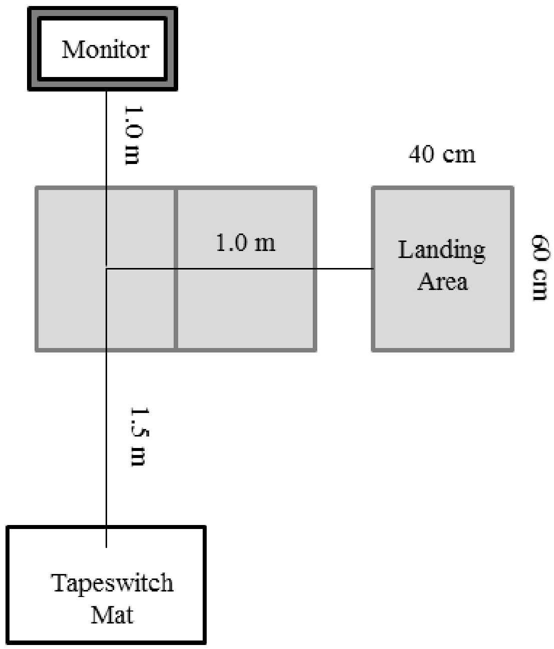

Figure 1. Testing setup for a participant that cut from their left (non-dominant) limb.

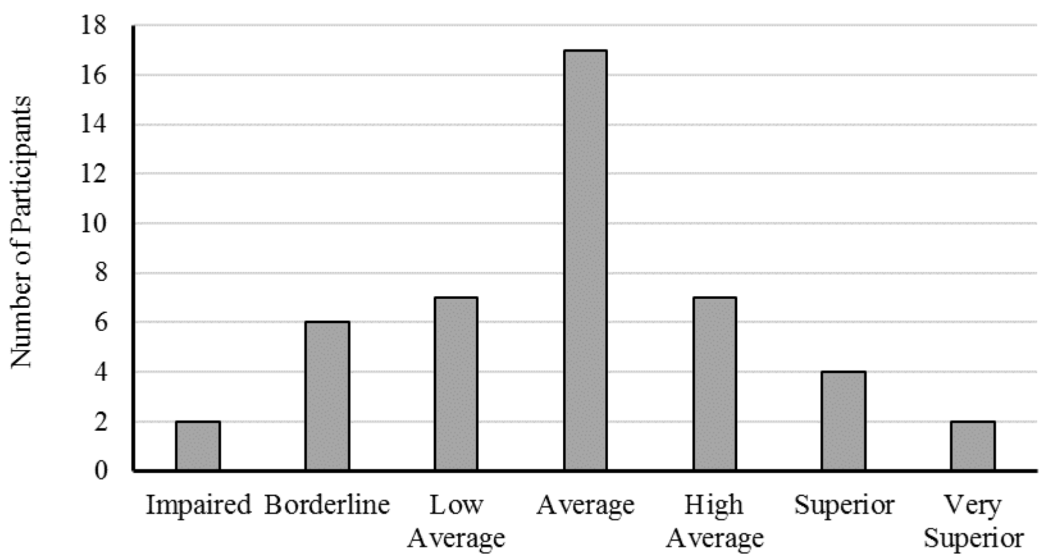

Figure 2. Number of participants in each category based on their performance on the ImPACT reaction time measure. Categories are from normative data for 'university women' (Iverson, Lovell, & Collins, 2003). Participants in the 'average' group (n=17) were not included in our analysis

Results

No significant differences existed between the groups (Slow RT vs. Fast RT) in regard to age ($p=.17$), mass ($p=.97$), height ($p=.65$), or activity level (Tegner Activity Level Scale scores) ($p=.62$) (Table 1). As expected, participants in the Slow RT group demonstrated higher reaction times (poorer performance) in comparison to participants in the Fast RT group ($p<.001$) (Table 1). In general, it appears that despite similarity in regard to demographics, the groups demonstrated differences in cognitive ability.

The mixed-model ANOVA results indicated that no group (Slow RT, Fast RT) by condition (PP, UN) interactions existed for any of the variables of interest (Table 2). However, there was a group main effect for the peak vGRF variable ($p=.01$; $\eta^2= 0.22$). As a follow-up analysis, we compared the peak vGRFs between the groups for both the PP and UN conditions using independent t-tests. The participants in the Slow RT group demonstrated higher peak vGRFs for both the PP (2.22 BW vs. 1.90 BW; $p=.03$) and the UN conditions (2.26 BW vs. 1.88 BW; $p=.01$) in comparison to participants in the Fast RT group (Figure 3). No other group main effects existed for any of the other variables of interest ($p>.05$).

	Slow RT	Fast RT	P-value	ES
Characteristics				
Age (years)	21.7 (1.8)	20.8 (1.8)	.17	0.50
Mass (kg)	64.5 (12.8)	64.3 (9.8)	.97	<0.01
Height (m)	1.66 (0.07)	1.67 (0.08)	.65	0.13
Activity level	6.1 (0.7)	6.2 (1.0)	.62	0.12
Reaction Time (s)	0.64 (0.04)	0.49 (0.02)	**<.001***	**5.00**

Mean (SD); * indicates statistical significance ($p<.05$)
Activity level = Tegner Activity Level Scale scores; ES = effect size

Table 1. Group characteristics for the Slow RT and Fast RT groups.

	Slow RT		Fast RT			
	PP	UN	PP	UN	P	η^2
Landing Stiffness						
IC hip flexion angles (°)	48.58 (8.89)	49.68 (8.39)	50.83 (7.19)	53.69 (7.48)	.58	0.01
Hip flexion ROM (°)	10.94 (4.70)	11.49 (4.17)	10.27 (3.24)	10.13 (2.93)	.24	0.05
IC knee flexion angles (°)	13.80 (6.21)	12.99 (5.25)	13.97 (3.85)	13.82 (4.12)	.49	0.02
Knee flexion ROM (°)	29.27 (4.15)	27.72 (4.12)	29.60 (5.08)	26.67 (3.75)	.28	0.04
Peak vGRF (BW)	2.22 (0.42)	2.26 (0.43)	1.90 (0.31)	1.88 (0.25)	.60	0.01
Valgus Collapse						
IC knee abduction angles (°)	1.31 (3.96)	1.43 (5.23)	-1.04 (1.92)	0.23 (2.00)	.20	0.06
Knee abduction ROM (°)	4.10 (1.59)	5.75 (2.54)	4.97 (2.17)	5.80 (2.39)	.18	0.07
Peak knee abduction moments (Nm/kg)	0.38 (0.19)	0.41 (0.15)	0.39 (0.18)	0.49 (0.16)	.31	0.04
Stance time (ms)	487.10 (70.70)	607.47 (118.20)	499.62 (83.27)	598.06 (81.18)	.57	0.01

Mean (SD); p-value (P) and partial eta squared statistic (η^2) are based on interaction results
IC = initial contact; ROM = range of motion; Positive values correspond with hip/knee flexion and knee abduction

Table 2. Group (Slow RT, Fast RT) by condition (PP, UN) interaction results for each of the biomechanical variables of interest.

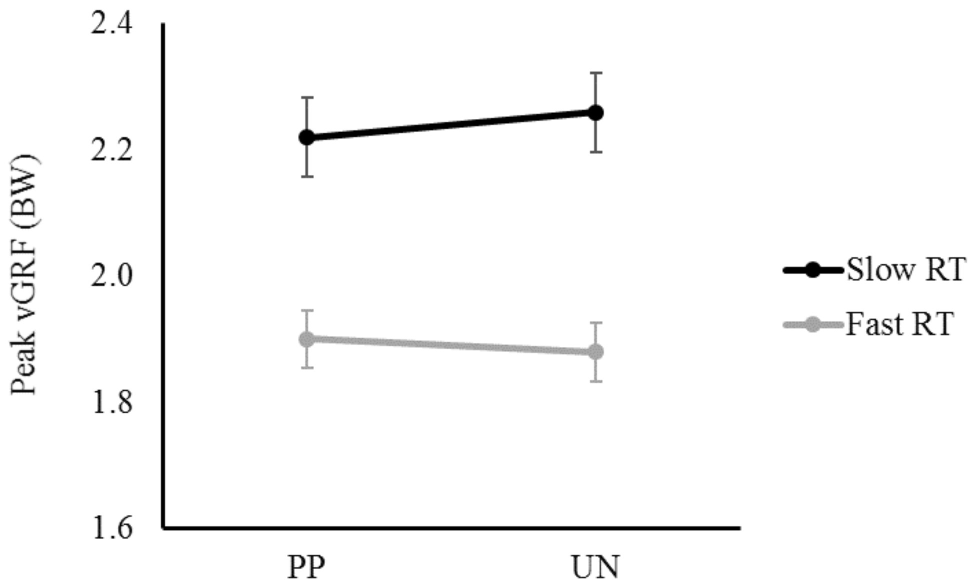

Figure 3. The mean peak vGRFs for the Slow RT and Fast RT groups in both the pre-planned (PP) and un-planned (UN) conditions. Error bars represent the standard error.

Discussion

The primary purpose of this study was to compare how individuals that demonstrate relatively slow reaction times (Slow RT) on a clinical test of cognitive function respond to temporal constraints on decision-making during lateral cutting in comparison to individuals that demonstrate faster reaction times (Fast RT). We hypothesized that the mechanics of the participants in the Slow RT group would be affected to a greater extent when temporal constraints were imposed on decision-making in comparison to participants in the Fast RT group. The results of our group (Slow RT, Fast RT) by condition (PP, UN) analysis did not support our hypothesis. However, we did find that the participants in the Slow RT group demonstrated higher peak vGRFs during the cutting maneuver in comparison to the Fast RT group, regardless of any temporal constraints on decision-making (i.e. for both the PP and UN conditions). Stiffer landings (i.e. higher vGRFs) could potentially increase the forces acting on the ACL (Laughlin et al., 2011; Southard, Kernozek, Ragan, & Willson, 2012) and prospective analyses indicate that female athletes that land with higher vGRFs may be at an increased risk of non-contact ACL injury (Hewett et al., 2005; Leppanen et al., 2016). In our study, it appears that individuals with slower reaction times tended to utilize a movement pattern that would place them at higher risk for ACL injury, regardless of the cognitive load associated with the task.

Although our PP condition required participants to perform the cognitive processing associated with selecting, organizing, and executing a complex movement (i.e. lateral cut), we did not anticipate that there would be group differences in landing mechanics since it was intended to serve as a baseline. Considering that the groups were differentiated based on their reaction times, our assumption was that differences in mechanics would only become apparent when participants were challenged to quickly perform the cognitive processing associated with decision-making (UN condition). However, there is evidence that the ImPACT reaction time measure may not assess processing speed independently of other cognitive functions that could also influence motor control (Maerlender et al., 2010, 2013). Maerlender et al. (2010) examined the criterion validity of ImPACT by comparing performance on each component to performance on a battery of neuropsychological measures designed to capture various aspects of cognitive function (e.g. processing speed, working memory, attention, etc.). The ImPACT reaction time measure demonstrated poor discriminant validity, as it often correlated with measures believed to represent constructs unrelated to cognitive processing speed. For instance, poorer performance on the ImPACT reaction time measure was associated with poorer performance on neuropsychological measures thought to reflect working memory capacity, which plays a prominent role in the planning and execution of movement (Nadkarni, Zabjek, Lee, McIlroy, & Black, 2010; Spiegel, Koester, & Schack, 2013). Assuming that the poorer performance on the reaction measure for the Slow RT group reflected a lower level of general cognitive function (not cognitive processing speed in isolation) it may not be surprising that these individuals executed the PP cutting maneuver with higher vGRFs in comparison to participants in the Fast RT group.

To our knowledge, there has not been a previous attempt to compare how individuals with varying cognitive abilities respond to an increase in cognitive load. However, Herman and Barth (2016) recently established a link between landing mechanics and cognitive ability. They categorized recreational athletes into two groups (High Performers, Low Performers) based on their performance on a computer-based cognitive test (Concussion Resolution Index). The components of the test used to differentiate the groups were also related to cognitive processing speed (simple reaction time, complex reaction time, processing speed). In addition to the cognitive testing, both groups completed a biomechanics testing protocol that involved jumping forward from a 30 cm height, landing with both limbs, and immediately performing one of three different maneuvers after landing (vertical jump, jump left, jump right). In an attempt to simulate the reactive nature of sports participation, the specific movement the athlete was to perform was dictated by the illumination of one of three arrow stimuli approximately 250 ms before the athlete landed from the initial jump (analogous to our UN condition). For the vertical jump trials, the athletes in the Low Performers group landed with higher vGRFs, greater knee abduction angles/moments, and less trunk flexion in comparison to the High Performers. It is possible that the group differences resulted because the Low Performers were less-equipped to control their movement under the cognitive demands of the testing protocol. However, in light of our findings, it also appears possible that group differences in landing mechanics may have been observed even if the testing protocol had imposed less of a cognitive demand (e.g. pre-planned land and jump task).

Although we framed our analysis around non-contact ACL injury, it is important to highlight the fact that our findings may also apply to a broader range of acute musculoskeletal injuries. Wilkerson (2012), assessed reaction times via ImPACT prior to the beginning of the season in a group of 76 male Division I football players and reported that the 23 athletes that went on to sustain a non-contact lower extremity musculoskeletal injury (not including ACL injuries) demonstrated poorer performance in comparison to the uninjured athletes. In fact, he identified a specific cutoff point (reaction time >0.545s) that discriminated between the injured and uninjured athletes. Athletes with scores greater than this cutoff point were over two-times more likely to experience an acute musculoskeletal injury. While it is difficult to determine how this specific cutoff point generalizes to our sample (females, predominantly recreational athletes), it is interesting to note the participants in our Fast RT and Slow RT groups performed well above and below this cutoff point, respectively. It appears that individuals with poorer cognitive abilities may be at greater risk for acute musculoskeletal injury in general, not simply non-contact ACL injury risk.

Greater insight into the role of cognitive function could certainly be gained by using more sophisticated measures (e.g. functional magnetic resonance imaging, magnetoencephalography, etc.). However, the exciting aspect of exploring the potential utility of computer-based tools (e.g. ImPACT) to assess non-contact ACL injury risk (or general acute musculoskeletal injury risk) is that these measures are already available to sports medicine professionals. As a result, they would be easy to implement on a large scale for the purpose of risk screening. Experts have begun to advocate for the development of training programs to specifically target cognitive factors related to injury (e.g. visuomotor training, dual-task training, mental imagery, etc.) (Brown et al., 2009; Grooms, Appelbaum, & Onate, 2015; Kipp et al., 2013). A key step in optimizing cognitive-oriented training is the development of feasible/effective methods to identify individuals that are amenable to this type of training. The results of our analysis indicate that the ImPACT reaction time measure may be useful in this regard. However, our findings also highlight that care may need to be taken when attempting to use the ImPACT measure to assess specific aspects of cognitive function (e.g. cognitive processing speed, working memory, etc.). Performance on the ImPACT reaction time composite may provide a more global view of cognitive function across multiple domains. Herman and Barth (2016) provided a similar caveat with respect to the Concussion Resolution Index.

While we believe that our findings make an important contribution to an under-developed body of literature, it is important that we highlight the limitations associated with our study. First, participants were required to respond in a pre-determined manner to one of three stimuli;

however, athletes competing in sports must often respond to a greater number of stimuli in an impromptu manner. Also, the visual stimuli we used to direct the participant's movement is unlikely to reflect that of sports. Previous studies have implemented testing protocols that require athletes to maneuver in response to more 'game-like' stimuli (e.g. video of soccer defenders) (Cortes et al., 2011; Lee et al., 2013). It is possible that incorporating a more cognitively demanding testing protocol could have resulted in group differences with respect to the influence of varying cognitive load. In addition, the participants (both the Fast and Slow RT groups) demonstrated longer stance times for the UN condition in comparison to the PP condition. This may have mitigated the cognitive demand associated with the UN condition because it could have allowed the participants to compensate for the temporal constraints imposed on decision-making. Next, it is possible that including a greater number of participants that were at the extremes with respect to cognitive function (e.g. 'impaired' vs. 'very superior') could have also helped us to explore potential differences in how individuals respond to increases in cognitive demand. The majority of the participants in the Slow RT and Fast RT groups were considered to be in the 'low average' or 'high average' categories, respectively. Finally, it is also important to highlight the fact that the participants in our sample did not have a history of ACL injury, despite competing in sports. As a result, the findings from our sample may not be reflective of individuals at risk for ACL injury.

