AN ABSTRACT OF THE THESIS OF

Mackenzie I. V. Curren for the degree of Baccalaureate of Science in Exercise and Sport Science Honors Associate presented on June 5, 2013. Title: The Effects of Sex and Task on Biomechanical Factors Related to ACL Injury.

Abstract approved:

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Marc F. Norcross

Abstract Body

Title: Curren, M. The Effects of Sex and Task on Biomechanical Factors Related to ACL Injury **Purpose:** To investigate the influences of sex and task on biomechanical factors associated with ACL injury. **Methods:** We used a nine camera motion capture system (Vicon, Inc.) using a standard retroreflective marker set (25 static, 21 dynamic) sampled at 120 Hz to capture lower limb kinematics of 14 healthy male and 16 healthy female subjects during double leg jump landing and side-step cutting. Kinematic data was used combined force place data to calculate the three-dimensional loads at the knee joint during tasks using standard inverse dynamics. **Results:** Females and males demonstrated greater peak anterior tibial shear force (ATSF) and knee extension moment (KEM) (P <.001) during side-step cutting than during double-leg jump landing. However, no main effects for sex (ATSF: $P = 0.198$; KEM: $P = 0.081$) or sex*task interaction effects (ATSF: $P = 0.115$; KEM: $P = 0.191$) were identified. We identified a main effect for sex in which females exhibited greater knee valgus angle at initial contact ($P = 0.003$) and greater peak knee valgus angle ($P = 0.011$) than males. Knee valgus angle at initial contact was also greater for both sexes during side-step cutting ($P = 0.006$). No other main effects or sex*task interaction effects were identified ($P > 0.05$). **Conclusion:** Males and females demonstrate less favorable sagittal plane knee kinetics related to ACL injury during SSC than DLJL. However, sex does not modify this effect. The results support that a SSC is more challenging to perform than DLJL, and the use of this more difficult task may better differentiate the use of "high-risk" biomechanics when comparing groups that may not be evident when using a less challenging task. All participants displayed greater knee valgus angle at IC during SSC, but there was not a difference between tasks for peak knee valgus angle. Females also consistently displayed greater peak and IC knee valgus angles than males. However, it is likely that the small magnitudes of these differences ($< 3^\circ$) are not clinically significant.

Key Words: ACL, jump landing, side-step cut, biomechanics, sex comparison

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The Effects of Sex and Task on Biomechanical Factors Related to ACL Injury

by

Mackenzie I. V. Curren

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Dedication

Thank you to my God, my fiancé, my family, my friends, teachers, professors, and my mentor.

Thank you for your faith, patience and perseverance.

Each of you has played a pivotal part in my journey.

Thank you,

Mackenzie

CHAPTER 1

Introduction

1.1 Introduction

Anterior cruciate ligament (ACL) injuries occur across many sports involving landing and cutting such as soccer and basketball.[1–3] With an estimated 200,000-250,000 ACL injuries per year and a cost of roughly $17,000 per injury for surgical reconstruction alone, identifying and quantifying landing mechanics that can potentially increase the likelihood of ACL injury remains important.[1,4] Additionally, sex differences in landing biomechanics have traditionally been proposed as risk factors for ACL injury in females because of the 2 – 6 x greater risk of injury in females.[5–7] Many researchers have attempted to identify and quantify differences in landing biomechanics that might influence ACL injury risk by comparing males and females biomechanics during different jump tests meant to simulate commonly reported injury mechanisms.[8–11]

Based primarily on *in vivo* cadaveric research, it is generally accepted that greater sagittal and frontal plane knee joint loading directly contributes to increased ACL strain.[1,5] Within the sagittal plane, the ACL has the specific job of preventing anterior translation of the tibia relative to the femur. Excessive sagittal plane loading of the ACL has been shown to cause ACL injury.[12,13] Generally, researchers attempt to infer ACL strain during movement tasks by quantifying factors that can contribute to ACL strain. Two biomechanical measurements of interest in the sagittal plane are anterior tibial shear force (ATSF) and internal knee extension moment (KEM); these have been shown to potentially contribute to ACL injury,[12,14] and are necessary to perform during stop-jumps, pivot and cutting such as in basketball and soccer. Greater ATSF during landing, which is indicative of a greater anterior pull on the tibia, likely results in greater ACL strain.[12,13,15] Similarly, internal knee extension moment (KEM), another biomechanical factor related to the quadriceps force, is also important because it is a measure of the torque exerted on the tibia during deceleration which can also strain the ACL.[5,14] Markolf et al.[14] and Demorat et al.[12] showed in cadaveric investigations that both ATSF and KEM can load the ACL and are capable of causing it to rupture. Markolf, et al.[14] induced ATSF by pulling anteriorly on the tibia, while Demorat, et al.[12] activated the quadriceps to generate a torque on the tibia, thereby creating internal KEM and ATSF. Both of these studies demonstrated the extreme ACL loading that can occur as the values of these biomechanical variables increase.[12,14] While these two factors result in similar sagittal plane ACL loading because of their interconnectedness anatomically and biomechanically, there are subtle differences that make it important to investigate them separately.

An additional set of factors of interest in ACL injury is frontal plane knee joint biomechanics, specifically internal knee varus moment and valgus angle which can influence ACL loading.[16–20] [2,13,20,21] Hewett et al. found that peak internal knee varus moment (KVM) and peak knee valgus (pKVA) angle were significant predictors of future ACL injury.[14] As a result, these factors are considered good indicators of ACL injury risk.[16,18,20,21] These frontal plane factors are thought to be important as there is a lack of musculature to specifically protect against medial and lateral deviation of knee, as a result too much lateral or medial deviation of the knee can load the ACL and place it at risk for injury.[2,5,16,18,20,22]

In combination, sagittal and frontal plane biomechanics affect ACL loading in a fashion that is greater than the sum of their individual parts.[14] In their cadaver study, Markolf et al. demonstrated that the application of ATSF, a sagittal plane factor, with knee varus, a frontal plane factor, led to greater ACL loading than the application of the individual components.[14] Therefore, more challenging movement tasks that combine frontal and sagittal plane movement, could potentially cause greater ACL loading Further, multi-planar movement tasks, such as cutting, may be necessary and more effective in eliciting differences in landing biomechanics when comparing high vs. low ACL injury risk groups (i.e Females vs. Males) than more uni-planar movement tasks (double-leg jump landings). However, it is currently unknown how the choice of movement task for a study (i.e., cutting vs. double-leg jump landings) influences an individual's landing biomechanics. While some studies, such as Besier et al.[16] and Lloyd et al.,[19] have found that more complicated or challenging tasks such as cutting versus straight-ahead running, will show greater knee valgus, varus, internal and external rotations,[16,19] many studies often evaluate biomechanics related to ACL injury using only one type of movement task (i.e., landing vs cutting). Researchers then attempt to compare the results of their investigation to previous work that potentially utilized a different type and difficulty of task.[1,14,16,20] Results derived from using these different types of tasks are then often grouped together, even though it is not clear how each task may influence landing biomechanics, or whether individuals at different risk for ACL injury (Males vs. Females) will be similarly affected by each type of task.

