# ANTICIPATORY EFFECTS ON LOWER EXTREMITY KINEMATICS AND KINETICS DURING CUTTING MOVEMENTS

By

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To everyone who constantly asked me when I would finish my thesis

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ANTICIPATORY EFFECTS ON LOWER EXTREMITY KINEMATICS AND KINETICS DURING CUTTING MOVEMENTS

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Although gender differences in ACL injuries are a fertile ground for research, the multitude of previous projects has not led to a decrease in injury rates. Many researchers have investigated anticipated athletic movements, but preplanned movements rarely occur during competition. Therefore, unanticipated movements warrant more investigation. The purpose of this study was to investigate the effects of anticipation on lower extremity kinematics and kinetics during movements that are considered high risk for ACL injury. Fifteen males and fifteen females were recruited from undergraduate classes to perform side cuts and crossover cuts. Approach speeds were required to be within the range of 5.0 to 7.0 m/s and cutting angles were required to be between 35 degrees and 60 degrees. Sampling rates for the cameras and force plates were set at 240 Hz and 2400 Hz, respectively. Concerning unplanned movement, the hip and knee were abducted during the side cut and adducted during the crossover cut. For the unplanned conditions, the movements were performed using similar frontal plane adduction moments at the hip and knee. When lacking the ability to preplan the maneuvers, a similar movement strategy was used. Thus, participants were unable to accommodate to the unplanned movements. Also, increased hip flexion was revealed during the unanticipated movements. Since participants prepared for the unanticipated movements through lowering the center of mass

height, accommodation to unplanned movements seems possible in the sagittal plane. Gender differences occurred at the hip as females used less hip abduction to perform the movements. Less hip abduction for females is closer to the "position of no return" seen in ACL injuries. Although our results confirmed published gender differences, this may have been due a combination of the difficulty of the tasks and the relatively low skill of the participants. Direction differences occurred as the crossover cut was performed with knee abduction and foot pronation while the opposite was true for the side cut. Furthermore, the crossover cut seemed to be performed by utilizing a preceding side cut. Therefore, the crossover cut seems to be a more dangerous movement. Although accommodation for unplanned movements may occur in the sagittal plane, unanticipated cutting movements are performed differently than anticipated cutting movements. Since anticipation can affect the performance of cutting movements, incorporation of unanticipated maneuvers should be included in training prevention programs. Also, increased development of methods for preventing anticipation is required to more closely simulate competition in the lab setting.

# CHAPTER 1
# INTRODUCTION

The anterior cruciate ligament (ACL) prevents anterior displacement of the tibia relative to the femur and functions in rotational stability of the knee.[1-3] In the United States, ACL ruptures occur approximately 100,000 times each year [4]. Although primarily occurring in athletic populations, women are four to six times more likely to suffer an ACL injury than men when playing the same sports.[5-8] The passing of Title IX in 1972 led to a dramatic increase of the participation of females in high school and college sports. Unfortunately, an increased number of ACL injuries accompanied this increase of female participation.[9-11]

The majority of injuries to the ACL occur during noncontact movements.[12, 13] High risk movements for ACL injury constitute one leg landings, rapid stops, and pivoting movements which produce a common position that combines a low knee flexion angle with knee valgus and internal rotation of a planted leg.[12, 14] This is classified as the "position of no return" for an ACL injury.[15, 16] In this position, the muscles that normally provide absorption of forces can not function properly due to a mechanical disadvantage, which leads to a greater predisposition for injury.

Due to the prevalence of injury and potential long term disability, prevention of ACL injury is a main concern of clinicians and scientists. Therefore, many potentially predisposing factors for ACL injury have been identified and researched. These factors are classified as anatomical, environmental, hormonal, and neuromuscular.[4] Anatomical factors tend to be immutable without surgical intervention. Environmental factors affect both genders and are difficult to separate their specific risk due to their intimate interrelatedness. Hormonal factors represent a potentially rich source of research due to the drastic gender differences in serum concentration levels of specific hormones. However, results have proven to be inconclusive due to the conflicting nature of many experiments. Neuromuscular factors consist of altered movement patterns, altered muscle activation patterns, inadequate muscle stiffness, and decreased muscle strength. With proper training neuromuscular factors tend to be modifiable.[17] Although no single factor represents the solitary cause of the alarming rate of female ACL injuries, focusing on the investigation of neuromuscular factors is rational due to their modifiable nature with proper training,

Gender differences in kinetics, kinematics, and muscle activation patterns have been documented during high risk movements.[4, 18] Female athletes tend to perform high risk maneuvers with less knee and hip flexion, increased knee valgus angles, and ankle eversion.[12, 14] However, many of these differences were observed during laboratory studies utilizing preplanned maneuvers. In order to gain an improved understanding of the kinematics and kinetics imposed on the lower extremity during competition, a more realistic comparison is required that employs unanticipated movements. Furthermore, kinetics and kinematics of the knee were predominantly examined during these studies. Therefore, the purpose of this study is to investigate the influence of gender and a voluntary reaction component on the lower extremity during running, side step cutting, and crossover cutting. Results from this research may be used to improve ACL injury prevention programs in order to reduce female injury rates more similar to the level of the injury rates of males.