Conclusion

We categorized females into groups (Slow RT, Fast RT) based on their reaction times on a clinical test of cognitive function. Participants in both groups performed lateral cutting trials in two conditions; pre-planned and un-planned. For the un-planned condition, participants were required to react to an external stimulus after initiating a trial in an attempt to impose temporal constraints on decision-making. Contrary to our hypothesis, we did not identify group by condition interactions for any of the variables we included in our analysis. However, participants with slower reaction times did demonstrate higher peak vGRFs in comparison to the participants with faster reaction times, regardless of the cognitive demands associated with the task. Landing with higher vGRFs may increase injury risk. This may help to explain why individuals with slower reaction times are at an increased risk of non-contact ACL injury.

Chapter 3

The Focus of Attention Influences Lower Extremity Mechanics

During Cutting in Female Athletes

Introduction

Anterior cruciate ligament (ACL) injuries are common in young female athletes competing in sports such as basketball (Agel, Arendt, & Bershadsky, 2005; Hootman et al., 2007). Unfortunately, many will not return-to-sport following an ACL injury (Ardern et al., 2011) and may miss out on the positive health-related benefits that are associated with participation in athletics (Pate et al., 2000). In addition, even those athletes that are able to successfully return-to-sport are at a significantly higher risk of sustaining a second ACL injury (Paterno, Rauh, Schmitt, Ford, & Hewett, 2012). As a result, there is an urgent need to reduce the number of ACL injuries sustained by female athletes. Achievement of this goal is dependent on an in-depth understanding of how both intrinsic (e.g. strength, range of motion) and extrinsic (e.g. the playing situation, player and opponent behavior) factors influence ACL injury risk (Bahr & Krosshaug, 2005).

The majority of ACL injuries sustained during sports participation do not result from a direct collision with a teammate or opponent (Boden et al., 2000; Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Krosshaug et al., 2016). This type of 'non-contact' ACL injury is particularly common when athletes are performing single-leg cutting and landing (Boden et al., 2000; Krosshaug, Nakamae, et al., 2007). Female athletes that sustain non-contact ACL injuries while executing these maneuvers often exhibit a 'stiff' landing pattern, which is characterized by limited hip and knee flexion (Olsen et al., 2004; Stuelcken et al., 2016). A 'valgus collapse' of the knee is also commonly observed; characterized by the knee moving medially with the distal end of the shank angling away from midline of the body (i.e. increased knee abduction) (Hewett, Torg, & Boden, 2009; Krosshaug, Nakamae, et al., 2007; Olsen et al., 2004; Stuelcken et al., 2016). As a result, cutting and landing with limited hip and knee flexion and high knee abduction is thought to reflect a 'risky' movement pattern with respect to non-contact ACL injury (Hewett, Paterno, & Myer, 2002).

Analysis of video taken during the time of an ACL injury can provide a detailed description of the circumstances surrounding the injury (Krosshaug, Andersen, Olsen, Myklebust, & Bahr, 2005). An interesting observation made from video analysis is that the majority of ACL injuries in team sports (e.g. basketball, handball) occur when an athlete is in possession of the ball (Boden et al., 2009; Krosshaug, Nakamae, et al., 2007; Olsen et al., 2004; Stuelcken et al., 2016). For instance, Olsen et al. (2004) reported that the athlete possessed the ball in each of the 19 non-contact ACL injuries they observed in female handball players. Unfortunately, video analysis does not elucidate why an athlete in possession of the ball may be at greater risk of non-contact ACL injury.

The greater occurrence of non-contact ACL injury when in possession of the ball may be due to the higher cognitive load at this time, as the athlete must allocate attentional resources to manipulate the ball and must also be aware of the location of their opponents, teammates, and the goal. Video analysis indicates that athletes often have their focus of attention directed toward a teammate, opponent, or the goal during the maneuver in which they sustain their ACL injury (Boden et al., 2009; Krosshaug, Nakamae, et al., 2007; Olsen et al., 2004; Stuelcken et al., 2016). This observation is often used to highlight the need for testing protocols, risk screening measures, and prevention programs that include these type of 'distracting' elements (Krosshaug, Slauterbeck, Engebretsen, & Bahr, 2007; Stuelcken et al., 2016). There is a small body of literature indicating that the focus of an athlete's attention can have a prominent influence on the manner in which they execute common sports maneuvers (e.g. cutting, landing, jumping, etc.) (Fedie, Carlstedt, Willson, & Kernozek, 2010; Ford et al., 2005; McLean, Lipfert, & van den Bogert, 2004; Mok, Bahr, & Krosshaug, 2015); however, it is still underdeveloped. In fact, the most recent ACL Research Retreat highlighted the need to improve our understanding of how cognitive factors, including the focus of attention, may influence an individual's risk of ACL injury (Shultz et al., 2015).

An alternative explanation for the increased risk of injury when an athlete is in possession of a ball is that holding/manipulating a ball may restrict the athletes' ability to use their arms during movement execution. Requiring participants to carry a football in the arm on the side of their plant limb has been shown to increase frontal plane knee loading during the execution of a lateral cutting task in comparison to baseline trials (Chaudhari et al., 2005). The same study reported similar findings when participants were required to carry a lacrosse stick during the cutting trials. In addition, having female basketball players conduct a 45° run-and-cut task while also dribbling a basketball had a similar influence on frontal plane knee mechanics when compared to trials conducted without the additional dribbling task (Chan et al., 2009). In light of these findings, it appears that at least part of the reason why athletes may be at greater risk of non-contact ACL injury when in possession of a ball is that their ability to utilize their upper extremities to assist in executing their maneuver may be limited.

The purpose of this study was to determine how possession of a basketball and the focus of attention influence lower extremity mechanics during lateral cutting and landing. We hypothesized that requiring participants to carry a basketball during cutting would result in a movement pattern that is thought to place an individual at greater risk of ACL injury. In addition, we hypothesized that requiring participants to focus their attention on performing an additional sports-related task (basketball chest pass) would add to the effects that resulted from carrying the basketball. The results of this study provide valuable insight to those interested in the development of testing protocols, risk screening measures, and injury prevention programs that may more adequately reflect the demands of the sports environment.

Methods

Participants

This study included 20 females between the ages of 18 to 25 years old. Participants were required to have experience competing in organized basketball (e.g. high school, intercollegiate) and were also required to be at least recreationally active based on a Tegner Activity Level Scale score of greater than four out of ten (Tegner & Lysholm, 1985). The majority of the participants reported that their highest level of competition was at the high school level; however, three of the participants did compete at the intercollegiate level. Six participants reported that they were currently competing in basketball at least once per week, while the remaining participants reported only prior basketball experience. Participants were excluded from the study if they had any medical condition that limited physical activity, any previous history of lower extremity surgery, or any lower extremity injury in the previous six months that limited their physical activity. The participants' mean (SD) age, mass, and height were 21.5 (1.8) years, 64.1 (11.2) kg, and 1.7 (0.1) m, respectively. We conducted an *a priori* sample size estimate using an $\alpha = .05$, a $\beta = .20$, a within-factor correlation of 0.7, and a partial eta squared effect size statistic of 0.06. This analysis indicated that 17 participants were required to ensure adequate power when considering the statistical analysis approach used within this study (repeated-measures ANOVA). The effect size criteria used in sample size estimation was chosen because this is typically considered a medium-sized effect (Cohen, 1988). G*Power software was used to perform the sample size calculation (Faul et al., 2007).

Instrumentation/Equipment

The three-dimensional (3D) position of retroreflective markers were recorded at 200 Hz using a ten-camera Eagle system (Motion Analysis Inc., Santa Rosa, CA, USA). In addition, ground reaction forces were synchronously recorded at 1000 Hz using two adjacent force plates (Bertec Corp., FP4060-NC, Columbus, OH, USA) embedded into a raised platform. The entire testing protocol was conducted in standard laboratory footwear (Saucony Jazz, Lexington MA, USA).

Testing Protocol

All data associated with this study were collected during a single session. An initial three-second standing calibration trial was conducted with both calibration and tracking markers. The calibration markers were placed bilaterally on the anterior-superior and posterior-superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. Four tracking markers attached to a rigid shell (marker cluster) were applied bilaterally to the thigh and shank in order to track the motion of these segments during the movement trials. An additional marker cluster was applied to the heel counter of each shoe in order to track the motion of the foot. Following the standing trial, all calibration markers were removed with the exception of the markers placed on the anterior-superior and posterior-superior iliac spines. These markers were used to track the motion of the pelvis during the movement trials.

Prior to initiating the movement trials, participants performed a standardized warm-up program consisting of bilateral bodyweight squats (2 sets, 8 repetitions) and bilateral maximum vertical jumps (2 sets, 5 repetitions) (Dingenen et al., 2015; Stensrud et al., 2011). Following this warm-up, participants began performing the movement trials. The maneuver the participants performed was a lateral cutting task. The participants initiated each trial 1.5 m from the center of the force plates. They were required to stride forward and land with their non-dominant limb on the force plate located on the same side (i.e. landing on the left limb occurred on the left force plate with respect to the participant). Immediately after landing on the force plate, the participants executed a lateral cut in the opposite direction and landed within a predesignated area on their opposite limb. A diagram of the testing setup is included in Figure 4. For the purposes of this study, the dominant limb was defined as the lower extremity that the participant would use to kick a ball the farthest (Hewett et al., 2005). The lateral cutting trials were conducted in three different conditions (PASS, BALL, CUT). For the PASS condition, the participants executed the lateral cutting trials while carrying a basketball and were also required to execute a chest pass to a research assistant immediately upon landing from the cut. The research assistant was positioned 3 m from the designated landing area at a 45° angle from the lateral direction (Figure 4). For the BALL condition, the participants once again performed the cutting trials while carrying a basketball, but were not required to perform the subsequent chest pass. For the CUT condition, the participants simply performed the lateral cut without holding a ball or performing the chest pass. The participants were not given any directions regarding where they should focus their attention for any of the conditions. Participants performed five successful trials for each of the conditions. The order of the conditions was randomized to distribute potential effects of fatigue.

Data Processing

Non-contact ACL injuries are common during both single-leg cutting and landing (Olsen et al., 2004). As a result, we analyzed both the limb responsible for executing the cut (plant limb; non-dominant) and the opposite limb that landed following cut (landing limb; dominant). For both the plant and landing limbs, we filtered the raw 3D marker data using a 4^{th}-order, zero lag, recursive Butterworth filter with a cutoff frequency of 20 Hz. Right-handed Cartesian local coordinate systems were defined to describe the position and orientation of the right and left thigh, leg, and foot, as well as the pelvis. The midpoint between the medial and lateral femoral epicondyles and the medial and lateral malleoli were used to estimate the knee and ankle joint centers, respectively. The hip joint center was estimated using a previously described regression approach (Bell et al., 1989, 1990). For the plant limb, the ground reaction force data were filtered in the same manner as the marker data (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Ground reaction force data were not available for the landing limb, since the landing did not occur on either of the force plates. We calculated 3D joint angles for both the plant and landing limbs using a joint coordinate system approach (Grood & Suntay, 1983). For the plant limb, we also calculated net joint moments using a Newton-Euler approach with previously estimated body segment parameters (Dempster, 1955). These moments were reported as external net joint moments and were resolved based on the local coordinate system of the distal segment. Net joint moments were also normalized to the participant's body mass (Nm/kg). Visual3D software (C-Motion Inc., Rockville, MD, USA) was used for all data processing.

Data Analysis

For both the plant and landing limbs, we analyzed the lower extremity kinematic and kinetic variables during the 100 ms after the participant made initial foot contact with their respective limb. We focused on early stance because it appears that non-contact ACL injuries typically occur shortly after an athlete makes initial contact with the ground (within the first 100 ms) (Koga et al., 2010; Krosshaug, Nakamae, et al., 2007). For the plant limb, initial contact was the time during the trial when the vertical ground reaction force (vGRF) first exceeded 20 N. For the landing limb, initial contact was the point during landing where the downward velocity of the center of mass of the participant's pelvis reached its peak. This approach has been previously utilized to identify initial contact during overground running and appears more consistent across different landing patterns (e.g. rearfoot vs. non-rearfoot) compared to other methods that rely only on the kinematics of the foot (Milner & Paquette, 2015). We anticipated that this method of analyzing the velocity of the center of mass pelvis would be superior to alternative methods that are dependent on foot kinematics since it appeared that participants were relatively inconsistent in the manner in which they landed following the cut (i.e. rearfoot vs. non-rearfoot).

For the plant limb, the kinematic variables of interest were the angles at initial contact as well as the range of motion (ROM) for hip flexion, knee flexion, and knee abduction. The ROM was the difference between the peak joint angle and the angle at initial contact for each trial. The kinetic variables of interest were the peak knee abduction moments and the peak vGRFs. Each of these kinematic and kinetic variables were identified during the first 100 ms after initial contact. For the landing limb, only kinematic variables were analyzed as force data was not available. The kinematic variables of interest were the peak hip flexion, knee flexion, and knee abduction angles. We chose to analyze peak angles for the landing limb because they are less dependent on the precise identification of initial foot contact. For both the plant and landing limbs, we included variables that appear to be related to either a stiff landing or a valgus collapse. The dependent variables of interest were identified for each trial and averaged within each of the conditions for all participants.

For both the plant and landing limbs, the difference among the conditions (CUT, BALL, PASS) for each dependent variable of interest were analyzed using a repeated measures ANOVA. In the case of a significant omnibus test, the difference between the CUT and BALL conditions and the BALL and PASS conditions were analyzed using paired t-tests. The difference between the CUT and PASS conditions was not analyzed since this comparison was not relevant to our hypotheses. All of the data appeared to satisfy the assumption of normality based on visual analysis of the histograms and evaluation of the skewness statistics. An alpha of .05 was used to assess statistical significance. All statistical testing was conducted using SPSS software (IBM Corp., Version 22.0, Armonk, NY, USA). The effect size (ES) was also calculated for the BALL vs. CUT and PASS vs. BALL comparisons by dividing the difference between the means by the standard deviation for the baseline condition. For the comparison between the BALL and CUT conditions, we used the standard deviation for the CUT condition. For the comparison between the PASS and BALL conditions, we used the standard deviation for the BALL condition. We evaluated effect sizes based on the following criteria: trivial (0-0.19); small (0.20-0.49); medium (0.50-0.79); and large (>0.80).