Greater clarity and depth as to whether or not individuals display similar movement patterns across different types and difficulties of movement tasks, and/or, if observed movement patterns in laboratory settings are specific to the type of task performed would be useful in determining whether or not one could generalize results from studies utilizing using the different tasks. This is important because if the choice of task greatly affects individuals' performances, we would then have to make a distinction between tasks when synthesizing the results of previous investigations. Furthermore, identifying what types of task are most likely to elicit differences in landing biomechanics between groups with different ACL injury risk, may help in explaining the inconsistent results related to sex differences in ACL-injury related biomechanics.

ACL injury risk is 4 to 6 times greater in females compared to males.[1,2,22–25] Despite this, some studies, such as McLean et al.,[9] Decker et al.,[26] and McNair et al.[27] have failed to show sex differences within the parameters of sagittal plane movement, while others such as Hewett et al.,[25] Fagenbaum et al.,[6] and Cowley et al.[17] have found clear differences in the way that women and men perform in laboratory settings. Even though we would expect women to display less favorable or riskier biomechanics in relation to ACL injury, based on their real-world known increased risk for ACL injury compared to males,[1,6,9,17,26,27] we do not always observe these expected differences. It is possible that sagittal plane tasks alone may not be challenging or stressful enough to elicit differences in landing biomechanics between the sexes, despite the notion that these differences should be present.[16,17] This disparity indicates a need to further investigate the influence of sex and task on specific biomechanical measures related to ACL injury.

The purpose of this study was to identify whether there are significant differences in biomechanical factors related to ACL injury in participants performing two different movement tasks (double-leg jump landing vs. side-step cutting), and whether or not sex influences the magnitude of any changes that may be observed in these biomechanical factors between the two movement tasks. Because cutting is, biomechanically, more complicated, we first hypothesized that males and females will exhibit less favorable biomechanical profiles related to ACL loading during side-step cutting compared to double leg jump landing. Second, we hypothesized that this effect will be magnified in females in that they will exhibit less favorable values than males on the cutting task. [12,14–18,20,25]

1.2 Research Question

Research Question: What are the influences of landing task (double leg jump and cut) and sex on the five following biomechanical factors related to ACL injury?

A. Anterior tibial shear force
B. Internal knee extension moment
C. Internal knee varus moment
D. Peak knee valgus angle
E. Knee valgus angle at initial contact

Research Hypothesis: We hypothesize all participants will show more unfavorable results in these five biomechanical measures during the cutting tasks compared to the double leg jump landing task, and that the landing biomechanics of females will be more affected than males when moving from a double-leg jump landing to a cutting task.

1.3 Operational Definitions

Initial ground contact (IGC): The beginning of the landing period was defined as the instant when the vertical component of the ground reaction force exceeded 10 Newtons.

Dominant limb: The limb used to kick a ball for maximal distance.

Double leg jump landing: Subjects stood atop a 0.30 m tall box positioned 50% of their height away from a force plate. They then jumped forward and down toward the plate and landed with each foot centered on a force place before immediately jumping up for maximum height.

Cutting: Subjects stood approximately 3 meters away from the force plate. They ran toward the force plate and planted with one foot centered on the force plate then cut to the opposite direction at an angle of 45 degrees as quickly as possible.

1.4 Assumptions & Limitations

The following assumptions were made:

1. Participants performed all testing protocols to the best of their ability and with maximum effort.

2. Participants were honest regarding their prior history with respect to the inclusion/exclusion criteria.

3. The biomechanical data collected during these experiments was reliable and valid for all participants.

1.5 Delimitations

The following delimitations were made for this thesis project.

1. All participants were between the ages of 18-30 at the time of testing.

2. All kinematic and kinetic data was sampled using the same motion analysis system and force plates.

4. All participants had no history of ACL injury, lower extremity surgery, neurological disorder, or lower extremity injury that restricted activity for more than 3 days within the 6 months preceding data collection.

5. All participants were physically active as defined by participation in at least 30 minutes of activity a minimum of three days per week.

CHAPTER 2

Literature Review

2.1 Introduction

More than 200,000 anterior cruciate ligament (ACL) injuries occur annually in the United States, at a cost of approximately $17,000 per injury for surgical reconstruction alone, and up to 12 months of rehabilitation required prior to return to sport.[28] As a result of the time intensive and financial costs of ACL injury for an individual, it remains important to investigate the underlying causes of this injury.[1] Although ACL injuries are attributed to multiple factors (i.e., anatomic, hormonal, biomechanical, etc.), the purpose of this project is to address the influences of task and sex on biomechanics related to ACL injury. To provide context and the necessary support for the research study activities, this literature review will address: 1) ACL injury epidemiology; 2) ACL loading and landing biomechanics; 3) previous sex comparisons of landing biomechanics; and 4) the effect of task on landing biomechanics.

2.2 ACL Injury Epidemiology

ACL injuries are most likely to occur during activities common to sports where when rapid deceleration and quick movement is required.[5,5,29,30] While ACL injuries tend to get a lot of press and attention in mass, sports and social media, ACL injury events are actually relatively rare with about one injury event per 100,000 hours of activity.[23] Mykelbust et al. found that when cruciate ligament injuries do happen, 97% of them are ACL injuries as opposed to posterior cruciate ligament injuries.[31] Another key characteristic of ACL injuries is that they typically happen during the second and third decades of life. The age of peak injury rates has been described by Shea and colleagues as between 16 and 18 years old,[12] by Ortiz as the "young adult" phase of development[18]. Generally, the consensus is that the age range for most ACL injuries is between 14 and 30 years of age.[22,32] Unfortunately, this is also a peak time of youth, health, and physical activity. Not only is this time of health and activity disrupted by this severe injury and rehabilitation, it has been found that injury, regardless of surgical reconstruction, brings about early onset osteoarthritis (OA)[33] and could contribute to other long-term health problems associated with decreased physical activity due to OA such as obesity, heart disease, and many other inactivity-related diseases.[34,35] Thus, the importance of preserving the quality of life for these individuals through both prevention and treatment through the continued investigation of ACL injury is obvious.