# CHAPTER 2
# LITERATURE REVIEW

## General Introduction

Injury to the anterior cruciate ligament (ACL) represents one of the most severely devastating injuries in sports.[19] Although occurring infrequently in the general population, one in 3000 individuals sustains an ACL injury per year in the United States with half of ACL injuries suffered by young athletes 15 to 25 years old.[5, 6] However, women are four to six times more likely to suffer an ACL injury than men when playing the same sports.[7, 8] With the passing of Title IX in 1972, a dramatic increase in ACL injuries followed the increased participation of females in high school and college sports.[9, 11, 20]

Prevention of ACL injury is a main concern of clinicians and scientists due to the financial cost, prevalence of injury, severity, and potential long term disability. Each injury can cost between $17,000 to $25,000 for surgery and rehabilitation.[17] In the U. S., the annual cost for the treatment of ACL injury totals over $1.5 billion.[4, 11] Of this total, $646 million is for ACL repair in high school and college female athletes.[6, 21] In addition, nearly 2/3 of patients who tear their ACL suffer from menisci damage and injury to articular surfaces.[22] However, the psychological costs that come from potential long-term disability and significantly greater risk of osteoarthritis are harder to measure monetarily and can be more harmful.[23]

Due to the severity of the injury and the elusiveness of attenuating injury rates, vast resources have been utilized to investigate a plethora of research topics influencing ACL injury rates. Upon delving into the complex factors that influence ACL injury rates, one quickly recognizes the closely intermingled nature of the different aspects. Although this project is primarily focused on neuromuscular factors, the following literature review explores many pertinent topics to give an overall understanding of the published research. An integral element of understanding what movements place the ACL in danger is the interaction of the muscles, bones, tendons, and ligaments of the knee. These topics are reviewed during the *anatomy* portion of the review. During normal movement, forces can be absorbed by all of the knee anatomy. However, high risk movements place the ACL under greater forces.[24] These movements are noted during the mechanism of injury portion of this review. Although high risk movements place the ACL under greater forces, anatomical factors can influence knee alignment and may predispose individual to be more susceptible to suffer an ACL injury. These factors are explored in the anatomical factors portion of the review. Also, hormone levels influence the ability of the passive components of the joints to absorb forces. The effect of hormone levels on joint laxity is documented in the hormonal factors section. In addition, factors that influence the amount of force absorbed by the body during movements are explored in the environmental factors segment. During high risk movements, the alignment of the knee may be placed in a position preventing adequate force absorption by the muscles. Also, fatigue can influence lower extremity alignment, force production, and force absorption. Therefore, lower extremity alignment and control is important during all levels of fatigue. These topics and the impact of prevention programs are explored in the section on neuromuscular factors.

## Anatomy

A prerequisite to understanding the complex interaction of factors influencing ACL tears is knowledge of the anatomical characteristics of the knee and its surrounding musculature. Considered the largest joint in the body, the knee has two articulations: the tibial-femoral joint and the patellofemoral joint. Ligaments, muscles, compressive forces, and joint geometry contribute to the stability of the knee. Therefore, the knee is susceptible to injury due to dependence on these soft tissues for stability.[25] The ACL is an important ligament of the knee that is the primary restraint to anterior translation of the tibia and the main stabilizer of the knee.[2]

The ACL absorbs 85% to 90% of anterior displacement forces.[1, 2] In addition, the ACL is an important factor in rotational stability of the knee and opposes internal rotation of the tibia.[3, 26] Therefore, it is the main stabilizer of the knee during pivotal activities and also prevents hyperextension.[1, 27]

Although the ACL is considered one ligament, Girgis et al.[1] noted that it is composed of two bundles: the anteromedial bundle (AMB), and the posterolateral (PLB). Others have described the ACL as having an additional bundle: the intermediate bundle.[3, 28] Originating at the posterior portion of the lateral femoral condyle, the ACL inserts to a fossa positioned laterally and anteriorly to the medial tibial spine.[29] The relative location of the bundles with respect to each other depends upon the knee flexion angle.[30] Also, the ACL is sturdier and broader near the femur.[1]