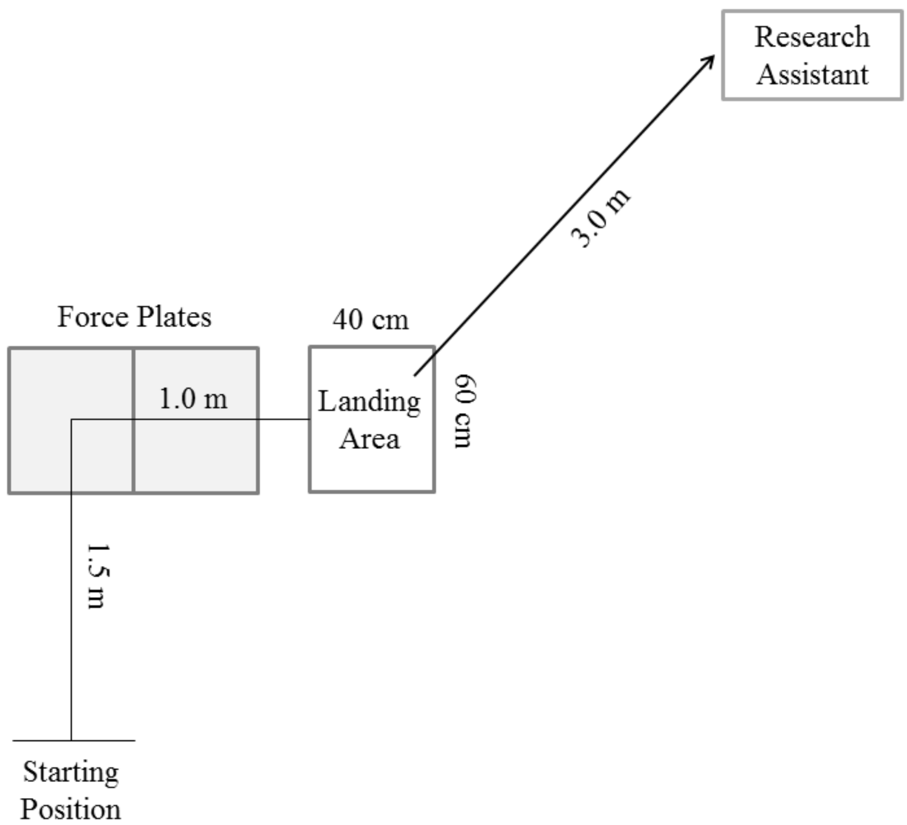

Figure 4. The testing setup for an individual that cut from their left (non-dominant) limb. The research assistant was only present for the PASS condition.

Results

The repeated measures ANOVAs indicated that there was a difference among the conditions for the initial contact hip flexion angles ($p=.02$) and the hip flexion ROM ($p=.04$) for the plant limb (Table 3). For the landing limb, there was a difference among the conditions for the peak knee flexion ($p<.001$) and peak knee abduction ($p=.01$) angles (Table 3).

BALL vs. CUT conditions

The participants demonstrated less hip flexion ROM for the BALL condition compared to the CUT condition for the plant limb ($p=.02$; ES=0.25). No other differences existed between the conditions for either the plant or landing limb.

PASS vs. BALL conditions

The participants demonstrated less hip flexion at initial contact for the PASS condition in comparison to the BALL condition for the plant limb ($p=.004$; ES=0.18). No other differences existed between the conditions for the plant limb. For the landing limb, the participants demonstrated lower peak knee flexion angles ($p<.001$; ES=1.19) and greater peak knee abduction angles ($p=.01$; ES=0.53) during the PASS condition compared to the BALL condition (Figure 5). The sagittal and frontal plane knee angle time series for the BALL and PASS conditions are included in Figure 6.

	CUT	BALL	PASS	P-value
Plant Limb				
IC hip flexion angles (°)	52.43 (8.69)	53.30 (8.46)	51.76 (8.98)	**.02**[b]
Hip flexion ROM (°)	10.41 (4.69)	9.24 (4.12)	9.17 (4.53)	**.04**[a]
IC knee flexion angles (°)	13.31 (3.81)	13.71 (4.55)	13.56 (4.77)	.69
Knee flexion ROM (°)	28.86 (4.12)	28.03 (3.14)	28.86 (3.60)	.13
IC knee abduction angles (°)	0.61 (3.41)	0.29 (3.14)	0.31 (3.06)	.39
Knee abduction ROM (°)	6.41 (2.59)	6.69 (2.84)	7.02 (3.23)	.20
Knee abduction moments (Nm/kg)	0.43 (0.16)	0.47 (0.16)	0.45 (0.15)	.25
vGRF (BW)	1.85 (0.39)	1.89 (0.32)	1.86 (0.38)	.26
Landing Limb				
Peak hip flexion angles (°)	51.65 (10.04)	52.49 (8.96)	49.41 (9.75)	.06
Peak knee flexion angles (°)	46.45 (5.58)	47.34 (5.40)	40.92 (6.15)	**<.001**[b]
Peak knee abduction angles (°)	11.57 (4.45)	10.08 (4.02)	12.23 (4.00)	**.01**[b]

Mean (SD); P-value is based on omnibus test; **bold** indicates statistical significance (p<.05)
Significant t-test (p<.05): BALL vs. CUT (a); PASS vs. BALL (b)
IC = initial contact; ROM = range of motion

Table 3. Lower extremity mechanics for the plant and landing limbs for each condition (CUT, BALL, PASS).

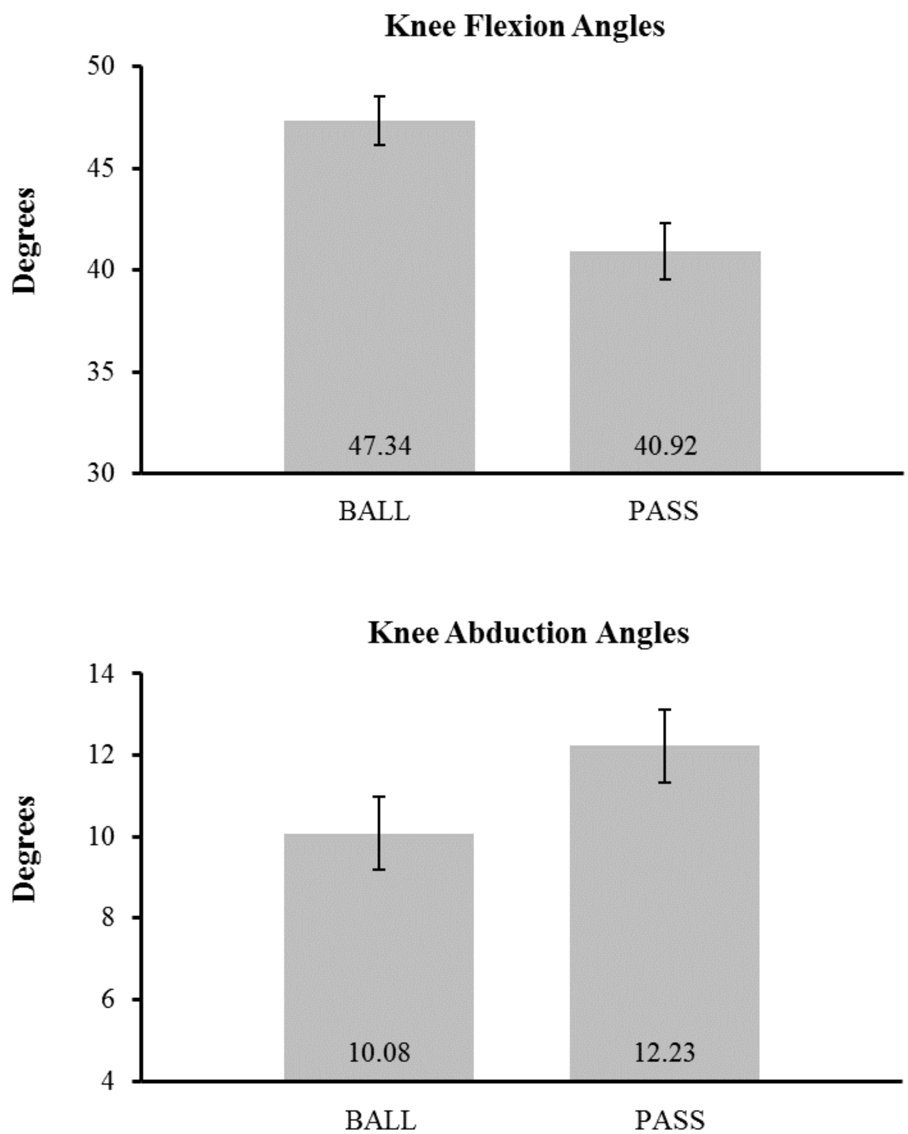

Figure 5. The means for the peak knee flexion and peak knee abduction angles for the landing limb in the BALL and PASS conditions. Error bars represent the standard error.

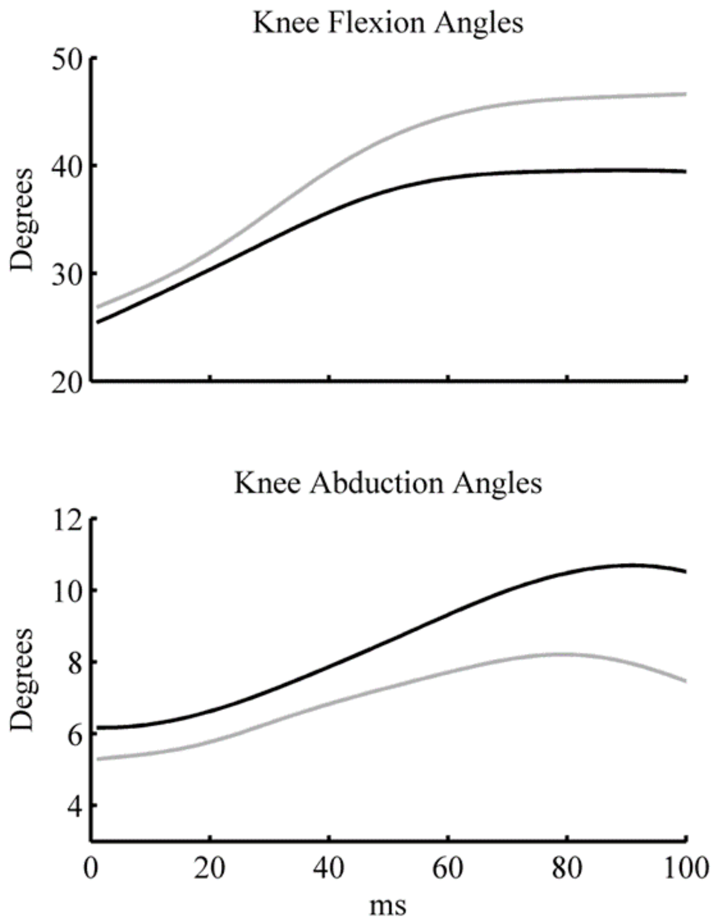

Figure 6. The ensemble average time series for the sagittal and frontal plane knee angles for both the BALL (grey) and PASS (black) conditions for the landing limb. X-axis: '0 ms' corresponds with initial foot contact.

Discussion

The purpose of this study was to determine how possession of a basketball and the focus of attention influence lower extremity mechanics during lateral cutting and landing. Our analysis included both the limb that executed the cut (plant limb) and the limb that landed following the cutting maneuver (landing limb). To assess the influence of the focus of attention, we required participants to perform an additional sports-related task (basketball chest pass) immediately following the completion of the cut. Requiring participants to focus their attention on performing the chest pass did not significantly influence the mechanics of the plant limb. However, it did have a prominent influence on the mechanics of the landing limb. The differences we observed (less knee flexion, greater knee abduction) represent a landing pattern that may place an individual at greater risk for ACL injury. Requiring the participants to perform the cutting task while carrying a basketball appeared to have a very limited influence on the mechanics of the lower extremity for the plant limb (small reduction in hip ROM) and no discernible influence for the landing limb, which did not support our initial hypothesis. Our results could help to explain why non-contact ACL injuries are common when an athlete's attention is focused on an opponent/teammate or the goal.

Requiring the participants to cut while carrying the basketball did not appear to have a prominent influence on their lower extremity mechanics. This was surprising and conflicted with the findings of Chaudhari et al. (2005), who reported that participants demonstrated greater frontal plane knee loading when carrying a football in the arm on the side of their plant limb or when carrying a lacrosse stick compared to baseline trials. This discrepancy may be due to the experience that the respective samples had with the sport that each testing protocol was designed to mimic. Chaudhari et al. (2005) included participants with no previous football or lacrosse experience. In fact, they reported that many of their participants were not familiar with how to correctly hold a football or a lacrosse stick prior to testing. In contrast, the participants in our study had all competed in organized basketball. As a result, it is fair to assume that they had experience performing under the demands of our testing protocol. It is also possible that these inconsistent findings may reflect differences in the degree which carrying a basketball inhibits the ability of an athlete to utilize their upper extremities during a lateral cut compared to carrying a football or a lacrosse stick. Chaudhari et al. (2005) indicated that the arm on the side of the plant limb was positioned farther from their trunk when participants performed the cut trials without the football or the lacrosse stick. They proposed that this arm may play a key role in helping individuals stabilize their body in the frontal plane during lateral cutting. We did not quantify arm position; however, it would seem that the manner that a basketball is typically held would be more conducive to assisting with stability during cutting since it can be easily adjusted (toward or away from the plant limb) throughout the cut. While we believe that these two factors (i.e. differences in the sports experience of the sample and/or the demands of carrying a basketball vs. a football/lacrosse stick) are the most logical explanations for why our results did not coincide with previous findings, there are a variety of other more subtle differences that could also explain this discrepancy.

Requiring the participants to focus their attention on executing the chest pass did not have a prominent influence on lower extremity mechanics for the plant limb. The participants did demonstrate less hip flexion at initial contact during the PASS condition; however, the difference between the conditions was less than 2° and is considered 'trivial' based on the magnitude of the effect size. Although the results for the plant limb did not support our initial hypothesis, we were not overly surprised by these findings. During testing it became apparent that the participants often adopted a strategy where they initially directed their attention to the cutting maneuver and then shifted their focus of attention toward the research assistant once they began to make the transition towards redirecting their movement in the opposite direction. Although this is somewhat speculative since this was strictly based on observations made during testing, it does coincide with the prominent effects for the landing limb. At the point where participants landed following the lateral cut, their attention appeared to have been redirected toward the research assistant based on eye gaze. We believe that this scenario (i.e. the athlete in possession of the ball with their attention focused on a teammate) aligns well with the observations from video analysis that have been used to describe the common circumstances surrounding a non-contact ACL injury.

The findings for the landing limb are certainly concerning, as landing from a cut with less knee flexion and increased knee abduction presents a high risk of ACL injury. Video analysis indicates that athletes often demonstrate limited knee flexion and greater knee abduction at the time of ACL injury (Olsen et al., 2004). In addition, musculoskeletal modeling indicates that landing with limited knee flexion may increase forces acting on the ACL (Laughlin et al., 2011; Southard et al., 2012) and cadaver analysis indicates that knee abduction motion may increase ACL strain during landing (Kiapour et al., 2016). When considered together, these mechanics may be reflective of a movement pattern where participants relied less on their sagittal plane musculature and more on passive restraints (e.g. ligaments) in the frontal plane to decelerate their center of mass (Pollard, Sigward, & Powers, 2010). Since the ACL serves a prominent role in preventing abduction of the knee in the frontal plane (Matsumoto et al., 2001), this pattern of ‘ligament dominance’ is thought to be a major contributing factor to ACL injury, particularly in female athletes (Hewett et al., 2002). Findings reported by Pollard et al. (2010) support the proposed link between the mechanics of the sagittal and frontal planes during landing. These authors dichotomized a cohort of young female soccer players based on the amount of hip and knee flexion they demonstrated during a drop landing (low vs. high flexion) and found that the athletes in the 'low flexion' group demonstrated significantly greater knee abduction angles compared to the athletes in the 'high flexion' group. Our results indicated that requiring the participants to focus their attention on performing the basketball chest pass resulted in a landing pattern that would likely place greater demands on the ACL.

We believe that studying athletes under the circumstances that they will face during competition may be a key to understanding the mechanics associated with any athletic injury. While there have been encouraging efforts to develop methods to track/analyze an athlete's movement during competition (Koga et al., 2011; Koga et al., 2010; Krosshaug & Bahr, 2005; Krosshaug, Slauterbeck, et al., 2007), these methods are still evolving. As a result, continuing to develop biomechanics testing protocols that may more adequately reflect the demands of the sports environment appears warranted. Subtle alterations to a testing protocol that may influence the focus of an individual's attention such as attending to a ball (Fedie et al., 2010; Ford et al., 2005), a defender (McLean et al., 2004), or a simulated teammate (our study) may have a prominent effect on an athlete's movement. Interestingly, even requiring individuals to perform a relatively simple secondary cognitive task (i.e. counting backwards) during movement was recently shown to influence landing mechanics (Dai et al., 2017). As a result, the focus of an individual's attention needs to be carefully considered if the goal is to develop/implement an ecologically valid testing protocol. It is likely that we will gain additional insight into the mechanics that contribute to non-contact ACL injury if we incorporate testing protocols that are reflective of the cognitive demands of the sports environment.