2.2a: Injury Incidence

Incidence estimates for cruciate ligament injury are somewhat debated on within the community of health care providers. De Loes et al. reported that the incidence of ACL injury is one injury per every 100,000 hours of high risk sports activity such as soccer or basketball.[23] Others have found an average of 1% overall incidence of ACL/posterior cruciate ligament (PCL) injury in these and similar high-risk activities.[31] There is clear evidence, however, that suggests that ACL injuries are more common than PCL injuries.[36] Arendt and Dick[37] and Arms et al.[38] observe the count of ACL injuries as roughly 200,000 per year as opposed to the typical 50-75,000 per year commonly cited in literature. While the difference between 200,000 and 50,000 is significant, they both suggest that a large number of people still suffer these injuries each year. This variability in ACL injury count shows that we do not have a good tracking system.

2.2b: Sex Differences in ACL Injury Risk

It is well known that females are 4-6 times more at risk to sustain an ACL injury than their male counterparts.[1,6,17,24,32,39] However, while females are at increased risk of injury,[32] males actually suffer a greater total number of ACL injuries each year.[23] The reason for the greater number of injuries in males, but greater injury risk in females, is because of greater male participation and exposure to sports in which ACL injuries are most common such as soccer[1–3,16,17,19] and basketball.[1–3,17,24]

Boden et al.[5] reported that nearly 70% of all ACL injuries are not due to an external force, such as contact with another player, but rather, they are due to the movement patterns of the individual who experiences an ACL injury event.[5] This suggests that most ACL injuries likely stem from improper movement patterns. During sports that commonly require “rapid deceleration” when planting, running, and cutting, which is the most commonly reported non-contact mechanism for ACL injury.[4,12,30,40] Thus, if females are at higher risk for ACL injury, , it suggests that females likely perform these movement tasks differently than males.

2.2c: Long-term Outcomes of ACL Injury

When considering the long-term outcomes of ACL injury, the monetary costs alone are overwhelming. As previously stated, recuperation from injury is expensive and time intensive, with variant costs for surgery and rehabilitation.[1,22] Additionally, the long term costs in quality of life, physical activity and costs associated with treatment of future osteoarthritis (OA), which increases with ACL deficiency and repair[41,42] are substantial when considering the effect ACL injury has on work, mobility and overall quality of life.

Butler et al. reported in 2009 that ACL rupture led to early onset OA[33] and Roos et al. estimated that early onset OA occurred only 5 to 15 years after the initial ACL injury event.[43] Kessler et al. found that 24% of their patients had early onset OA after ACL reconstruction,[44] while Seon et al. found that 67% experienced knee OA after ACL injury and reconstruction.[45] Additionally, some individuals do not return to the same activity levels after injury and reconstruction. Kostogiannis et al. found that individuals with low-impact, low intensity, non-contact activities returned to normal functioning levels, while individuals active in contact sports and activities of daily living of high intensity struggled with returning back to previous levels of physical activities and were less satisfied after reconstruction with their quality of life.[46] In addition, Stevenson et al. found that 36% of ACL reconstruction patients will suffer a second injury, thus incurring more costs associated with repeated reconstruction and rehabilitation.[47] Physical activity is important for long-term health outcomes for individuals, so when normal levels of physical activity are not maintained, it puts patients at risk for diseases associated with lowered physical activity such as obesity, cardiovascular disease, a lowered immune system,[34,35] which generally reduces their quality of life.

In terms of money, time, and long-term health costs, ACL injury makes for an incredibly expensive recovery process, especially when an individual may not return to previous levels of activity.[46] Therefore, furthering our understanding of this injury will give us the ability to develop more effective prevention protocols, and to potentially decrease the total medical costs associated with ACL injury.

2.3 ACL Anatomy and Loading Biomechanics

The ACL is an intraarticular ligament of the tibiofemoral joint. It runs from the anterior intercondylar notch of the tibia in a superior, posterior, and lateral direction and attaches at the lateral femoral condyle. It is a static knee stabilizer that, along with the dynamic stabilization provided by the hamstrings, primarily functions to prevent excessive anterior translation of the tibia relative to the femur.[12,14–17,48] As the ACL runs from posterior to anterior in the knee, it does so at a slight angle from lateral to medial. This orientation runs the ACL through all three cardinal planes of movement and therefore, is oriented so that it may be loaded by movement in any of the three planes of movement. This investigation focused on the sagittal and frontal planes of movement as previous work has identified specific biomechanical variables in these planes that are particularly relevant to ACL loading and injury.

2.3a Sagittal Plane Knee Biomecahnics and ACL Injury

Within the sagittal plane, internal knee extension moment (KEM) is a primary variable of interest, as greater KEM can result in increased strain on the ACL.[12] This is because the quadriceps, the primary source of force that produces KEM, inserts on the anterior aspect of the shank at the tibial tuberosity. Quadriceps contraction produces force that initiates a torque on the shank causing the shank to rotate into a relatively more extended position. As it does this, it pulls on the anterior tibia. A component of the force causes the tibia to translate anteriorly; potentially resulting in ACL loading because the ACL functions to resist this motion. Boden et al.,[5] Myer et al.[3] and Beynnon et al,[49] have reported that that the quadriceps force related to knee extension moment (KEM) can be detrimental to the ACL. Furthermore, Myer et al. found that subjects with ACL injuries had a greater quadriceps to hamstring strength ratio.[3] Within cadaver studies, DeMorat and Li found KEM was likely to contribute to ACL injury.[12,13] Further, Li observed that hamstring activation alone was not enough to prevent ACL rupture when the knee was directly loaded through the activation of the quadriceps muscle.[13] A second sagittal plane variable of interest is this study was anterior tibial shear force (ATSF). ATSF is a measurement of the net internal force acting on the tibia, primarily through quadriceps muscle activation, and is intimately related to knee extension moment. Markolf et al. found that ATSF was the most direct mechanism of loading the ACL and increased the strain on the ACL, especially when combined with frontal plane factors.[14] Thus, both KEM and ATSF (during landing) are commonly used to infer ACL loading due to sagittal plane mechanisms within traditional biomechanics studies.