Regardless, the bundles cooperate to stabilize the knee during movement, but tension is not distributed uniformly.[31] Also, during flexion and extension the bundles are not of a uniform length. According to Hollis et al.[32], the AMB lengthens and tightens in flexion, while the PLB shortens and becomes relaxed. During extension, the PLB becomes taut, while the AMB is slack.[3] When the knee is fully extended, the AMB is significantly longer than the PLB at an average of 34 mm and 22.5 mm, respectively.[29] According to Amis and Dawkins[3], the AMB is the major antagonist to anterior translation during flexion, and the PMB performs the same function during extension. During internal and external rotation, the PMB becomes stiff.[30] Interestingly, single ligament reconstruction imitates the anatomy only of the AMB, and may not restore normal resistance to tibial rotation.[33] The narrowest portion of the ACL is the midsubstance, which can be 3.5 times smaller than the points of origin and insertion.[34] However, Chhabra et al.[30] state the most common rupture of the AMB occurs at the femoral insertion site, but the PMB may rupture at the tibial or femoral insertion site or midsubstance.

Any alteration in a segment of the lower extremity affects the kinetics and kinematics at all joints.[35] Therefore, ACL injury rates are influenced by movement at the ankle and hip.[36, 37] The ankle is composed of two separate hinge joints: the talocrural and the subtalar.[38] Plantarflexion and dorsiflexion occur at the talocrural joint, while pronation and supination occur at the subtalar joint.[25, 39] Motion of the foot can influence movement of the knee.[40] During stance, ground reaction forces are absorbed by the foot and ankle and transfer loads to the knee.[37] Also, tibial internal rotation and foot eversion are coupled by the ankle.[41] In women, knee injuries directly correlate with rear foot pronation.[42] Dynamic valgus at the knee, the dangerous position that characterizes many ACL noncontact injuries, is marked by ankle eversion.[35] Therefore, ankle eversion and inversion angles are important to identify individuals at an increased risk for ACL injury.[35]

## Mechanism of Injury

Injury to the ACL occurs predominantly without contact during single limb support ranging from initial contact to peak knee flexion.[36] Noncontact mechanisms are responsible for 70% of ACL injuries.[12, 13] Although a consensus exists within the literature about the occurrence of contact or lack of contact during an ACL injury, the definition of a noncontact ACL injury differs among researchers. A noncontact injury occurs when there is an absence of player to player contact. A contact injury occurs when an injury to the ACL is preceded by a direct blow to the knee. However, ACL injuries occur during body to body contact with an opposing player, but the contact did not involve a direct blow to the knee. Hewett et al.[10] defined this type of injury to be a noncontact ACL injury with perturbation. Due to the broad nature of this definition, these injuries are difficult to classify. However, other players can influence the movements of an individual during the game and in controlled settings without contacting the injured player.[42, 43]

In general, noncontact injuries to the ACL entail one of three categories: planting and cutting, straight knee landings, and rapid, one leg stops.[12, 21] All of the previous movements produce a common position that occurs with the knee near full extension during landing, planting, or stopping.[12, 14] This position includes a flexed and rotated lower back, adduction and internal rotation of the hip, flexion and valgus positioning at the knee, external tibial rotation, and a planted foot. Also, a loss of control of the opposite foot often occurs. In this position, the muscles that would normally help the athlete remain erect cannot function properly because they are working at a mechanical disadvantage, which leads to a greater predisposition for injury. This is known as the "position of no return" for an ACL injury.[15, 16] This body position has been corroborated using video analysis of the orientation of the body.[14, 43] However, these studies have also revealed the difficulty of elucidating an accurate representation of the mechanism. In addition, gender differences exist in movement patterns during everyday activities like walking.[36]

**Predisposing Factors for Injury**

Potentially predisposing factors for ACL injury have been classified as anatomical, environmental, hormonal, and neuromuscular.[4] Anatomical factors associated with an increased risk of ACL injury include separate measures of anatomical alignment, ACL size and shape, and body mass index (BMI). Unfortunately, the majority of these factors are mostly immutable without surgery. Environmental factors comprise meteorological conditions, shoe-surface interaction, and knee braces. Although environmental factors tend to be modifiable, more research is needed in order to clarify discrepancies. Also, interventions for environmental factors may lower the overall ACL injury rate without a decrease in the difference in the ratio of female ACL tears to ACL tears in men. Next, hormonal factors include the effects that hormones have on knee laxity, muscle function, and strength of tendons and ligaments. Although hormonal factors potentially represent a huge forward leap in prevention of ACL injuries, previous research conflicts in linking specific periods of the menstrual cycle to increases in ACL injury. Finally, neuromuscular factors consist of altered movement patterns, altered muscle activation patterns, inadequate muscle stiffness, and decreased muscle strength. With proper training neuromuscular factors tend to be modifiable.[17] Although no single factor represents the solitary cause of the alarming rate ACL injuries to women, neuromuscular factors tend to be amendable with proper training. Therefore, the concentration of time and resources towards their investigation seems logical.