The results of our study may also provide insight that could help to improve ACL injury risk screening and prevention. At this time, tasks used in ACL injury risk screening typically allow an athlete to more fully attend to their movement. At present, the analysis of an athlete's lower extremity mechanics during a drop vertical jump is often used as a screening tool for non-contact ACL injury risk. Unfortunately, reports from prospective analyses conflict as to whether or not performance on the drop vertical jump can predict subsequent non-contact ACL injury (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen et al., 2016; Padua et al., 2015; Smith, Johnson, et al., 2012). Interestingly, two studies have reported that having athletes attend to an object overhead has a prominent influence on lower extremity mechanics during a drop vertical jump (Ford et al., 2005; Mok et al., 2015). It is possible that our ability to consistently identify individuals that are at risk for ACL injury would improve if we analyzed an athlete's movement when their focus of attention was directed elsewhere. ACL injury prevention may also be limited by the failure to adapt training programs to reflect the attentional demands of the sports environment. Prevention programs often incorporate 'movement training' in an attempt to alter the manner in which athletes execute common sports maneuvers (Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Pfeiffer, Shea, Roberts, Grandstrand, & Bond, 2006). However, athletes are typically allowed, or encouraged, to focus their attention on their movement during training. For example, athletes are often directed to 'keep your knees over your toes' or 'land softly' as part of these programs. Considering the attentional demands of the sports environment, it is difficult to believe that movement training of this nature would translate to competition, which may help to explain the limited effectiveness of ACL injury prevention programs (Noyes & Barber-Westin, 2014). Some novel approaches to ACL injury prevention such as virtual reality training, dual-task training, mental imagery, and visuomotor training have been proposed (Brown et al., 2009; Grooms et al., 2015; Kipp et al., 2013; McLean & Samorezov, 2009). Approaches of this nature offer an exciting opportunity to train athletes in a manner that could more closely reflect the cognitive demands of sports.

Some important limitations need to be considered with respect to this study. First, the majority of the participants in our sample were not currently competing in organized basketball. Therefore, we are unaware of how our findings may generalize to individuals that are currently competing in basketball on a regular basis. In addition, our sample may not be reflective of a population that is at risk for ACL injury, since none of our participants had previously sustained an ACL injury. Considering their playing experience, it is likely that they had ample exposure to circumstances conducive to injury. Finally, the manner that we determined initial contact for the landing limb may also be considered a limitation. Although the establishment of a vGRF threshold is considered the 'gold standard' for determining initial foot contact, this approach was not possible for the landing limb since the participants did not make contact with a force plate. We acknowledge that our approach for determining initial contact for the landing limb may have slightly missed the true point of contact in many instances. However, based on visual analysis of the time series for each trial it appears that the peaks for each of the variables of interest typically occurred after the frame we identified as initial contact. This is also apparent in the ensemble average time series graphs (Figure 6). As a result, any potential influence on our kinematic findings would likely be systematic across our conditions.

Conclusion

Requiring participants to perform a lateral cutting task while in possession of a basketball did not have a prominent effect on lower extremity mechanics. However, participants did land with less knee flexion and greater knee abduction when they were required to focus their attention on performing an additional sports-related task (basketball chest pass) following the completion of the cut. Our findings supplement a small, but growing, number of investigations which indicate that the focus of an athlete's attention can have a prominent influence on their movement. The findings from this study may help to explain the observation that athletes are often attending to an opponent/teammate or the goal at the time of their ACL injury. Our results may provide insight to other investigators attempting to develop more ecologically valid testing protocols or ACL injury risk screening/prevention programs that may more adequately reflect the demands of the sports environment.

Chapter 4

Cognitive Demands Influence Lower Extremity Mechanics

During a Drop Vertical Jump Task in Female Athletes

Introduction

Participation in sports is associated with numerous health-related benefits (Pate et al., 2000). Unfortunately, the incidence of acute injury during sports participation is alarmingly high (Hootman et al., 2007; Powell & Barber-Foss, 1999). Anterior cruciate ligament (ACL) injuries are of particular concern as they can potentially end an athlete's playing career (Ardern et al., 2011) and may predispose an individual to develop premature knee osteoarthritis, even in the case of a successful surgical reconstruction (Lohmander et al., 2004; Meuffels et al., 2009). Female athletes are approximately three-times more likely to sustain an ACL injury during sports participation than males (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). As a result, the development of screening protocols to identify female athletes that are at risk for ACL injury is an area of significant emphasis (Hewett et al., 2005; Mizner, Chmielewski, Toepke, & Tofte, 2012; Myer, Ford, Khoury, Succop, & Hewett, 2010).

Assessment of lower extremity mechanics during the execution of a drop vertical jump is a very common tool in ACL injury risk screening (Leppanen et al., 2016; Mizner et al., 2012; Myer, Ford, Brent, & Hewett, 2007; Padua et al., 2015; Padua et al., 2009). The emphasis on this specific task is likely related to the findings of the landmark study conducted by Hewett et al. (2005), where baseline three-dimensional (3D) biomechanical analyses were conducted for over 200 uninjured young female athletes as they performed a drop vertical jump. After completion of the baseline testing, ACL injuries were tracked in this cohort of athletes for over a year. These authors reported that the nine individuals who went on to sustain a non-contact ACL injury demonstrated greater initial contact and peak knee abduction angles, peak knee abduction moments, and peak vertical ground reaction forces, as well as lower peak knee flexion angles and shorter stance times. Their findings appear to be further supported by additional investigations that have observed female athletes often demonstrating ‘valgus collapse’ (i.e. greater knee abduction) and a ‘stiff landing’ (i.e. less knee flexion) during the maneuver where they sustain their injury (Hewett et al., 2009; Koga et al., 2010; Krosshaug, Nakamae, et al., 2007; Olsen et al., 2004; Stuelcken et al., 2016).

Despite a rather wide-spread use in injury risk screening, the drop vertical jump task is not without criticism in regard to its ability to predict ACL injury. A recent study conducted a 3D biomechanical analysis of over 600 female athletes without a history of ACL injury as they executed the same drop vertical jump task described by Hewett et al. (2005) (Krosshaug et al., 2016). These authors tracked ACL injury incidence over a seven year span and reported 41 new non-contact injuries. Interestingly, they reported that knee frontal plane angles and moments were not significantly different between the ACL injured and uninjured athletes. There were also no group differences for the peak knee flexion angles or vertical ground reaction forces. Although it is difficult to determine the underlying reason(s) for the limited predictive validity, these authors proposed that the drop vertical jump task may not represent the unique demands and challenges of the sports environment.

One of the potential limitations of the drop vertical jump task is that it may not impose cognitive demands that are consistent with sports participation. Previous studies have shown that the inclusion of additional cognitive demands to a testing protocol can have a prominent influence on lower extremity mechanics (Ford et al., 2005; Mache, Hoffman, Hannigan, Golden,

& Pavol, 2013; Mok et al., 2015). For instance, Mache et al. (2013) had a group of recreational athletes perform a vertical jump after dropping from a suspended position in two different conditions. For one of the conditions, the athletes knew that they would perform the vertical jump upon landing. In the other condition, they were unaware of whether they would perform the vertical jump or simply land until after they had initiated the trial. The authors reported that the participants demonstrated greater knee abduction angles (initial contact and peak) for the trials that incorporated decision-making (i.e. when the athletes did not know if they would land vs. land-and-jump until after initiating the trial). Incorporating decision-making into performance (i.e. not allowing an individual to pre-plan/select their movement) is thought to place significant temporal constraints on the processes involved in motor control (Besier et al., 2001). In addition to decision-making, the focus of an individual's attention may also have a prominent influence on their movement (Fedie et al., 2010; Ford et al., 2005; Mok et al., 2015). For example, Ford et al. (2005) compared lower extremity mechanics during a drop vertical jump task in a group of intercollegiate athletes in two different conditions; one where the athletes were simply required to jump as high as possible after landing and another where a basketball served as an overhead goal. For the trials where the basketball was included, the athletes jumped up and grabbed the ball as if they were attempting to grab a rebound. The authors reported that the athletes demonstrated a significantly greater knee extension moment in the condition that included the overhead basketball. They proposed that this difference in knee mechanics was the result of requiring the athletes to allocate attentional resources towards acquiring the ball. While both decision-making and the focus of attention have the potential to influence lower extremity mechanics in isolation, the combined influence of these factors may need to be considered since participation in sports requires an athlete to select/execute movements under significant temporal constraints while also attending to additional task demands (Fedie et al., 2010).

The purpose of this study was to investigate the influence of additional cognitive demands (decision-making, focus of attention) on lower extremity mechanics during the execution of the drop vertical jump task. We hypothesized that, in isolation, decision-making and the focus of attention would result in a relatively stiff landing (increased vertical ground reaction force, decreased knee flexion), as well as an increase in variables that correspond with a valgus collapse (knee abduction angles and moments). In addition, we hypothesized that the combination of these factors would have a compounding influence on lower extremity mechanics.

Methods

Participants

This study included 20 females between the ages of 18 to 25 years old. Participants were required to be recreationally active based on a Tegner Activity Level Scale score of greater than four out of ten (Tegner & Lysholm, 1985). In addition, all participants were required to have experience competing in organized basketball (e.g. high school, intercollegiate). Exclusion criteria included: 1) any medical condition that limited physical activity, 2) any previous history of lower extremity surgery, or 3) any lower extremity injury in the previous six months that limited training. The participants' mean (SD) age, mass, and height were 21.5 (1.8) years, 64.1 (11.2) kg, and 1.7 (0.1) m, respectively. Six participants included in this study reported that they were currently participating in basketball at least once per week, while the remaining participants reported only prior participation. Three of the participants indicated that they were currently competing or had previously competed at the intercollegiate level while the remaining participants reported that their highest level of competition was at the high school level. The sample size used in this study was based on an *a priori* estimate. Using an $\alpha = .05$, a $\beta = .20$, a within-factor correlation of 0.7, and a partial eta squared effect size statistic of 0.06, 15 participants would be required to ensure adequate power considering the statistical analysis approach used within this study (repeated-measures ANOVA). The effect size statistic used for sample size estimation was chosen because this is typically considered a medium-sized effect (Cohen, 1988). G*Power software was used to perform this sample size calculation (Faul et al., 2007).

Instrumentation/Equipment

The 3D position of retro-reflective markers were recorded at 200 Hz using a ten-camera Eagle system (Motion Analysis Inc., Santa Rosa, CA, USA), while ground reaction forces were synchronously recorded at 1000 Hz using two adjacent force plates (Bertec Corp., FP4060-NC, Columbus, OH, USA) embedded into a raised platform. The entire testing protocol was conducted in standardized laboratory footwear (Saucony Jazz, Lexington MA, USA).

Testing Protocol

All data associated with this study were collected during a single session. First, calibration markers were placed bilaterally on the anterior-superior iliac spines, posterior-superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. In addition to the calibration markers, four tracking markers attached to a rigid shell (marker cluster) were applied bilaterally to the thigh and shank in order to track the motion of these segments during the movement trials. An additional marker cluster was applied to the heel counter of each shoe in order to track the motion of the foot. Prior to the beginning of the movement trials, an initial three-second standing calibration trial was conducted with both the calibration and tracking markers applied. All calibration markers were removed following the standing trial, with the exception of the markers placed on the anterior-superior and posterior-superior iliac spines. These markers were used to track the motion of the pelvis during the movement trials.

Prior to initiating the movement trials, participants performed a standardized warm-up program consisting of bilateral bodyweight squats (2 sets, 8 repetitions) and bilateral maximum vertical jumps (2 sets, 5 repetitions) (Dingenen et al., 2015; Stensrud et al., 2011). Following the warm-up, the drop vertical jump task was conducted in four different conditions: 1) without decision-making or an overhead goal (DVJ), 2) with decision-making, but no overhead goal (DM), 3) without decision-making, with an overhead goal (OG), and 4) with both decision-making and an overhead goal (DMOG). During the DVJ condition, participants performed the trials based on the protocol described by Hewett et al. (2005), where they initially stood on top of a 31 cm high box with their feet 35 cm apart. The box was positioned 15.24 cm behind the force plates (Earl, Monteiro, & Snyder, 2007). The participants were then required to drop off of the box, land with both feet on separate force plates, and immediately perform a maximum vertical jump, raising both arms as if they were jumping to grab a rebound. The same setup was utilized for the rest of the conditions; however, there were additional cognitive demands associated with decision-making and/or the focus of attention. In the DM condition, the participant did not know whether they would land and vertically jump or simply land on the force plates until after they initiated the trial, in a manner consistent with the protocol described by Mache et al. (2013). The specific movement they were to perform was governed by the illumination of one of two different stimuli presented on a screen positioned 1.0 m in front of the force plates. The illumination of the stimulus was triggered using a Tapeswitch signal mat (Tapeswitch Corp., CVP, Farmingdale, NY, USA) positioned on top of the box, which was interfaced with a custom LabVIEW program (National Instruments Corporation, Austin, TX, USA) (Meinerz et al., 2015). The stimulus was presented to the participant approximately 250 ms prior to contact with the force plates (Mache et al., 2013). For the OG condition, the participant was required to grab a ball that was suspended above the force plates, at the top of their vertical jump. A custom built apparatus allowed the height of the ball to be adjusted. The height used for testing was determined during preceding practice trials where the ball was initially suspended at a height of 2.6 m. If the participant was able to successfully grab the ball at this height and maintain control of the ball throughout the subsequent landing, it was raised 5.08 cm. The participant was given one chance at each height unless there was a noticeable disruption during the maneuver, such as a stumble. This was continued until they could no longer acquire the ball. If the participant could not acquire the ball at the initial height it was lowered in 5.08 cm increments in the same manner. The maximum height that the participant could grab and successfully maintain the ball during practice trials was used during testing. The DMOG condition incorporated both the decision-making and overhead goal components (i.e. when the vertical jump stimulus illuminated the participant jumped up and grabbed the ball). Participants performed three practice trials for each of the conditions prior to the initiation of testing. During testing, participants completed three successful trials for each condition (DVJ, DM, OG, DMOG). For the tasks that involved decision-making (DM and DMOG), only the trials that required the individual to perform the vertical jump were analyzed. The order of the conditions was randomized to distribute any fatigue or learning effects across conditions.

Data Processing

The raw 3D marker and force data were filtered using a 4^{th}-order, zero lag, recursive Butterworth filter with a cutoff frequency of 20 Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012). Right-handed Cartesian local coordinate systems were defined to describe the position and orientation of the right and left thigh, leg, and foot, as well as the pelvis. The midpoint between the medial and lateral femoral epicondyles and the medial and lateral malleoli were used to estimate the knee and ankle joint centers, respectively. The hip joint center was estimated using a previously described regression approach (Bell et al., 1989, 1990). Only the participant's non-dominant limb was analyzed. For the purposes of this study the dominant limb was defined as the lower extremity that the participant would use to kick a ball the farthest (Hewett et al., 2005). We analyzed the non-dominant limb because ACL injuries are more common for the non-dominant limb in female athletes (Brophy, Silvers, Gonzales, & Mandelbaum, 2010; Krosshaug et al., 2016). We calculated three-dimensional joint angles using a joint coordinate system approach (Grood & Suntay, 1983) and net joint moments using a Newton-Euler approach with previously estimated body segment parameters (Dempster, 1955). We reported these moments as external net joint moments and resolved them into the local coordinate system of the distal segment. Net joint moments were also normalized to the participant's body mass (Nm/kg). Lower extremity mechanics were analyzed during the stance phase, which was defined as the time when the vertical ground reaction force (vGRF) exceeded 20 N. Trials were time normalized to 101 data points to reflect the percentage of stance. We performed all data processing using Visual3D software (C-Motion Inc., Rockville, MD, USA).