2.3b Frontal Plane Knee Biomechanics and ACL Injury

The frontal plane is the other primary plane of interest. Frontal plane biomechanical factors have been more directly tied to ACL injury, as two frontal plane variables have been shown to be predictive of future ACL injury.[36] Hewett et al. found that knee valgus angle at initial ground contact[1] was predictive of future ACL injury; and Myer et al. suggested that avoiding excessive knee valgus, or medial bending of the knee joint, during activity by co-contraction of knee stabilizers such as the quadriceps and hamstrings may help to decrease ACL injury risk.[3] Similarly, peak external knee valgus moment, or the peak moment during landing that attempts to create valgus motion about the knee, has also been identified as a predictor of future ACL injury.[1] Consequently, Hewett,[1] Besier[16] and Olsen[29] have suggested that greater external knee valgus moment results in a greater strain on the ACL,[1,16] while Oh et al. suggested that combined internal knee varus moment with extension, compression, and pivot loading lead to ACL rupture.[21] Therefore, an increase in any of these factors, knee valgus angle at initial contact,[1] peak knee valgus angle,[3,32] or peak internal knee varus moment[16,25,29] can negatively affect the ACL. Therefore, they were deemed important factors to consider in this investigation of ACL injuries.

2.4 Effect of Movement Task on Landing Biomechanics

Previous biomechanics research related to ACL injury has utilized different types of landings such as terminal landings,[3,11] jump-landings,[17,19] and plant-cut landings.[16,17,19,29] For example, in their 2001 study, Besier et al. showed that subjects performing a cutting task, a multiplanar movement, showed greater values for valgus angle and varus moment when compared to straight ahead running.[16] Furthermore, Besier et al.[16] and Cowley[17] suggest that more complicated, multi-planar, or more demanding movements such as cutting, might result in greater ACL loading. Houck, Duncan and Haven, found that using a sidestep cut versus straight walking can change frontal and sagittal plane lower extremity biomechanics.[50] However, these differences are not something that have been delineated consistently in research and, unfortunately, general knowledge on biomechanical performance between tasks is limited. Furthermore, there are only a relatively few studies comparing double and single leg tasks and their effects on ACL-injury related biomechanics. This is why comparing individuals' biomechanical performance between tasks is important: it can potentially help clarify why these differences are not consistently observed in the current research literature.

2.5 Sex Comparisons of Landing Biomechanics

In an attempt to identify biomechanical differences between men and women, researchers try to mimic the different types of landings patterns often reported in non-contact ACL injuries like double leg jump landings and side-step cuts. However, Alentorn-Geli et al.,[51] in their 2009 review paper, highlighted that there is a relative lack of consensus on sex differences in biomechanics within the performance of a task. For example, it is unobserved, generally, whether females cut with more,[6,39] the same,[1,9,10] or with less[52,53] knee flexion between two different sagittal plane tasks than men, even though women are 4-6 times more likely to injure their ACL.[6,17,22,24,25,32,39] However, this study only compared males and females' performances between two different uniplanar tasks. Thus, this lack of consensus about biomechanical gender differences could be because the tasks chosen to compare sexes are not difficult enough and are only uniplanar. In fact, Cowley,[17] Besier,[16] and Houck et al.[50] suggest that complicated, multi-planar movements do influence biomechanical responses more than uniplanar movements, and that in turn these may have a greater effect on ACL loading. Therefore, further research evaluating the influences of task and sex on landing biomechanics is warranted.

2.6 Conclusion

It is clear that recovery from ACL injuries are difficult, expensive, and can negatively affect individuals during their peak years of physical activity and fitness.[32] Long-term outcomes of ACL injury can include increased likelihood of re-injury and osteoarthritis; and, therefore, a lower quality of life compared to those individuals without ACL injury. ACL injuries are typically non-contact events and occur during rapid deceleration movements[1,2,17,24] due to extreme loading on the ACL.[4,5,30,40,54] We have identified two planes of movement (sagittal and frontal) and five specific biomechanical variables that are related to ACL injury. It has been shown using both *in vivo* and cadaveric studies, that within the sagittal plane, KEM (the resultant torque due primarily to force generated by the quadriceps)[3,49] and ATSF (the net force acting on the tibia)[14,15] are connected to ACL loading. Frontal plane measures, specifically peak internal knee varus moment,[1,21] and initial contact and peak knee valgus angles,[1,16] are also very important to study when examining ACL-injury related biomechanics. When these frontal and sagittal plane factors are combined, like they are in multiplanar tasks, the end result of ACL loading is likely greater than the individual sum of each variable.[14] Futhermore, there is consensus that while men have a greater overall exposure and incidence of ACL injury, women are more likely to experience an ACL injury event.[24] However, a firm consensus on biomechanical differences between men and women that might help to explain the greater rate of ACL injury in women has yet to be definitively shown.[51] So, it is important to further research how sex and task might influence frontal and saggital plane factors that are considered to be related to ACL loading. It is also important to determine if comparing the results of studies using different tasks produces accurate interpretation of results or sound practice when studying ACL biomechanics. Therefore, this study addresses these limitations by examining the influences of task and sex on five key biomechanical variables associated with ACL injury.

CHAPTER 3

Methods

3.1 Subjects

Twenty-eight volunteer subjects, 14 males (age: 20.31±1.25yrs; height: 177.57±6.22cm; mass: 77.97±8.77kg) and 16 females (age: 22.06±2.52 yrs; height: 162.35±6.48 cm; mass: 63.36±9.03 kg), were recruited and included in this study from the Oregon State University population. Subjects were recruited from announcements in classes as well as informational flyers and emails according to the policies of the Institutional Review Board (IRB). Criteria for participant inclusion in the study were: 1) 18-30 years of age, 2) healthy and physically active as defined by participation in at least 30 minutes of physical activity in a minimum of three times per week, 3) no history of ACL injury, lower extremity surgery, or neurological disorder, and 4) no lower extremity injury within the six months preceding data collection. Before participating, all subjects read and signed an IRB-approved informed consent form that described the procedures and risks associated with participation in the study. After the informed consent process, subject height and mass were measured and used for model generation and normalization of the outcome measures.

3.2 Subject preparation and experimental procedures

Prior to each testing session, subjects warmed up at a self-set pace on a stationary bike for 5 minutes. Afterwards, they were fitted bilaterally with standard retroflective markers placed bilaterally on the acromion process, anterior superior iliac spine, greater trochanter, anterior thigh, medial and lateral femoral epicondyles, anterior shank, medial and lateral malleoli, the sacrum, as well as the approximate locations of the calcaneus, 1st and 5th metatarsal heads. Nine motion capture cameras (Vicon, Inc., Centennial, CO, USA) were used to record participant kinematics during double leg jump landings and side step cuts following a static subject calibration trial.