**Anatomical Factors**

Anatomical factors associated with ACL injury are misalignment of the lower extremity, a narrowed intercondylar notch, physiological laxity, increased Q angle, increased pelvic width, tibial rotation, and BMI. Although anatomical factors appear to have an impact on ACL injury, anatomical factors characterize the hardest factors to amend when compared to the other groups. Of the anatomical factors BMI represents the most potential for modification, but the evidence has been conflicting. Some researchers contend that a high BMI correlates with an increased risk of ACL injury.[44] However, Ostenberg and Roos[45] were unable draw conclusions about the relationship between BMI and ACL injury due to the small percentage of ACL injuries in their sample. Logically, an increase in body mass increases forces during landing.

Q angle, the angle formed between the lines that link the anterior superior iliac spine and the midpoint of the patella and the line connecting the tibial tubercle with the midpoint of the patella, can cause a more valgus knee position. Larger Q angles increase the knee valgus angle and place increased medial stress on the knee from the quadriceps femoris muscle.[22, 46] Normal ranges for Q angles are approximately 8° to 17° during full extension with women consistently having higher Q angles than men.[47-51] Female college basketball players had larger Q angles than male college basketball players.[52] Shambaugh et al.[46] reported that recreational basketball players who injured their knees had a higher Q angle than uninjured players. However, Q angle was not a significant predictor of injury during dynamic movement.[53] Also, significant correlations do not exist between Q angle and peak knee valgus during stance phase.[54]

Numerous studies have been performed to elucidate a relationship between ACL injury and femoral notch size and shape. The notch width index (NWI) measures the width of the anterior outlet of the notch divided by the total notch width at the level of the popliteal groove. Logically, a narrower notch would lead to a smaller ACL unable to tolerate loads as well as a larger one.[55] Andersen confirmed that ACL size correlates with the NWI.[56] However, results from research investigating a relationship between ACL size and injury rates has conflicted.[28, 56-58] The notch width of a unilateral ACL injured knee was smaller than a sized matched uninjured control group.[7] Also, females have a smaller sized ACL when compared to males in general and when matched to males of a similar height.[57, 59] However, Fayad et al.[60] found no gender differences when adjusted by body height. Also, Anderson et al.[56] found no gender differences of the NWI. Other measures that investigate the dimensions of the intercondylar notch include the notch shape index (NSI) and the notch area index (NAI).[61] When comparing all three of the intercondylar notch measures, the NSI was the only measure to display significant gender differences with males displaying a larger NSI.[61] Although evidence for a causal relationship is lacking for ACL injury and femoral notch dimension, an association may exist.

Women tend to have more joint laxity than men.[12, 62] However, joint laxity has not been directly correlated with ACL injury. Nicholas[63] showed that male football players who were categorized as having increased looseness were more susceptible to knee ligament rupture. However, a subsequent study did not support Nicholas' results.[64] Woodford-Rogers et al.[65] showed that ACL injured athletes had a greater knee joint laxity than healthy controls. In a prospective study, knee laxity correlated with ACL injury.[66] Also, female athletes resisted knee rotation less effectively than male athletes.[67-69] In a study by Huston and Wojtys[70], knee laxity of Division I male and female athletes was compared to the knee laxity of recreational male and female athletes. Although the Division I female athletes showed more knee laxity than their male counterparts, they did not show more knee laxity than the recreational male or female athletes.[70] Perhaps the decreased laxity was a result of training performed by the female athletes. The passive and active structures that span the knee joint can potentially contribute to the stiffness resisting tibial displacement by increasing joint contact force, decreasing tibiofemoral displacement, and lowering the force sustained by the ACL.[6, 69] Also, Chandrashekar et al.[71] reported a striking development by indicating that the structural qualities of the female ACL are not only based on size but can be attributed to gender differences in resisting mechanical stress and strain.