Data Analysis

The dependent variables of interest included the initial contact and peak knee flexion and abduction angles, the peak knee abduction moments, and the peak vGRF. The vGRF variable was normalized to the participant's bodyweight (BW). The vertical jump height and the stance time (time the foot was in contact with the force plate) were also analyzed. Vertical jump height was estimated by identifying the maximum height of the center of mass of the pelvis (Chiu & Salem, 2010). The dependent variables of interest were identified for each trial and averaged within each of the conditions for all participants. The difference among the conditions (DVJ, DM, OG, DMOG) for each dependent variable of interest was analyzed using separate repeated-measures (within-subjects) ANOVAs. In the case of a significant omnibus test, Bonferroni post-hoc tests were conducted. Effect sizes were reported as partial eta squared statistics (η^2). An alpha of .05 was used for all significance testing. All statistical testing was conducted using SPSS software (IBM Corp., Version 22.0, Armonk, NY, USA).

Results

The mean (SD) maximum height of the pelvis during the vertical jumps for the DVJ, DM, OG, and DMOG conditions were 1.30 (0.06) m, 1.29 (0.05) m, 1.30 (0.05) m, and 1.29 (0.06) m, respectively. The results of the repeated-measures ANOVA indicated that participants did not demonstrate a difference in jump height among the conditions ($p=.06$; $\eta^2=0.12$), and thus any differences in lower extremity mechanics could not be attributed to differences in jump height. The mean (SD) stance time for the DVJ, DM, OG, and DMOG conditions were 0.44 (0.13) s, 0.48 (0.10) s, 0.35 (0.10) s, and 0.47 (0.14) s, respectively. The results of the repeated-measures ANOVA revealed that there was a difference among the conditions ($p<.001$; $\eta^2=0.41$). The post hoc analysis indicated that the stance time was significantly shorter for the OG condition in comparison to the DVJ ($p=.001$), DM ($p<.001$), and DMOG ($p<.001$) conditions.

The results of the repeated-measures ANOVAs indicated a difference existed among the conditions for the peak vGRFs ($p=.02$; $\eta^2=0.15$), the peak knee flexion angles ($p=.002$; $\eta^2=0.23$), and the peak knee abduction angles ($p<.001$; $\eta^2=0.27$). However, no differences existed among the conditions for the initial contact knee flexion angles ($p=.26$; $\eta^2=0.07$), the initial contact knee abduction angles ($p=.51$; $\eta^2=0.04$), or the peak knee abduction moments ($p=.14$; $\eta^2=0.10$). The results of the post hoc analyses illustrated differences among the conditions where participants demonstrated higher vGRFs ($p=.003$) (Figure 7) and lower peak knee flexion angles ($p=.02$) (Figure 8) in the OG condition in comparison to the DVJ condition. The peak knee abduction angles were significantly greater for the DM ($p=.003$), OG ($p=.008$), and DMOG ($p=.03$) conditions in comparison to the DVJ condition (Figure 9). Table 4 includes the mean (SD) for each variable in all of the conditions, as well as the results of the repeated-measures ANOVAs.

	DVJ	DM	OG	DMOG	P
Peak vGRF (BW)	1.62 (0.38)	1.73 (0.50)	1.77 (0.42)†	1.75 (0.51)	**.02***
Initial contact knee flexion angles (°)	18.94 (9.44)	17.09 (7.75)	19.04 (6.77)	17.39 (6.10)	.26
Peak knee flexion angles (°)	85.36 (10.70)	83.18 (10.91)	79.42 (10.70)†	81.73 (11.10)	**.002***
Initial contact knee abduction angles (°)	1.16 (3.18)	1.31 (3.40)	1.47 (3.66)	1.69 (3.02)	.51
Peak knee abduction angles (°)	12.69 (5.43)	13.60 (5.78)†	14.13 (5.59)†	13.79 (5.38)†	**<.001***
Peak knee abduction moments (Nm/kg)	0.43 (0.29)	0.38 (0.22)	0.61 (0.59)	0.49 (0.28)	.14

Mean (SD); P-value is based on results of omnibus test; * indicates statistical significance (p<.05)
Significant post hoc tests (p<.05): † vs. DVJ; ‡ vs. DM; § vs. OG; ‖ vs. DMOG
Knee flexion angles, abduction angles, and abduction moments are positive values

Table 4. Results for each of the biomechanical variables of interest for all conditions (DVJ, DM, OG, DMOG).

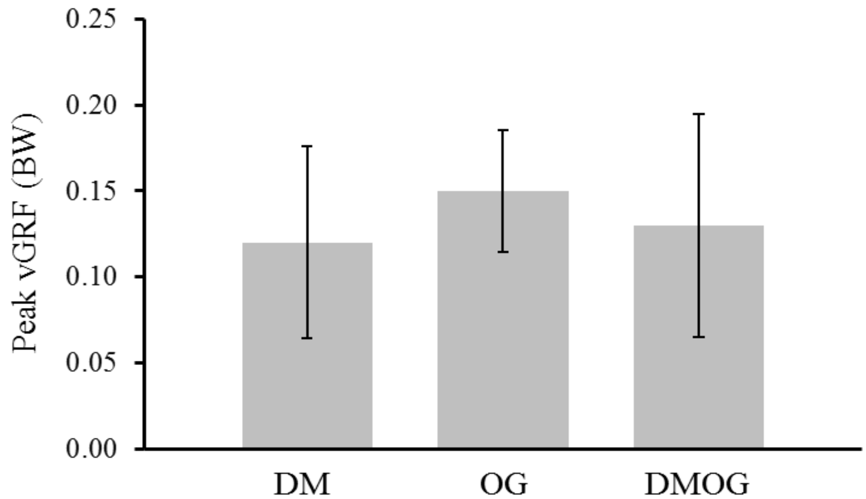

Figure 7. The mean of the differences in the peak vGRFs for the DM, OG, and DMOG conditions relative to baseline (DVJ condition). Positive values correspond with an increase in the peak vGRF vs. baseline. Error bars are based on the standard error of the differences in the means.

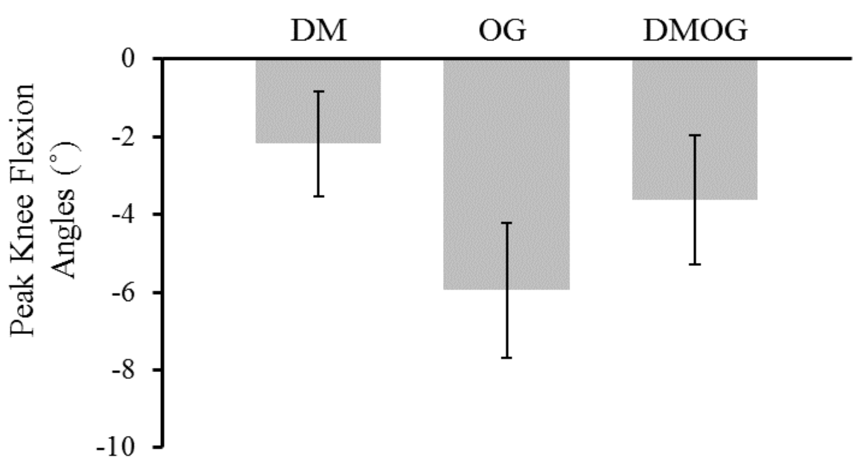

Figure 8. The mean of the differences in the peak knee flexion angles for the DM, OG, and DMOG conditions relative to baseline (DVJ condition). Negative values correspond with a decrease in knee flexion vs. baseline. Error bars are based on the standard error of the differences in the means.

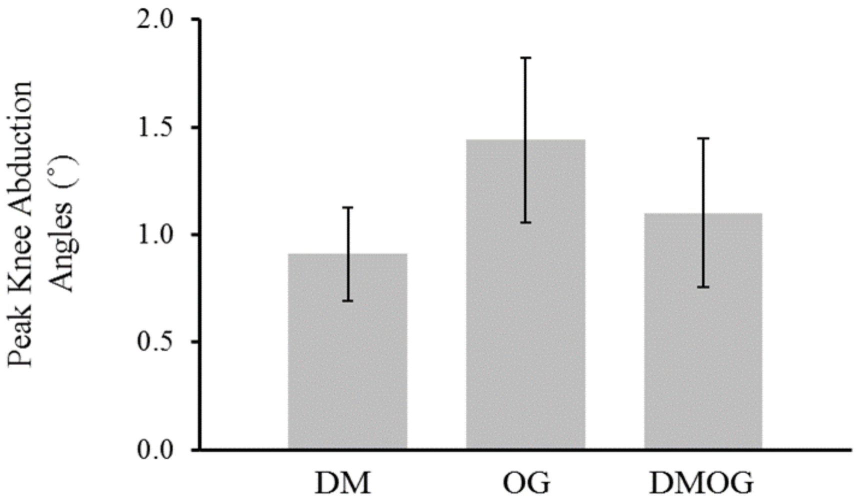

Figure 9. The mean of the differences in the peak knee abduction angles for the DM, OG, and DMOG conditions relative to baseline (DVJ condition). Positive values correspond with an increase in knee abduction vs. baseline. Error bars are based on the standard error of the differences in the means.

Discussion

The purpose of this study was to investigate the influence of additional cognitive demands (decision-making, focus of attention) on lower extremity mechanics during the execution of the drop vertical jump task. Imposing additional cognitive demands influenced landing mechanics in a manner that may increase an individual’s risk of sustaining an ACL injury (i.e. higher vGRFs, lower knee flexion angles, and greater knee abduction angles), which supported the hypothesis of this study. However, it does not appear that the combined influence of decision-making and the focus of attention altered lower extremity mechanics in a manner that exceeded the effect that each of these cognitive demands had in isolation. These results support the premise that the standard drop vertical jump task may not adequately reflect the demands of the sports environment. This may help to explain its limited predictive validity as an ACL injury risk screening tool and supports the inclusion of additional cognitive demands to this task.

The participants in this study demonstrated higher vGRFs and lower peak knee flexion angles during the OG condition compared to the baseline condition (DVJ). The same trend (higher vGRFs, lower knee flexion) was also present for the DM and DMOG conditions in comparison to baseline; however these differences were not statistically significant. Higher vGRFs and lower knee flexion angles are indicative of a relatively stiff landing pattern, which may increase the forces acting on the ACL (Laughlin et al., 2011; Southard et al., 2012). The participants in our study also demonstrated greater peak knee abduction angles for each of the conditions that imposed additional cognitive demands (DM, OG, DMOG), in comparison to baseline. Collectively, it appears that the additional cognitive demands resulted in a landing pattern where participants relied more on passive restraints of the knee in the frontal plane (which include the ACL) to decelerate their center of mass (Hewett et al., 2002; Sigward &

Powers, 2006). Pollard et al. (2010) have reported that young female athletes that demonstrate stiffer landings display greater knee abduction. This pattern of ‘ligament dominance’ is believed to play a prominent role in non-contact ACL injury among young female athletes (Hewett et al., 2002). The fact that the additional cognitive demands tended to result in a more ligament dominant landing pattern could indicate that we may be missing some individuals that are potentially at risk for ACL injury when using the standard drop vertical jump task.

Our findings for the OG condition are consistent with a previous study that analyzed 3D lower extremity mechanics during a drop vertical jump task in over 500 elite female soccer and handball players (Mok et al., 2015). They required the athletes to perform a drop vertical jump in two conditions; one where they simply dropped from a 30 cm high box, landed onto two separate force platforms, and immediately performed a maximum vertical jump and a second condition where they performed the same task with an overhead target. For the trials with the overhead target present, the athletes attempted to jump up and contact the target with their head. Similar to our findings, these athletes demonstrated increased vGRFs, decreased knee flexion, and increased knee abduction during the condition that included the overhead goal. The influence of an overhead goal on movement quality likely reflects the fact that the participant can no longer focus their attention (at least solely) on the execution of the drop vertical jump maneuver.

For the DM condition, our results are consistent with Mache et al. (2013), as the participants in their study also demonstrated a significant increase in peak knee abduction angles when they were not allowed to pre-plan/select their movement. Incorporating decision-making into testing is an attempt to simulate the dynamic nature of the sports environment, where athletes must move in response to external visual stimuli (e.g. teammates, opponents, the ball). A three-stage model that involves the identification of relevant stimuli (stimulus identification), selection of a motor response (response selection), and organization of the motor system to execute this response (movement programming), is often used to describe the processing involved in controlling movement under these conditions (Schmidt & Lee, 2014). From a motor control perspective, our testing protocol was fairly simple; the stimuli-response relationship was designed to be compatible and the participants were only required to respond to one of two stimuli (land vs. jump). As a result, we believe that the differences in landing mechanics for the decision-making condition are a result of the temporal constraints imposed on the central processes involved in motor control. Besier et al. (2001) proposed a similar explanation for his finding that male soccer players demonstrated greater loading of the knee during running-and-cutting in a decision-making condition in comparison to a baseline condition.

To our knowledge, no previous studies have incorporated both decision-making and an overhead goal in combination. Participants in our study did demonstrate greater peak knee abduction angles in the DMOG condition in comparison to baseline. However, incorporating decision-making and requiring an individual to attend to the ball did not affect landing mechanics to a greater extent than either of these additional cognitive demands in isolation. It is possible that these demands did not have a compounding effect because they were not imposed simultaneously during the maneuver. The sequential nature of the demands may have allowed participants to respond to each individually.

The results of this study contribute to a relatively underdeveloped body of literature; however, it is necessary to discuss the limitations of this work. First, despite our efforts to better mimic the demands of the sports environment with our testing protocol, the tasks performed are still likely to pose less demand than sport participation. For instance, our decision-making condition required athletes to respond in a predetermined manner to one of two stimuli. The sports environment provides much greater cognitive demand since athletes are required to respond to numerous external stimuli in an impromptu manner. It should also be noted that having to suppress a movement in response to a stimulus (i.e. land vs. land-and-jump), is not as challenging from a cognitive perspective as having to respond in a different manner to two stimuli (e.g. land-and-jump vs. land-and-run). In addition, our overhead goal condition may also not adequately reflect the demands of the sports environment since rebounding a basketball is typically more dynamic since a player must often react to various trajectories of ball movement due to the carom of the ball off of the rim. Developing protocols that impose the cognitive demands of the sports environment while also maintaining the standardization and control needed for testing and screening is a challenge. In addition to the limitations associated with the testing protocol, it is also important to highlight the limitations associated with our sample. The participants in this study varied considerably regarding their years of basketball experience and highest level of competition. In addition, the majority of the participants were not currently participating in organized basketball. Future studies may consider including a more homogenous sample that is currently participating in basketball on a regular basis. Finally, the participants included in this study had not previously sustained an ACL injury. As a result, it is possible that their responses to the testing protocol may not be reflective of an individual that is at risk for ACL injury since they likely had many exposures, but remained uninjured.

Conclusion

The inclusion of additional cognitive demands (decision-making, focus of attention) had a significant influence on the mechanics of the lower extremity during a drop vertical jump task. Requiring athletes to focus their attention on an overhead ball resulted in a stiffer landing pattern (i.e. increased vGRFs, decreased knee flexion), as well as an increase in knee abduction. Not allowing an individual to pre-plan/select their movement prior to the initiation of a trial also resulted in an increase in knee abduction in comparison to the baseline drop vertical jump condition. The combination of incorporating decision-making and requiring participants to focus their attention on a ball overhead did not have a compounding effect on lower extremity mechanics. The results of our analysis indicate that imposing additional cognitive demands can have a prominent influence on an individual's lower extremity mechanics during a drop vertical jump. This may help to explain the limited predictive validity of the standard drop vertical jump task as an ACL injury risk screening tool. Attempts should be made to develop injury risk screening tasks that may more adequately reflect the demands of the sports environment.