For double-leg jump landings, subjects stood atop a 30 cm high box placed 50% of their height away from the edges of 2 force plates (Type 4060-08, Bertec Corporation, Columbus, OH, USA). Participants were instructed to jump forward and down with their feet landing in the middle of each force plate and then, with both legs, immediately jump up for maximum height using a continuous motion. For cutting trials, subjects started 3 meters from the force plates and were instructed to run toward the plates, plant their dominant foot in the center of the force plate, and perform a 45 degree cut toward the direction of their non-dominant limb. Participants were instructed to perform the approach run and cut as quickly as possible.

Prior to recording the testing trials, each participant performed a minimum of 3 practice trials for each task. Rest breaks of 30 seconds between each of the five, successful testing trials for each task were taken to lessen the potential effects of fatigue. A successful double leg jump landing trial was characterized by the subject landing with both feet centered on their corresponding force plate at the same time and performing the task in one fluid motion. A successful side step cut trial was characterized by the subject planting the designated foot in the center of the force plate and cutting into a lane marking 45 degrees in the opposite direction and doing so with maximum speed and agility. Leg dominance was determined by asking participants which leg they would use to kick a soccer ball for distance.

3.3 Data Sampling, Processing, and Reduction

We used Vicon Workstation motion capture software (Vicon, Inc., Centennial, CO, USA) to sample kinematics and force plate data at sampling rates of 120 and 1560 Hz, respectively. We then used imported raw three-dimensional kinematic coordinates and force plate data into The MotionMonitor motion analysis software (Innovative Sports Training, Chicago, IL, USA). This software was then used for biomechanical model generation. Midpoints between the medial and lateral malleoli and the medial and lateral femoral condyles defined the ankle and knee joint centers, while external landmarks described by Bell et al. (1989) were used to predict the hip joint center. Local, segmental coordinate axis systems were defined for the sacrum, thigh, shank, and foot with the positive x-axis directed anteriorly, the positive y-axis pointing left, and the positive z-axis directed superiorly. Kinematic and force plate data were lowpass filtered at 10 and 50 Hz, respectively, using 4th order zero-phase lag Butterworth digital filters. Kinematic data was time synchronized to kinetic data and re-sampled at 1560 HZ. Ankle motion was defined as the foot relative to the shank, knee motion as the shank relative to the thigh, and hip motion as the thigh relative to the sacrum. Based on the right hand convention, joint angular positions were calculated using Euler angles in aY (flexion/extension), X' (adduction/abduction), and Z'' (internal/external rotation) rotation sequence. Intersegmental forces and moments of force were calculated within The MotionMonitor using the methods described by Gagnon and Gagnon 1992.[55] Custom computer software (LabVIEW Inc.) was used to identify dominant limb peak KEM, ATSF, and KVM during the 100 ms immediately after IGC; and initial contact and peak knee valgus angles during each trial. Mean values for each dependent variable were calculated over the 5 trials for each task. ATSF was normalized to participant body weight, while KEM and KVM were normalized to the product of subject's height and weight.

3.4 Statistical Analyses

Separate 2 (Task: Double-leg vs. Cutting) x 2 (Sex) repeated-measures ANOVAs were used to evaluate the influences of sex and task on the five biomechanical outcome measures. Where indicated, planned pairwise comparisons were completed using t-tests and a Bonferroni correction.

CHAPTER 4

Results

4.1 Kinetics

We identified a main effect for task ($F_{1, 28}$= 82.576, *P*= <.001) for ATSF but found no main effect for sex ($F_{1, 28}$= 1.742, *P*= 0.198) or sex*task interaction ($F_{1, 28}$= 2.642, *P*= 0.115)(Figure 1). All participants displayed less favorable values for ATSF during the cutting task than they did in the double leg jump-landing task. However, there was no significant difference between the ways the sexes performed both tasks or responded to the change in task. We also identified a main effect for task ($F_{1, 28}$= 21.647, *P*= <.001) for KEM, but again did not identify a main effect for sex ($F_{1, 28}$= 3.273, *P*= 0.081) or task*sex ($F_{1, 28}$= 1.797, *P*= 0.191)interaction effect (Figure 2). Similar to ATSF, we found that both sexes displayed less favorable KEM in the cut than they did in the double leg jump landing. However, KEM was not different between sexes and sex did not modify the influence that task had on KEM. For KVM, we failed to identify main effects for task ($F_{1, 28}$= 1.662, *P*= 0.208) or sex ($F_{1, 28}$= .289, *P*= 0.595) or a task*sex interaction effect ($F_{1, 28}$= 2.409, *P*= 0.132)(Figure 3). There was no difference in peak KVM between tasks or sexes.

4.2 Kinematics

For peak knee valgus angle, we identified a main effect for task ($F_{1, 28}$= 3.273 *P*= 0.081) and a main effect for sex ($F_{1, 28}$= 7.359, *P*= 0.011) but no task*sex interaction ($F_{1, 28}$= .073, *P*= 0.0.789)(Figure 4). We also identified main effects for task ($F_{1, 28}$= 8.696, *P*= 0.006) and sex ($F_{1, 28}$= 10.474, *P*= 0.003), but no task*sex ($F_{1, 28}$= .212, *P*= 0.649) interaction for knee valgus angle at initial contact (Figure 5). All individuals displayed less favorable pKVA and KV@IC values during the side-step cut than the double leg jump landing, and females exhibited less favorable initial contact and peak knee valgus angles than males in both tasks.

4.3 Tables and Figures

Figure 1. Males' and Females' Anterior Tibial Shear Force during Double Leg Jump Landing and Side Step Cutting.

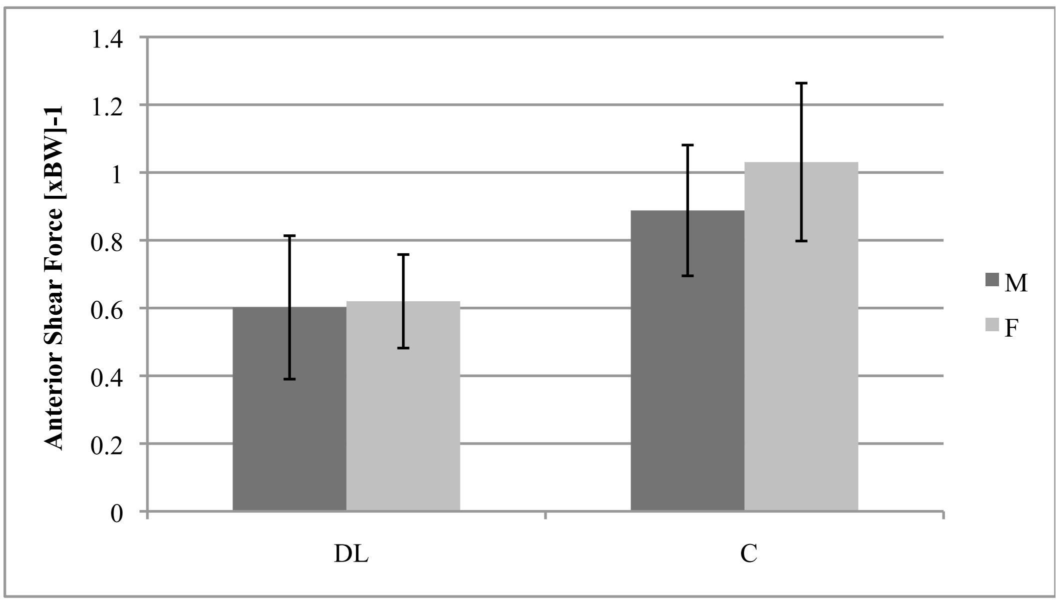


Figure 2. Males' and Females' Internal Knee Extension Moment during Double Leg Jump Landing and Side Step Cutting.

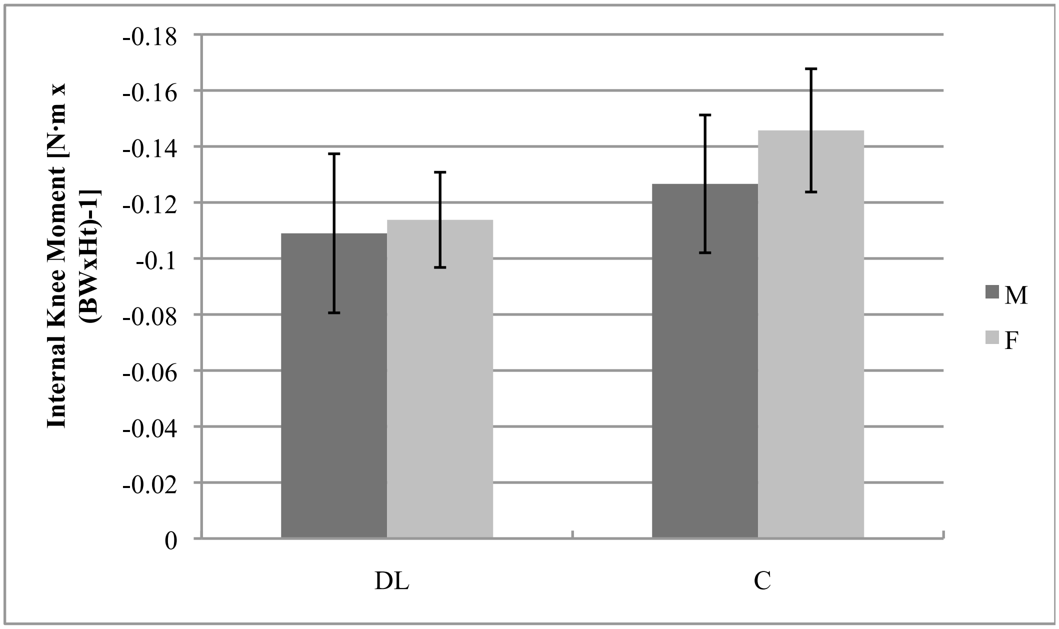


Figure 3. Males' and Females' Internal Knee Varus Moment during Double Leg Jump Landing and Side Step Cutting.

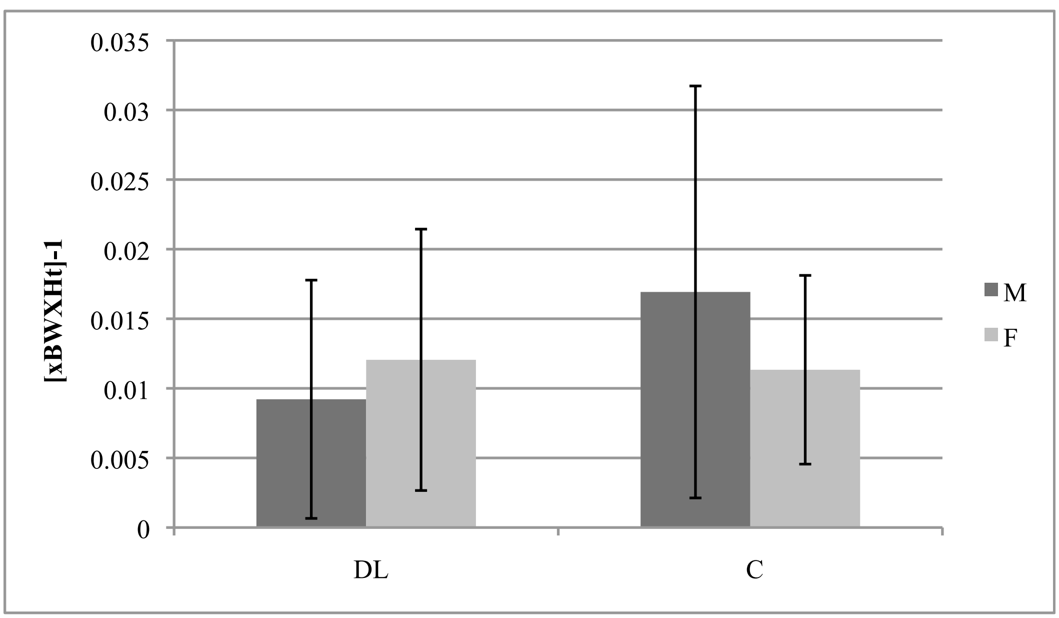


Figure 4. Males' and Females' Peak Knee Valgus (+) Angle during Double Leg Jump Landing and Side Step Cutting.