Chapter 5

The Utility of a 2D ACL Injury Risk Screen Measure to Assess Changes in Landing Mechanics Related to Cognitive Task Demands

Introduction

Anterior cruciate ligament (ACL) injuries are common during sports participation, particularly in female athletes (Agel, Rockwood, & Klossner, 2016; Stanley, Kerr, Dompier, & Padua, 2016). ACL injuries can have a significant psychological toll on a young athlete (Mainwaring, Hutchison, Bisschop, Comper, & Richards, 2010) and may increase their risk of premature knee osteoarthritis (Harris et al., 2015). Unfortunately, ACL injury rates continue to rise despite a continued emphasis on injury prevention (Agel et al., 2016). As a result, efforts to improve the effectiveness of ACL injury prevention programs appear warranted (Stevenson, Beattie, Schwartz, & Busconi, 2015). A key step in optimizing injury prevention programs may be the development of risk screening measures that can be used to identify individuals that are likely to be amenable to training (DiStefano, Padua, DiStefano, & Marshall, 2009; Myer et al., 2007; Sorenson, Kernozek, Willson, Ragan, & Hove, 2015).

The majority of ACL injuries do not involve a collision with an opponent or a teammate (Agel et al., 2016). The mechanics of the knee in the sagittal, frontal, and transverse planes may all contribute to these 'non-contact' ACL injuries (Quatman, Quatman-Yates, & Hewett, 2010). However, frontal plane knee mechanics are typically of particular interest as female athletes often demonstrate valgus collapse of the knee at the time of injury (Hewett et al., 2009; Krosshaug, Nakamae, et al., 2007; Olsen et al., 2004) and valgus motion may increase ACL strain (Kiapour et al., 2016). In addition, increased knee valgus during landing is a risk factor for subsequent non-contact ACL injury in female athletes (Hewett et al., 2005). As a result, the assessment of an athlete's frontal plane knee mechanics is often an emphasis of ACL injury risk screening (Myer et al., 2007; Myer et al., 2010; Padua et al., 2015; Padua et al., 2009).

Attempts to identify biomechanical risk factors for ACL injury often rely on a three-dimensional (3D) analysis of lower extremity mechanics (Hewett et al., 2005; Krosshaug et al., 2016; Leppanen et al., 2016). However, conducting an analysis of this nature requires costly equipment, a large space, and significant time and expertise for data collection/processing (Myer et al., 2010; Myer et al., 2014). In addition, collection of 3D motion data is typically limited to a laboratory setting. As a result, the feasibility of wide-spread 3D biomechanical testing for the purpose of ACL injury risk screening is limited at this time. As a result of the barriers associated with implementing 3D biomechanical testing, two-dimensional (2D) measures have been developed to assess frontal plane knee mechanics (Mizner et al., 2012; Sigward, Havens, & Powers, 2011). These measures require minimal equipment (i.e. a standard video camera), less data collection and processing time, and can be implemented outside of the laboratory. A variety of 2D metrics are used to assess frontal plane knee mechanics; one measure that is commonly utilized is the knee-to-ankle separation ratio (2D KA ratio), which is the ratio of the distance between the visually estimated knee joint centers and ankle joint centers (Mizner et al., 2012; Ortiz et al., 2016). A 2D KA ratio of less than 1.0 (i.e. knee joint centers closer than the ankle joint centers) may be indicative of a valgus knee position. The 2D KA ratio has excellent intra- and inter-rater reliability (ICC >0.90) and demonstrates a moderate association with 3D knee valgus angles (Mizner et al., 2012; Ortiz et al., 2016). As a result, it appears that the 2D KA ratio could serve as a useful field measure to assess frontal plane knee mechanics.

A drop vertical jump task is commonly used to assess non-contact ACL injury risk (Hewett et al., 2005; Mizner et al., 2012; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). The standard drop vertical jump task involves an athlete dropping from a box, landing bilaterally, and immediately performing a maximum vertical jump. A criticism of the standard drop vertical jump task is that it may not reflect the cognitive demands associated with maneuvering in sports (Krosshaug et al., 2016). The dynamic nature of the sports environment does not allow athletes to pre-plan/select the movement they will perform, as they are often required to move in response to their teammates, opponents, and/or the ball. This may place temporal constraints on the cognitive processes involved in movement selection (‘decision-making’). In addition, athletes are required to focus their attention on various external stimuli (e.g. the ball) and are not able to attend to their movements. One way to impose temporal constraints on decision-making during execution of a drop vertical jump is by having athletes react to a stimulus presented on a screen (land vs. land-and-jump). This paradigm has been shown to result in increased knee valgus in comparison to baseline (i.e. the standard drop vertical jump task) (Mache et al., 2013). In addition, requiring athletes to attend to an overhead goal while executing a drop vertical jump has a similar effect on knee valgus (Mok et al., 2015). In general, it appears that altering the cognitive demands associated with the drop vertical jump task can have a prominent influence on frontal plane knee mechanics.

Although the reliability (intra- and inter-rater) and concurrent validity of the 2D KA ratio have been explored, it is unknown if the 2D KA ratio is sensitive to differences in landing mechanics that may result from the inclusion of additional cognitive demands. Therefore, the purpose of this study was to determine if the 2D KA ratio measure can detect differences in frontal plane knee mechanics that may result from increasing the cognitive load associated with the drop vertical jump task. We hypothesized that there would be a significant decrease in the 2D KA ratio (greater knee valgus) as the cognitive load associated with the drop vertical jump task progressed.

Methods

Participants

This study included 20 females between the ages of 18 to 25 years old. Participants were required to be recreationally active based on a Tegner Activity Level Scale score of greater than four out of ten (Tegner & Lysholm, 1985). In addition, all participants were required to have experience competing in organized basketball (e.g. high school, intercollegiate). Exclusion criteria included: 1) any medical condition that limited physical activity, 2) any previous history of lower extremity surgery, or 3) any lower extremity injury in the previous six months that limited activity. The participants' mean age, mass, and height were 21.5 ±1.8 years, 64.1 ±11.2 kg, and 1.7 ±0.1 m, respectively. Six participants reported that they were currently participating in basketball at least once per week, while the remaining participants reported only prior participation. Three of the participants indicated that they were currently competing or had previously competed at the intercollegiate level while the remaining participants reported that their highest level of competition was at the high school level. The sample size used in this study was based on an *a priori* estimate. Using an $\alpha = .05$, a $\beta = .20$, a within-factor correlation of 0.7, and a partial eta squared effect size statistic of 0.06, 15 participants were required to ensure adequate power considering the statistical analysis used within this study (repeated-measures ANOVA). The effect size statistic used for sample size estimation was chosen because this is typically considered a medium-sized effect (Cohen, 1988). G*Power software was used to perform this sample size calculation (Faul et al., 2007).

Instrumentation/Equipment

Two adjacent force plates embedded into a raised platform were used to collect ground reaction forces at 1000 Hz (Bertec Corp., FP4060-NC, Columbus, OH, USA). A digital video recorder (HDR-CX240, Sony Corp., Tokyo, Japan) was used to capture 2D video at 30 Hz. The video recorder was placed 3 m in front of the center of the force plates at a height of 0.3 m (Mizner et al., 2012). In addition to the 2D video, the 3D position of retro-reflective markers were recorded at 200 Hz using a ten-camera Eagle system (Motion Analysis Inc., Santa Rosa, CA, USA). The entire testing protocol was conducted in standardized laboratory footwear (Saucony Jazz, Lexington MA, USA).

Testing Protocol

Although the primary focus of this study was on the analysis of the 2D video, we also collected data using the 3D motion capture system as part of an investigation into how progressive increases in the cognitive demands associated with the drop vertical jump task influence 3D lower extremity mechanics. As a result, participants were prepared for a full 3D biomechanical analysis prior to testing. First, calibration markers were placed bilaterally on the anterior-superior iliac spines, posterior-superior iliac spines, greater trochanters, medial and lateral femoral epicondyles, medial and lateral malleoli, and the 1st and 5th metatarsal heads. In addition to the calibration markers, four tracking markers attached to a rigid shell (marker cluster) were applied bilaterally to the thigh and shank in order to track the motion of these segments during the movement trials. An additional marker cluster was applied to the heel counter of each shoe in order to track the motion of the foot. An initial three-second standing calibration trial was conducted with both the calibration and tracking markers applied. All calibration markers were removed following the standing trial, with the exception of the markers placed on the anterior-superior and posterior-superior iliac spines.

Prior to initiating the movement trials, participants performed a standardized warm-up program consisting of bilateral bodyweight squats (2 sets, 8 repetitions) and bilateral maximum vertical jumps (2 sets, 5 repetitions) (Dingenen et al., 2015; Stensrud et al., 2011). Following the warm-up, the drop vertical jump task was conducted in four different conditions: 1) without decision-making or an overhead goal (DVJ), 2) with decision-making, but no overhead goal (DM), 3) without decision-making, with an overhead goal (OG), and 4) with both decision-making and an overhead goal (DMOG). During the DVJ condition, participants performed the trials based on the protocol described by Hewett et al. (2005), where they initially stood on top of a 31 cm high box with their feet 35 cm apart. The box was positioned 15.24 cm behind the force plates (Earl et al., 2007). The participants were then required to drop off of the box, land with both feet on separate force plates, and immediately perform a maximum vertical jump, raising both arms as if they were jumping to grab a rebound. The same setup was utilized for the rest of the conditions; however, there were additional cognitive demands associated with temporal constraints on decision-making and/or the focus of attention. In the DM condition, the participant did not know whether they would land and vertically jump or simply land on the force plates, in a manner consistent with the protocol described by Mache et al. (2013). The specific movement they were to perform was governed by the illumination of one of two different stimuli presented on a screen positioned 1.0 m in front of the force plates. The illumination of the stimulus was triggered using a Tapeswitch signal mat (Tapeswitch Corp., CVP, Farmingdale, NY, USA) positioned on top of the box, which was interfaced with a custom LabVIEW program (National Instruments Corporation, Austin, TX, USA) (Meinerz et al., 2015). The stimulus was presented to the participant approximately 250 ms prior to contact with the force plates (Mache et al., 2013). For the OG condition, the participant was required to grab a ball that was suspended above the force plates, at the top of their vertical jump. A custom built apparatus allowed the height of the ball to be adjusted. The height used for testing was determined during preceding practice trials where the ball was initially suspended at a height of 2.6 m. If the participant was able to successfully grab the ball at this height and maintain control of the ball throughout the subsequent landing, it was raised 5.08 cm. The participant was given one chance at each height unless there was a noticeable disruption during the maneuver (e.g. a stumble). This was continued until they could no longer acquire the ball. If the participant could not acquire the ball at the initial height it was lowered in 5.08 cm increments in the same manner. The maximum height that the participant could grab and successfully maintain the ball during practice trials was used during testing. The DMOG condition incorporated both the decision-making and overhead goal components (i.e. when the vertical jump stimulus illuminated the participant jumped up and grabbed the ball). Participants performed three practice trials for each of the conditions prior to the initiation of testing. During testing, participants completed three successful trials for each condition (DVJ, DM, OG, DMOG). For the tasks that involved decision-making (DM and DMOG), only the trials that required the individual to perform the vertical jump were analyzed. The order of the conditions was randomized to distribute any fatigue or learning effects across conditions.

3D Data Processing

In addition to the traditional 2D KA ratio, we also calculated an analogous knee-to-ankle separation ratio for comparison using data from the 3D motion capture system (3D KA ratio) (Mizner et al., 2012; Ortiz et al., 2016). The raw 3D marker and force data were filtered using a 4th-order, zero lag, recursive Butterworth filter with a cutoff frequency of 20 Hz. We calculated 3D joint angles using a joint coordinate system approach (Grood & Suntay, 1983). The 3D KA ratio was calculated by dividing the horizontal distance between the knee joint centers by the horizontal distance between the ankle joint centers during the drop vertical jump trials. The knee and ankle joint centers were established during the standing calibration trial and tracked using the marker clusters on the shank and foot. The 3D motion capture data was downsampled to 30 Hz to coincide with the sampling rate used for the 2D video data. For each trial, the 3D KA ratio was identified at the time of the peak knee flexion angle for the dominant limb during the stance phase. The stance phase was the time during the trials when the vertical ground reaction force exceeded 20 N. The dominant limb was the limb that the participant reported they would use to kick a ball farthest (Hewett et al., 2005). Preliminary processing of the biomechanics data was performed using Visual3D software (C-Motion Inc., Rockville, MD, USA). We used custom MATLAB code to calculate the 3D KA ratios (The MathWorks Inc., Natick, MA, USA).

2D Data Processing

In order to calculate the 2D KA ratios, the digital video was uploaded into Windows Movie Maker software for conversion into still images (Microsoft Corp., Redmond, WA, USA). For each trial, a still image was created for the frame that the participant reached peak knee flexion after landing. For the 2D KA ratio, we estimated peak knee flexion by identifying the point during the trial where it appeared that the participant began to extend their knee in order to transition into the vertical jump phase of the task, and then moving back a single frame (Mizner et al., 2012; Ortiz et al., 2016). We uploaded the still images into an open access image processing program provided by the National Institute of Health (ImageJ). Within ImageJ, the distance between the knee joint centers and the distance between the ankle joint centers were measured. We calculated the 2D KA ratio by dividing the distance between the knee joint centers by the distance between the ankle joint centers. Figure 10 includes an example of an image used to calculate a 2D KA ratio. The individual that performed the 2D KA ratio calculations was unaware of the specific intent of the study to limit potential bias in data processing.

Data Analysis

The 2D and 3D KA ratios were identified for each trial and averaged within each of the conditions for all participants. As a preliminary analysis, we compared the KA ratios (2D vs. 3D) for each of the conditions using paired t-tests. Next, the difference among the conditions (DVJ, DM, OG, DMOG) for both the 2D and 3D KA ratios were analyzed using repeated measures ANOVAs. We reported the partial eta squared statistic (η^2) as a measure of the effect size. In the case of a significant omnibus test, Bonferroni post-hoc tests were conducted. An alpha of .05 was used for all significance testing. All statistical testing was conducted using SPSS software (IBM Corp., Version 22.0, Armonk, NY, USA).

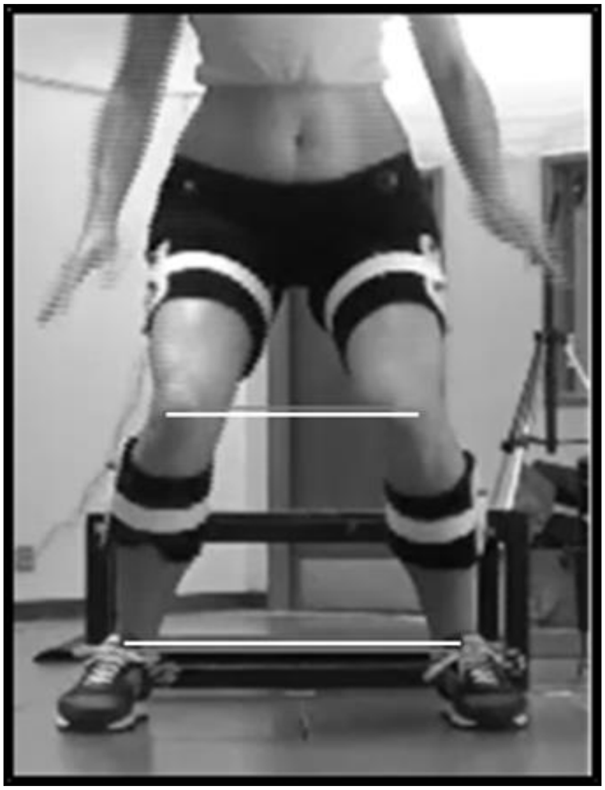

Figure 10. Example of an image used to calculate the 2D KA ratio. For this image, the 2D KA ratio was 0.742 (i.e. the knee joint centers are closer in relation to the ankle joint centers).

Results

The mean 3D KA ratio for the DVJ, DM, OG, and DMOG conditions were 0.824 ±0.141, 0.808 ±0.128, 0.770 ±0.129, and 0.771 ±0.158, respectively, while the mean 2D KA ratios for the DVJ, DM, OG, and DMOG conditions were 0.857 ±0.124, 0.841 ±0.138, 0.800 ±0.139, and 0.828 ±0.131, respectively (Figure 11). The paired t-tests indicated that no differences existed between the 3D and 2D KA ratios for the DVJ (p=.11), DM (p=.08), OG (p=.10), or DMOG (p=.06) conditions.