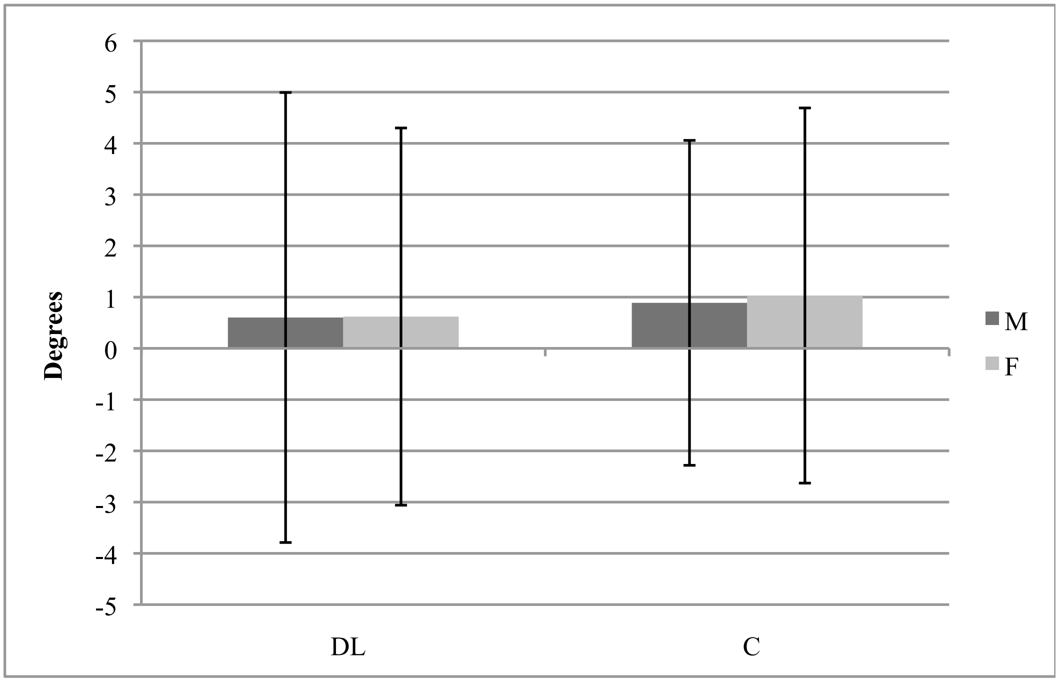


Figure 5. Males' and Females' Frontal Plane Knee Angle [Valgus (+)/Varus (-)] at Initial Contact during Double Leg Jump Landing and Side Step Cutting.

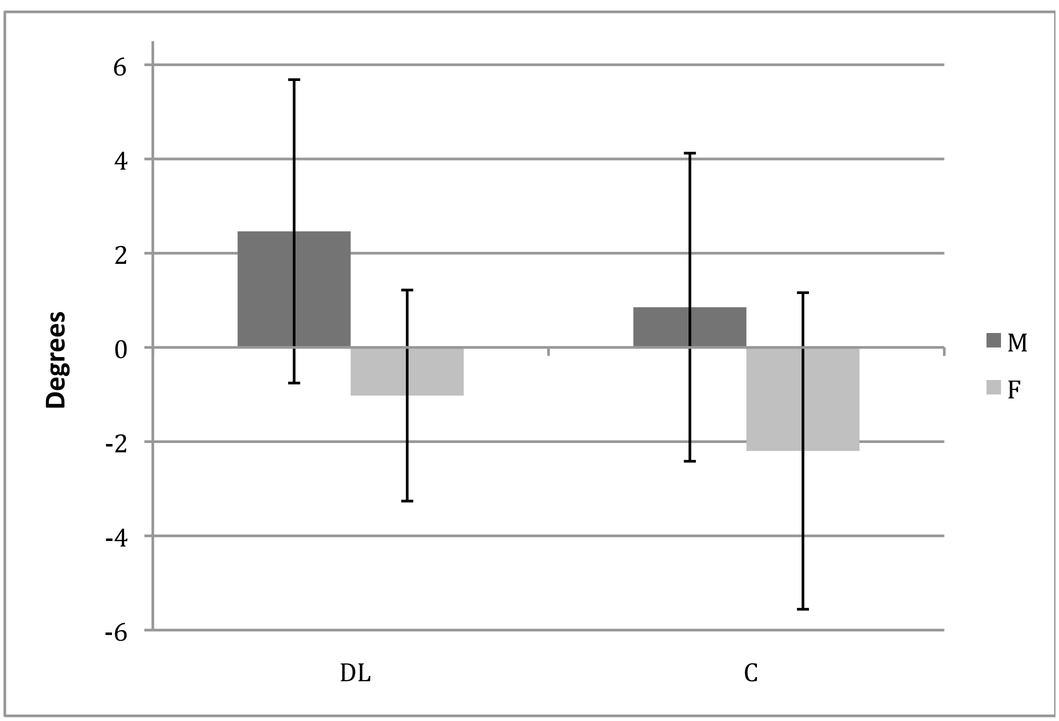
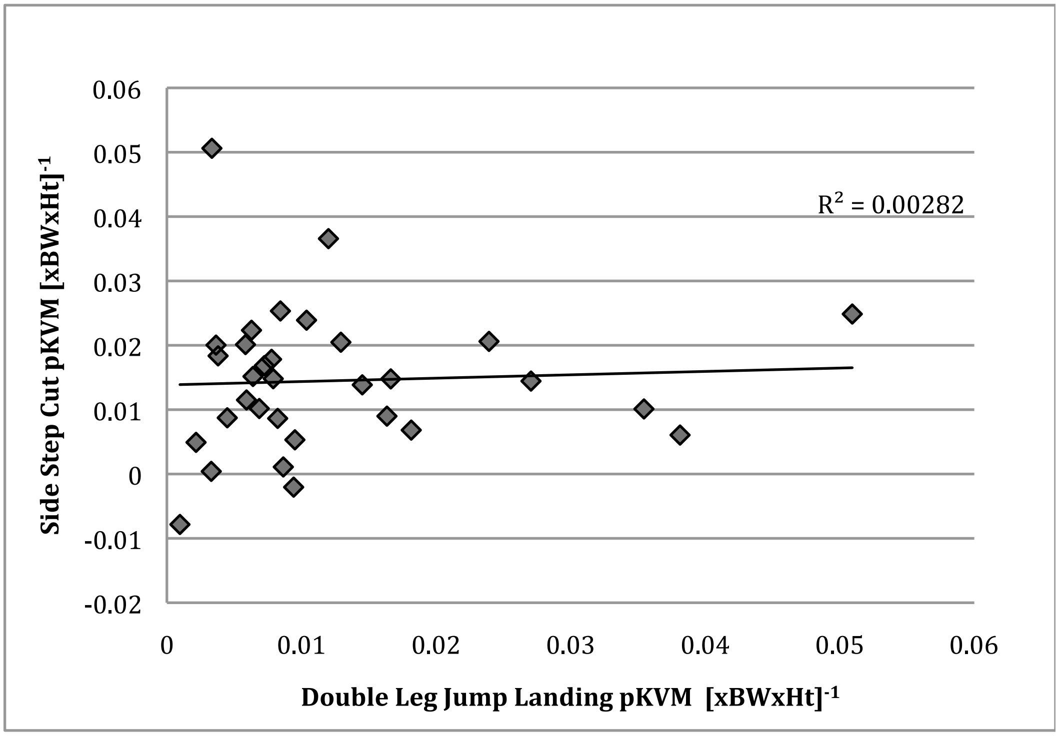


Figure 6. Task Comparison of Individuals' Performances in Relation to Knee Varus Moment.



CHAPTER 5

Discussion

5.1 Introduction

The primary findings of this investigation are that landing biomechanics related to ACL injury are influenced by movement task, but the differences observed between tasks are not modified by sex. In addition, females display less favorable frontal plane kinematics than males across landing in both tasks investigated.

5.2 Sagittal Plane Kinetics: ATSF & KEM

We observed a similar trend for both sagittal plane kinetic measures as both males and females performed side side-step cutting with greater ATSF (Figure 1) and KEM (Figure 2) than during DLJL. This makes sense given that, intuitively, side-step cutting is a more difficult (single-leg and multi-planar) task than DLJL (bilateral and uni-planar) and therefore should place greater demands on the knee. These results are significant because they clearly indicate that the side step cutting task is harder to do than DLJL, and therefore this task may be more useful for distinguishing groups of participants that might otherwise demonstrate similar landing biomechanics when performing an "easier" task in laboratory settings. If a researcher were to choose to do a cutting task or another task of similar difficulty in place of a DLJL, they might be able to interpret their results and draw conclusions regarding their groups knowing that they likely chose a task with sufficient difficulty to elicit group differences in landing biomechanics and one that more closely simulates real-life movements when ACL injury events occur.

Our failure to identify a significant main effect for sex or sex*task interaction effect suggests that sex differences in sagittal plane kinetics that have been identified in previous studies were likely driven by the subjects in each study (i.e., the sample) rather than the choice of task. Specifically, we believe that any observed differences between sexes in these studies were not the result of different tasks being performed, but rather that those sex differences would have been seen regardless of cutting or jumping task due to the specific individuals that were included in the study.

5.3 Frontal Plane Kinematics: pKVA & KV@IC

With respect to frontal plane kinematics, we found that females displayed significantly greater values for pKVA (Figure 4) and KV@IC (Figure 5) than males across tasks, and that all individuals demonstrated significantly greater KV@IC during the side-step cutting task than during DLJL. While our results make sense theoretically, as individuals are likely to perform worse in a more difficult task than they would in an easier or less complicated task, the magnitude of the differences were roughly 3˚. It is likely that this relatively small difference is not clinically relevant. Furthermore, while pKVA and KV@IC are important, as they are predictors of ACL injury, these values are merely measurements of joint angle at a single point in time and are not necessarily related to actual knee joint loading. This is significant because the knee could have a significant load, or not, and be positioned in exactly the same angular position. As a result, the loading of the knee coupled with the joint's angular position is likely more important than just position alone as it is these factors that in combination influence ACL loading. Nonetheless, our results do provide evidence that the frontal plane kinematics of males and females are not differentially influenced by the choice of movement task.

5.4 Frontal Plane Kinetics: KVM

As with the sagittal plane kinetic measures, we failed to identify sex differences in KVM during both cutting and DLJL, which was contrary to our hypothesis. We propose that one of the reasons we may not have identified sex differences in sagittal and frontal plane kinetic is because we chose not to standardize cutting velocity. Previous studies that have identified sex differences, such as Mclean et al.,[9,10] typically standardized velocity for all subjects between 4.5 and 7.0 m/s. We chose to instruct our participants to complete the task "as quickly as possible," which resulted in measured center of mass velocities at initial contact that were between 3.5 and 4.5 m/s.

Our rationale for not standardizing cutting velocity is that we do not think this methodological technique results in a movement task that places similar demands on males and females. Given that females are generally smaller, have shorter stride lengths, and demonstrate maximum velocities that are less than males, we believe that requiring females to perform cuts at the same velocity as males results in the task being typically more difficult for females than males. As a result, we attempted to eliminate this potential confounding effect by asking each individual participant to complete the cutting task as quickly as possible and accepted the limitation that all participants would consistently provide maximal effort during their testing session.

A second potential reason that we may not have observed sex differences in knee kinetics is our study population. McLean et al.,[9,10] Besier et al.,[16] and Lloyd et al.[19]

examined college-aged athletes as their population. Our population consisted of all college students, but we were not as restrictive on the types of physical activities performed. This difference in test populations, we think, may have potentially affected the results.

Additionally, we failed to identify a main effect for task for KVM. This result was especially surprising given that we observed differences between tasks in sagittal plane kinetics (ATSF and KEM). As such, we expected that we should have also seen a main effect for task in KVM as the cutting task was both unilateral and multiplanar (Figure 3). We hypothesized that this lack of a task effect could be driven by the fact that participants may not utilize a consistent frontal plane loading strategy between tasks because the tasks might affect people differently. More specifically, it is possible that individuals do not respond to a change in the two tasks in a similar manner. To evaluate this notion, we performed a secondary analysis in which we correlated individual participant KVM values during the side-step cutting and DLJL tasks and found that there was no significant relationship between these two measures (r=-0.096, P=0.613)(Figure 6). This result indicates that the magnitudes of KVM exhibited by an individual during a cutting and DLJL task tend to be independent, and suggests that KVM results from studies utilizing these two different tasks should not be directly compared.

5.5 Limitations

As mentioned previously, we did not standardize cutting velocity and worked under the assumption that subjects ran as hard as they could and did so consistently for all trials of their testing session. In addition, our participants may or may not have been truthful in reporting their physical activity levels. Additionally, we didn't restrict for type of physical activity in our minimum physical activity requirements.

5.6 Conclusion

The primary finding of this investigation is that landing biomechanics related to ACL injury are influenced by the choice of landing task, but these changes are not modified by sex. In addition, while females display significantly greater pKVA and KV@IC, it is likely that the magnitudes of these differences are not clinically meaningful. Furthermore, comparisons of KVM between studies using cutting and DLJL tasks should be made with caution, as the magnitudes of KVM exhibited by individuals during these tasks tend to be independent.

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