For the 3D KA ratio, the repeated-measures ANOVA illustrated that a difference existed among the conditions (p=.02; η^2=0.16). The post-hoc analysis indicated that the participants demonstrated lower 3D KA ratios (greater knee valgus) for the OG condition in comparison to the DVJ condition (p=.03). In light of this finding, we expected to observe a concomitant decrease in the 2D KA ratio for the OG condition in comparison to the DVJ condition.

For the 2D KA ratio, the repeated-measures ANOVA indicated that no differences existed among the conditions (p=.12; η^2=0.10). As a follow-up analysis, we also compared the difference between the group means for each of the conditions to the minimal detectable difference (MDD) associated with the 2D KA ratio measure. The MDD is the smallest amount of change for a measure that is considered to be greater than potential measurement error (Portney & Watkins, 2015). To estimate the MDD we initially calculated the standard error of the measure (SEM) (Equation 1). We used previously reported intra-rater reliability data (ICC= interclass correlation coefficient), also from female athletes performing a drop vertical jump, to calculate the SEM (Mizner et al., 2012). The standard deviation (SD) used to estimate the SEM was from our baseline condition (DVJ). The MDD was calculated based on a 95% confidence interval (z = 1.96) (Equation 2).

$$SEM = SD * \sqrt{(1 - ICC)} \tag{1}$$

$$MDD = z * SEM * \sqrt{(2)} \tag{2}$$

Participants demonstrated a reduction in the 2D KA ratio for the OG condition relative to the DVJ condition (mean difference= 0.057) that was greater than the difference that could be attributed to measurement error (MDD= 0.055). None of the other mean differences exceeded the MDD.

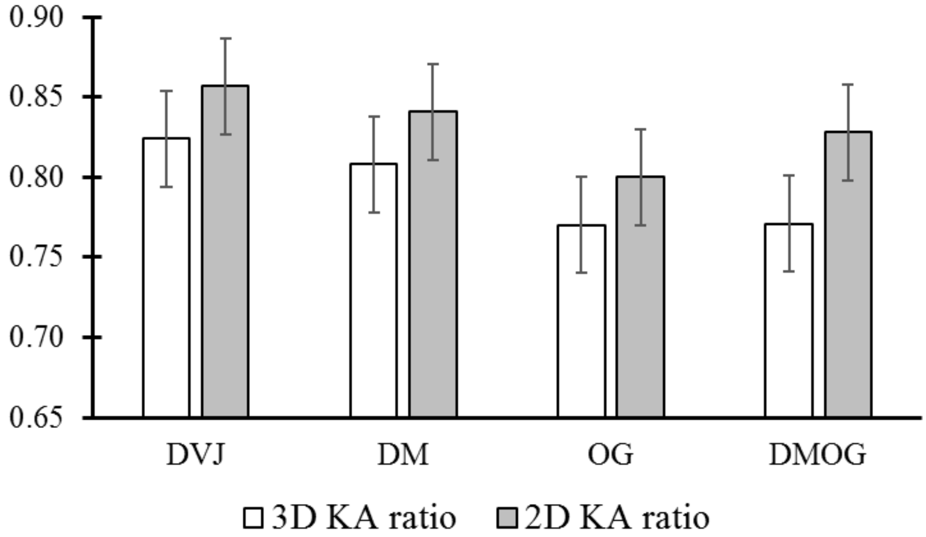

Figure 11. Mean KA ratios (3D, 2D) for each condition. Error bars represent the standard error.

Discussion

The purpose of this study was to determine if the 2D KA ratio measure can detect differences in frontal plane knee mechanics that may result from increasing the cognitive load associated with the drop vertical jump task. Our analysis which relied on the KA ratio estimated using the 3D motion capture system (3D KA ratio), indicated that participants demonstrated a decrease in the KA ratio (increased knee valgus) for the OG condition relative to baseline (DVJ condition). As a result, we expected to observe a concomitant decrease in the KA ratio for the OG condition relative to baseline when the KA ratio was estimated using 2D video (2D KA ratio). Our initial analysis (repeated measures ANOVA) did not detect differences among the conditions. However, a follow-up analysis indicated that the decrease in the 2D KA ratio for the OG condition relative to baseline exceeded the limit associated with potential measurement error. As a result, it appeared that the 2D KA ratio measure showed the same general pattern across the conditions in comparison to the 3D KA ratio measure.

The 2D and 3D KA ratios are analogous measures as they both assess bilateral frontal plane landing mechanics. However, there are multiple additional sources of error associated with estimating the KA ratio using 2D video (2D KA ratio). First, analysis of frontal plane knee mechanics using 2D video can be influenced by motion occurring in other planes. For instance, knee flexion can appear to be knee valgus when viewed in the frontal plane if the hip is in an internally rotated position (Nagano, Sakagami, Ida, Akai, & Fukubayashi, 2008). In addition, there is potential error associated with identifying joint centers from 2D images. Finally, it is important to highlight the fact that identifying the peak knee flexion angle based on visual inspection of 2D video (vs. 3D motion capture) is also an additional source of error. Considering these limitations, we were encouraged by the fact that the KA ratios estimated from the 2D video demonstrated the same general pattern across the conditions in comparison to the KA ratios estimated using the 3D motion capture system. Considering the substantial burden associated with 3D motion capture, it appears that the 2D KA ratio could potentially serve as a useful surrogate measure to assess knee valgus during landing.

The finding that participants demonstrated lower KA ratios (both 2D and 3D) for the OG condition relative to baseline is indicative of greater knee valgus with the inclusion of the overhead goal. Since the KA ratio captures bilateral landing mechanics, lower KA ratios may closely align with the ‘kissing knees motion’ that is used to describe a movement pattern where the knees collapse inward toward midline (Mok & Leow, 2016). Landing in this manner may place an individual at high risk for ACL injury since it corresponds with valgus collapse of either one or both knees. The inclusion of an overhead goal during testing is a relatively minor adjustment to the standard drop vertical jump test. Considering that including an overhead goal has the potential to influence landing mechanics, we believe that sports medicine professionals should consider adopting this slight modification. Mok et al. (2015), are currently conducting a large prospective cohort study (>500 female soccer and handball players) aimed at identifying biomechanical risk factors for non-contact ACL injury using the drop vertical jump task. Interestingly, they are already experimenting with the inclusion of an overhead goal during testing.

It was interesting that the participants demonstrated lower KA ratios for the condition that included the overhead goal in isolation (OG condition), but not the condition that incorporated both temporal constraints on decision-making and the overhead goal (DMOG condition). We expected that that DMOG condition would be the most demanding from a cognitive perspective, and as a result, would have the most prominent influence on lower extremity mechanics. The DMOG task required participants to first attend to the screen to determine which maneuver to perform (i.e. land vs. jump) and then switch their focus of attention during the landing to locate the ball overhead. It is possible that the participants had not switched their focus of attention to the ball at the time the KA ratios were captured and that this mitigated the effects of the overhead goal. However, this is certainly speculative since we do not know what participants were attending to during the trials. Regardless, it appears that the inclusion of the overhead goal in isolation had the most prominent influence on landing mechanics.

The findings from this study may be of interest to sports medicine professionals interested in developing ACL injury risk screening tasks that may more closely reflect the demands of sports participation. However, it is important to acknowledge the limitations associated with this work. First, the individual that performed the 2D KA ratio estimates is considered a novice with respect to 2D video analysis. In contrast, the reliability data we used to estimate the MDD was based on experienced evaluators. However, prior to data analysis we compared the novice rater’s 2D KA ratio estimates to those of a more experienced rater for the baseline condition and found excellent inter-rater reliability (ICC = 0.92). An additional limitation is that our testing protocol is still far less demanding from a cognitive perspective than participation in sports such as basketball. A more challenging testing protocol could potentially elicit greater changes in landing mechanics than what we observed. However, one of the strengths of our study is that the approaches we used to progress the cognitive load associated with the drop vertical jump task (e.g. suspending a ball overhead) could be easily adopted for the purpose of risk screening. Regardless, continuing to develop more ecologically valid testing protocols and risk screening measures appears warranted. Also, it is important to highlight the fact that the participants included in our sample did not have a history of ACL injury, despite experience competing in sports such as basketball where ACL injuries are common. As a result, it is possible that their responses to the additional cognitive demands may not be reflective of individuals that are at risk for ACL injury. Finally, it is important to highlight the fact that we assessed knee valgus solely in the frontal plane. However, the term 'knee valgus' is often used to describe a multi-joint, tri-planar movement (Quatman & Hewett, 2009), which cannot be assessed using 2D measures. This is not a limitation per se, but does warrant clarification.

Conclusion

We assessed knee valgus during a drop vertical jump task using a standard video camera (2D KA ratio) and a 3D motion capture system (3D KA ratio). The cognitive demands associated with the drop vertical jump task were progressed in order to determine if the 2D KA ratio could detect subtle differences in landing mechanics. A preliminary analysis of the 3D KA ratio data indicated that participants demonstrated an increase in knee valgus when they were required to attend to an overhead goal in comparison to baseline. The 2D KA ratio data appeared to follow the same general pattern as participants demonstrated an increase in knee valgus that exceeded the limits associated with potential measurement error with the overhead goal (vs. baseline). Sports medicine professionals must carefully consider the cognitive demands associated with the tasks they use for ACL injury risk screening.

Chapter 6

Summary & Conclusions

Traditionally, models used to describe risk factors for non-contact anterior cruciate ligament (ACL) injury have incorporated anatomical, hormonal, and neuromechanical (i.e. neuromuscular and biomechanical) factors (Griffin et al., 2006; Smith, Vacek, et al., 2012). However, there is a small, but growing, body of literature which suggests that cognitive factors could also play a prominent role (Stuelcken et al., 2016; Swanik, 2015; Swanik et al., 2007). Sports medicine professionals have highlighted the need to develop a better understanding of the contribution that cognitive factors (e.g. decision-making, attention, reaction time, etc.) make with respect to non-contact ACL injury in athletes (Shultz et al., 2015). This notable gap in the literature served as the impetus for the work conducted as part of this dissertation. We believe that improving our understanding of the role that cognitive factors play in non-contact ACL injury may be important to optimizing risk screening and prevention.

The global objective of this dissertation was to explore how cognitive factors contribute to non-contact ACL injury risk. We indirectly assessed the potential role of cognitive factors on non-contact ACL injury by analyzing how individual cognitive abilities/attributes and task-related cognitive demands influence an individual's movement pattern. Our logic was that if cognitive factors altered movement in a manner that may increase ACL loading, then it would support the premise that cognitive factors may play a role in non-contact ACL injury. We performed a review of the literature in order to develop an understanding of what would constitute a 'high-risk' movement pattern with respect to non-contact ACL injury. Our review incorporated studies involving 3D motion analysis (e.g. Hewett et al., 2005), human cadaver models (e.g. Kiapour et al., 2016), assessment of bone bruising patterns (e.g. Viskontas et al., 2008), and observations from video taken at the time of injury (e.g. Olsen et al., 2004). Based on our review, we concluded that a movement pattern where individuals demonstrate a relatively stiff landing (high ground reaction forces, limited hip and knee flexion) with greater knee valgus (increased knee abduction angles and moments) may place them at an increased risk for non-contact ACL injury. As a result, we assessed variables related to this movement pattern across our series of studies.

Our analysis of cognitive factors focused on the influence of individual cognitive attributes/abilities (intrinsic) and task-related (extrinsic) cognitive demands. Anatomical, hormonal, and/or neuromechanical factors undoubtedly contribute to non-contact ACL injury risk. However, we also believe that there is a subgroup of athletes that sustain non-contact ACL injuries because they are ill-equipped to perform the complex cognitive processing required to maneuver within the sports environment, without placing themselves at an increased risk of injury. There may also be extrinsic factors that place greater demands on an athlete from a cognitive perspective, such as having to maneuver while attending to a teammate/ball or needing to respond quickly to changes in the environment (e.g. movement of a defender). We believe that the influence of individual cognitive attributes/abilities (intrinsic factors) and task-related cognitive demands (extrinsic factors) may be closely intertwined. In fact, we anticipate that the most likely scenario for non-contact ACL injury could be when an athlete with lower cognitive ability(ies) is required to execute a maneuver under a high extrinsic cognitive load. As a result, we also attempted to explore the potential interaction between an individual's cognitive ability and the influence of task-related cognitive demands within our analyses.

One of our primary goals was to develop a better understanding of how the movement patterns of individuals with varying cognitive attributes/abilities are influenced as the cognitive demands associated with a task progress (Chapter 2). We anticipated that this would provide insight into the interaction between individual cognitive ability (intrinsic factor) and task-related cognitive demands (extrinsic factor). Aside from our focus on individual cognitive abilities/attributes, we also wanted to better understand how the cognitive demands associated with a movement task (i.e. task-related cognitive demands) influence lower extremity mechanics (Chapters 3, 4, & 5). One approach we used to manipulate the cognitive demands of a movement task was to require individuals to execute a maneuver while attending to a simulated teammate (Chapter 3) or to a ball overhead designed to mimic rebounding a basketball (Chapters 4 & 5). We also altered the task-related cognitive demands by imposing temporal constraints on movement selection (‘decision-making’) by requiring individuals to maneuver in response to an external stimulus (Chapter 4 & 5). We believe that the results of our analyses make a substantial contribution to an evolving body of literature. Our findings will serve as the basis for future studies and may also help to guide sports medicine professionals interested in optimizing ACL injury risk screening and prevention.

The Role of Individual Cognitive Attributes

To investigate the potential role that individual cognitive attributes play in non-contact ACL injury, we utilized a computer-based clinical test to assess cognitive function for a group of 45 uninjured young (ages 18-25 years old) females (Chapter 2). The cohort was delineated into groups based on their performance on the reaction time component of the cognitive test (slow reaction times vs. fast reaction times). Participants in both groups performed a movement task in two randomly ordered conditions (pre-planned, un-planned). The goal of the un-planned condition was to prevent the participant from being able to pre-plan/select the movement they were to perform prior to initiating the trial, potentially imposing temporal constraints on decision-making. For the pre-planned condition the participant was aware that they were to perform the lateral cut prior to initiating a trial (i.e. they could pre-plan/select their movement). What we expected to find was that the groups would demonstrate similar movement patterns during the baseline condition, but that group differences would arise as the cognitive demands associated with the task progressed (i.e. for the un-planned condition). Interestingly, this was not the case. In fact, we actually found that the participants with slower reaction times landed with higher ground reaction forces regardless of the cognitive demands associated with the task (i.e. for both the pre-planned and un-planned conditions). Our findings indicate that individuals with poorer cognitive function may demonstrate a movement pattern that would be considered high risk from an ACL injury perspective, even when the cognitive demands associated with a movement task are relatively limited.

One potential reason why we did not observe differences in the way the groups responded to the increase in cognitive load may be that there was not a large enough discrepancy between the conditions (pre-planned vs. un-planned) with respect to their cognitive demands. Although our intent was to mimic maneuvering within the sports environment, our un-planned condition was still relatively simple from a cognitive perspective. Participants were required to respond in a pre-determined manner to one of three stimuli; whereas athletes are presented with a myriad of stimuli during competition and must respond in an impromptu manner. In addition, the visual stimuli that we used to direct the participant's movement (arrows) did not reflect the visual scene of the sports environment. It is possible that requiring athletes to respond to a more realistic visual display (e.g. video of basketball/soccer players) could have influenced the results of our analysis. Perhaps continuing to progress the cognitive demands associated with the un-planned condition may have resulted in a greater response from the individuals that demonstrated poorer cognitive performance. However, it could just as easily be argued that instead of overestimating the cognitive demands associated with our un-planned condition, we may have underestimated the cognitive demands associated with our ‘baseline’ condition. This may speak to the importance that cognitive function plays with respect to an individual’s ability to perform the cognitive processing required to select, plan, and organize a movement such as lateral cutting, even when there are not additional cognitive demands imposed.

We chose to analyze performance on the reaction time component of the cognitive test because we anticipated that it would closely align with the nature of the cognitive demands that we intended to impose (temporal constraints on decision-making). However, the fact that individuals with relatively slow vs. fast reaction times responded in a similar manner to the progressive increase in cognitive load associated the un-planned condition may call into question the role that temporal constraints on decision-making have on an individual’s movement pattern. It is possible that differences in lower extremity mechanics between un-planned vs. pre-planned maneuvers which are often ascribed to temporal constraints on decision-making may actually result (at least partially) from the increased attentional demands associate with having to attend to a screen while executing a movement. Additional analyses into the underlying cognitive basis (i.e. increased attentional demands vs. temporal constraints on decision-making) for the differences in movement patterns between un-planned and pre-planned maneuvers appears warranted.

We believe that there is tremendous potential in continuing to investigate the role that individual cognitive attributes play with respect to an athlete's ability to control their movement without an increased risk of non-contact ACL injury. Although our analysis focused exclusively on a clinical measure of reaction time in an attempt to capture cognitive processing speed, there are numerous other cognitive attributes that have the potential to influence motor control, which should also be explored (e.g. working memory capacity). Also, additional insight into the role of individual cognitive attributes could certainly be gained by incorporating more sophisticated measures with greater specificity (e.g. magnetoencephalography, functional magnetic resonance imaging). The benefit associated with using clinical tools to assess cognitive function is that they could be seamlessly integrated for the purpose of ACL injury risk screening, as they are already being utilized by sports medicine professionals. However, clinical measures may only provide a global view of cognitive function across multiple domains, which could limit our ability to develop a precise understanding of how various cognitive attributes contribute to non-contact ACL injury risk (e.g. processing speed vs. working memory capacity) (Herman & Barth, 2016). The ability to assess isolated domains of cognitive function may be key to understanding the role that different cognitive attributes play in an athlete's ability to maneuver without an increased risk of injury.

In addition to incorporating more sophisticated measures of cognitive function, we also believe that another key may be to begin to study adolescent athletes. Our analysis included college-aged females that had not sustained a previous ACL injury, despite experience participating in sports where ACL injuries are common (e.g. basketball, soccer, etc.). As a result, our comparison was of two groups of individuals that are both unlikely to be at risk for non-contact ACL injury. Theoretically, studying younger athletes may allow us to capture individuals that are at risk, but have yet to sustain an ACL injury because of a limited number of exposures (i.e. practices, games). In addition, it is also possible that cognitive factors may be particularly relevant to younger athletes that are less developed from a cognitive perspective (McCrory, Collie, Anderson, & Davis, 2004).

The Influence of Task-Related Cognitive Demands

In addition to our analysis of the role of individual cognitive attributes, we also investigated how altering the cognitive demands of a movement task influences lower extremity mechanics. Our analysis included 20 uninjured young females with experience (current and/or previous) participating in organized basketball. In our first study, participants were required to perform lateral cutting trials in conditions with and without basketball handling (Chapter 3). Requiring the participants to simply carry the ball during the cutting trials had a negligible effect on lower extremity mechanics in comparison the trials conducted without the ball. As a result, it appears that having to maneuver while carrying a basketball is unlikely to place an individual at greater risk for ACL injury. Interestingly, requiring participants to carry the ball and perform a subsequent chest pass resulted in a landing pattern that is high risk from an ACL injury perspective (decreased knee flexion, greater knee abduction) in comparison to the condition in which they were simply required to carry the ball (i.e. without the additional chest pass).

The decrement in movement quality when participants were required to attend to executing the additional chest pass likely reflected the fact that they had fewer attentional resources available to allocate toward executing the landing. Although we hypothesized that requiring participants to attend to performing the chest pass would alter landing mechanics, the magnitude of the effect was more prominent than we expected (e.g. more than a 6˚ reduction in knee flexion with the inclusion of the additional chest pass). We were surprised because the attentional demands associated with performing the chest pass are limited in comparison to what athletes typically experience during competition. For instance, the research assistant was stationary in our analysis. However, athletes competing in basketball are required to maneuver while tracking the location(s) of their teammate(s). In addition, our chest pass did not involve any type of decision-making; whereas basketball players are typically unable to pre-determine their action (e.g. pass vs. no-pass) prior to initiating a maneuver.

To continue our investigation into the influence of additional cognitive demands on movement we conducted an analysis that incorporated the drop vertical jump task, which is commonly utilized in ACL injury risk screening (Chapters 4 & 5). Participants were required to perform the drop vertical jump task in four different randomly ordered conditions including decision-making and a goal-directed overhead reach for a ball. We incorporated a ball to alter the athlete's focus of attention during the maneuver. For each condition, we compared movement patterns for the trials where the participants landed and vertically jumped. Participants demonstrated a relatively high-risk landing pattern for each of the conditions that imposed additional cognitive demands (temporal constraints on decision-making and/or the focus of attention) in comparison to the standard drop vertical jump task.

In general, our findings from the analysis of the drop vertical jump task supported our cutting results from Chapter 2, which indicated that subtle alterations to limit an individual's ability to fully attend to their movement can have a fairly prominent influence on lower extremity mechanics. Interestingly, requiring participants to attend to performing the chest pass (Chapter 3) and the ball overhead (Chapters 4 & 5) appeared to have a consistent influence on landing mechanics. In each case participants demonstrated a reduction in knee flexion motion and a concomitant increase in knee abduction motion. Landing in that manner (less knee flexion, greater knee abduction) may reflect a landing pattern where individuals relied less on muscle control in the sagittal plane and more on the passive restraints of the knee in the frontal plane (including the ACL) to decelerate their center of mass (Hewett et al., 2002; Pollard et al., 2010). This type of 'ligament dominant' landing may be indicative of a relatively crude movement pattern that results when individuals are unable to solely attend to their movement. Perhaps there is a greater reliance on passive restraints (e.g. ligaments) because this may require less cognitive control in comparison to coordinating the musculature of the lower extremity to decelerate during landing.

Although we believe that our analyses provide excellent insight into the role that task-related cognitive demands have on movement, we believe that there is also ample opportunity to continue to develop this body of literature. For instance, we plan to explore how altering the stimulus-response compatibility associated with an un-planned task influences landing mechanics (e.g. a right arrow indicates cut left). We also intend to analyze how altering the relative frequency of each stimulus influences an individual's response. Studies that have analyzed un-planned maneuvers (including ours) have utilized testing protocols where each stimulus has an equal chance of being presented. However, we believe that additional insight could be gained by analyzing how individuals execute a maneuver in response to an infrequent stimulus. This may reflect a scenario during competition where an athlete wrongly anticipates the maneuver they will need to perform and must quickly react with an alternative movement (e.g. the athlete anticipates landing, but is required to cut).

Virtual reality also offers a unique opportunity to continue to expand on our understanding of the influence that task-related cognitive demands have on movement quality, as it may allow us to create testing protocols that more closely mimic the sports environment (Bideau et al., 2010). Another benefit of virtual reality is that the testing environments can be designed to react to the actions of the participant, instead of the participant simply reacting to external stimuli. In addition, we also believe that our findings support continued efforts to develop methods to track/analyze athlete's movement during competition (e.g. model-based image-matching) (Koga et al., 2011; Krosshaug & Bahr, 2005). Developing ways to study athlete's movement during competition would certainly provide excellent insight into factors that influence athletic injuries.

Practical Implications

Our findings indicate that cognitive factors (individual intrinsic cognitive attributes, extrinsic task-related cognitive demands) can have a prominent influence on movement. Individuals with poorer cognitive function demonstrated landing mechanics that may place them at greater risk for ACL injury (Chapter 2) and progressing the cognitive demands associated with a movement task tended to result in a movement pattern that would place greater demands on the ACL (Chapters 3, 4, & 5). Considering these findings, we believe that a comprehensive model of ACL injury risk factors needs to consider cognitive factors in addition to anatomical, hormonal, and neuromechanical factors. A failure to acknowledge the potential role that cognitive factors may play in non-contact ACL injury could significantly limit our ability identify athletes that are risk for injury and effectively intervene.

Although we are only beginning to understand the role that cognitive factors may play in non-contact ACL injury, we believe that our findings have immediate practical implications for both risk screening and prevention. Anterior cruciate ligament injury risk screening often involves the analysis of an athlete's movement as they perform maneuvers such as landing, cutting, and jumping. The underlying premise of risk screening is that the mechanics that athletes demonstrate during testing are reflective of their movement during competition. However, our findings challenge this premise, as we found that subtle alterations to a movement task to reflect the cognitive demands of sports, such as having an athlete attend to a teammate or ball, can have a fairly prominent influence on lower extremity mechanics. In addition, including these task-related cognitive demands altered landing mechanics in a manner that would indicate high risk from an ACL injury perspective. As a result, failure to incorporate additional cognitive demands during risk screening may result in a failure to identify some individuals that are at risk for non-contact ACL injury. It is possible that greater insight into an athlete's risk of ACL injury could be gained by assessing their movement when they are attending elsewhere (e.g. to a ball). In addition, our analysis may also provide a basis for incorporating cognitive measures related to motor control into ACL injury risk screening protocols. It is possible that assessing cognitive function may also help to identify athletes that are misclassified (i.e. low risk for ACL injury) using traditional measures that rely on assessment of the capacity of the musculoskeletal system in isolation.

Anterior cruciate ligament injury prevention programs typically incorporate some combination of plyometrics, stretching/strengthening, and/or movement training. Unfortunately, the authors of a recent systematic review which assessed the effectiveness of ACL injury prevention programs for female athletes concluded that there is insufficient evidence to support the wide-spread use of these programs considering their limited effectiveness and the potential burden associated with their implementation (i.e. time, cost, etc.) (Stevenson et al., 2015). As a result, there is a need to develop more effective programs of this nature. The results of our analysis indicate that an individual's level of cognitive function may influence their ability to maneuver without an increased risk of non-contact ACL injury. This may support the development/implementation of cognitive-orientated training to supplement (or potentially replace) traditional training programs designed to target peripheral factors (e.g. muscle strength, flexibility, etc.). Cognitive-oriented training is already being explored as a way to improve athletic performance (Faubert & Sidebottom, 2012) and the possibilities have been discussed in relation to rehabilitation and injury prevention (Grooms et al., 2015). We hope that our work can help to serve as a catalyst for efforts to develop training of this nature. In addition, our findings may highlight the limited potential of conventional movement training approaches. Movement training typically encourages athletes to focus their attention on their mechanics (Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2005; Pfeiffer et al., 2006). For example, athletes are often directed to 'keep your knees over your toes' or 'land softly' during training. The intent is to alter the manner in which athletes execute maneuvers during competition. However, based on our findings it is difficult to believe that training of this nature would translate to a safer movement pattern during competition, when athletes are unable to attend (at least solely) to their movement.

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Curriculum Vitae

Education

University of Wisconsin-Milwaukee
Ph.D. Kinesiology
Dissertation: 'Cognitive Contributions to Anterior Cruciate Ligament Injury Risk'

University of Wisconsin-La Crosse
Doctor of Physical Therapy - May 2013

University of Wisconsin-La Crosse
B.S. Exercise Science - December 2009

Peer-Reviewed Publications

Benson, L., Almonroeder, T.G., & O'Connor, K.M. (2017). Quantifying Knee Mechanics During Balance Training Exercises. *Human Movement Science*. 51, 138-145.

Almonroeder, T.G. & Benson, L. (2016). Sex Differences in Lower Extremity Kinematics and Patellofemoral Kinetics During Running. *Journal of Sports Sciences*. 1-7.

Almonroeder, T.G., Benson, L., & O'Connor, K.M. (2016). The Influence of a Prefabricated Foot Orthosis on Lower Extremity Mechanics During Running in Individuals with Varying Dynamic Rearfoot Motion. *Journal of Orthopaedic & Sports Physical Therapy*. 46(9), 749-755.

Collins, J., Almonroeder, T.G., Ebersole, K.T., & O'Connor, K.M. (2016). The Effects of Fatigue and Anticipation on the Mechanics of the Knee During Cutting in Female Athletes. *Clinical Biomechanics*. 35, 62-67.

Almonroeder, T.G., Garcia, E., & Kurt, M. (2015). The Effects of Anticipation on the Mechanics of the Knee During Single-Leg Cutting Tasks: A Systematic Review. *International Journal of Sports Physical Therapy.* 10(7), 918-928.

Almonroeder, T.G., Benson, L., & O'Connor, K.M. (2015). Changes in Patellofemoral Joint Stress During Running with the Application of a Prefabricated Foot Orthotic. *International Journal of Sports Physical Therapy.* 10(7), 967-975.

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Wouters, I., Almonroeder, T.G., Dejarlais, B., Laack, A., Willson, J.D., & Kernozek, T.W. (2012). Effects of a Movement Training Program on Hip and Knee Frontal Plane Running Mechanics. *International Journal of Sports Physical Therapy*. 7(6), 637-646.

Other Publications

Almonroeder, T.G. Move Forward PT. *PT Connections,* October 2016.

Almonroeder, T.G. The Physiotherapy Evidence Database (PEDro). *PT Connections,* April 2016.

Almonroeder, T.G. Developing a Successful Journal Club. *PT Connections,* October 2015.

Almonroeder, T.G. & O'Connor, K.M. Foot Orthoses and Patellofemoral Pain: Frontal Plane Effects During Running. *Lower Extremity Review,* May 2015.

Presentations

Almonroeder, T.G., Benson, L., & O'Connor, K.M. Sex Differences in the Vertical Ground Reaction Force Time Series During Running. American Physical Therapy Association, Combined Sections Meeting, San Antonio, TX. February 2017. (Podium).

Almonroeder, T.G., Benson, L., & O'Connor, K.M. Gender Differences in Lower Extremity Mechanics During Running. UW-Milwaukee, College of Health Sciences, Fall Research Symposium, Milwaukee, WI. December 2015. (Podium).

Almonroeder, T.G., Benson, L., & O'Connor, K.M. The Effect of a Foot Orthotic on Frontal Plane Joint Mechanics During Running in Groups with Varying Rearfoot Motion. American Physical Therapy Association, Combined Sections Meeting, Indianapolis, IN. February 2015. (Poster).

Almonroeder, T.G., Benson, L., & O'Connor, K.M. The Effect of a Prefabricated Foot Orthotic on Frontal Plane Joint Mechanics During Running. World Congress of Biomechanics, Boston, MA. July 2014. (Poster).

Almonroeder, T.G., Benson, L., & O'Connor, K.M. The Effect of a Prefabricated Foot Orthotic on Frontal Plane Joint Mechanics During Running. UW-Milwaukee, College of Health Sciences, Fall Research Symposium, Milwaukee, WI. April 2014. (Podium).

Almonroeder, T.G., Wouters, I., & Willson, J.D. Comparison of Patellofemoral Stress During Running in Males and Females. American Physical Therapy Association, Combined Sections Meeting, San Diego, CA. February 2013. (Poster).

Funded Projects

Huddleston, W. & Almonroeder T.G. (2016). Cortical Correlates to Lower Limb Movement Variability. Medical College of Wisconsin, Center for Imaging Research, Intramural Research Grant. Amount: $10,000.

Almonroeder, T.G. & O'Connor, K.M. (2015). The Role of Neurocognitive Function in ACL Injury Risk in Female Athletes. UW-Milwaukee, Student Research Grant. Amount: $1,650.

Almonroeder, T.G. & O'Connor, K.M. (2013). The Effect of a Prefabricated Foot Orthotic on Frontal Plane Joint Mechanics During Running. UW-Milwaukee, Student Research Grant. Amount: $2,000.

Scholarships & Awards

UW-Milwaukee
Distinguished Dissertation Fellowship (2016-2017)
Distinguished Graduate Student Fellowship (2015-2016)
Department of Kinesiology Scholarship (2013, 2014)
College of Health Sciences Scholarship (2013, 2014)
Chancellor's Graduate Student Award (2013, 2014)

UW-La Crosse
Most Outstanding Student Award, Physical Therapy Program (2013)
Wisconsin Physical Therapy Association Fund, Student Award (2012)
Cindi Stoller Polek Scholarship, Physical Therapy Program (2011-2012)