Frequently linked to knee injury, excessive subtalar pronation may be a factor in ACL injury.[72] During ground based movement, the foot and the lower leg shift in relation to each other. During pronation of the foot, an internal rotation of the tibia takes place.[40] As a restraint to rotation, this position may place the ACL in a hazardous position. Navicular drop, the distance traveled by the navicular tuberosity upon transitioning from seated to standing, has been employed as a gauge for foot pronation.[73, 74] Also, navicular drop may be used to predict anterior translation of the tibia.[75] Excessive navicular drop has been documented in ACL injured athletes when compared to uninjured participants.[65, 74] However, an association between excessive navicular drop in ACL injured athletes of both genders was not found when compared to uninjured athletes.[76]

**Environmental Factors**

Environmental factors include playing surface type, meteorological conditions, footwear type, and ground hardness. Outdoor sports produce a greater number of injuries during the dry part of the season when the ground surface is warmer, drier, and harder.[77, 78] Increase in water evaporation and decreases in rain fall produce such a setting.[79] The impact of drier conditions on injury rates has been corroborated in many sports and countries. In Holland, children suffered from increased and more severe injuries in spring than in the winter.[80] Over the last decade in Australia, warmer climate teams have had a greater injury incidence than the teams based in a colder climate.[78] In addition, a dry season bias was shown for increased ACL injury rates in open stadiums with AstroTurf, but not in closed stadiums containing AstroTurf.[78]

Other factors that influence the coefficient of friction are cleat number and location and type of playing surface. Longer cleats on the peripheral of the shoe sole with shorter spikes on the interior were worn during more ACL injuries in a three year span than three other cleat types. The more dangerous cleat design produced greater traction on artificial and natural turf.[81] In regards to playing surface, there was no statistically significant difference between the overall incidence rate of ACL injury and surface type when comparing natural grass to turf.[78, 82-84] However, an increased risk of injury exists when comparing artificial indoor floors to wooden floors.[14]

Although the previous studies provided solid evidence for environmental factors having an effect on ACL injury, there are some potential limitations. Due to environmental factors being so closely related, there is a possibility of confounding errors between known factors in addition to previously unforeseen factors. The connection among ground hardness, shoe-surface interaction, and meteorological conditions may cause difficulty when trying to distinguish among them.[85] In addition, the firmness of playing surface can be inconsistent throughout the season due to disparate levels of rainfall.[78] Also, previous researchers have not investigated the variability through the season of shoe and spike selection, overall game speed, or the influence of player position on injury rates.

Although environmental factors tend to be modifiable to an extent, more research is needed in order to clarify some discrepancies. However, Orchard[78] asserts an important appraisal of altering environmental conditions. Athletes may resist a manipulation of environmental factors for preventative reasons because a decrease in sports performance may result. Athletes and fans may not be willing to decrease the injury rate due to a possible decrease in performance. Although an intervention that potentially decreases the risk of injury at the detriment of performance may not be practical for professional sports, such an intervention could be a boon for amateur and recreational sports because it is so easily modifiable. However, Girard et al.[86] showed a decrease in friction between shoe and surface will reduce acute injuries, but will produce greater "muscle strains/spasms." More research is needed to investigate the precise coefficient of friction for each sport and, if possible, each individual.

Further confounding the problem of environmental factors is the influence of competition level on injury rates. Overall injury rates are increased during competition compared to practice.[87, 88] Similarly, ACL injuries occurred more often in handball games compared to handball practices.[89] An increase of injuries during competition when compared to practice could be explained by a greater motivation and desire to succeed during competitions.

**Hormonal Factors**

Comprised of three divisions, the standard menstrual cycle lasts 28 days. During days 1-9, follicular phase comprises the first day of menses until ovulation.[11] Marked by low concentrations of progesterone and estrogen, an increase in estrogen and leutinizing hormone brings about the ovulatory phase.[90] This phase is usually around 10-14 days past menses during which estrogen reaches peak secretion. During the luteal phase, comprising days 15-28, progesterone reaches peak concentration.[91] Also, relaxin levels rise during the follicular and luteal phases.[92] In addition, testosterone levels fluctuate with the menstrual cycle.[93]

The hormones of the menstrual cycle are capable of affecting many facets of performance. Ovarian hormones such as estrogen, progesterone, and relaxin modify joint laxity and affect the neuromuscular system.[94-96] According to Sarwar et al.[97], estrogen levels significantly affect muscle function, tendon, and ligament strength. In addition, decreases in $VO_{2max}$ and motor skills have been found during the luteal phase.[98, 99] Slauterbeck et al.[100] showed that the tensile properties of rabbit ACL were reduced when estrogen was introduced. However, the reliability of studies involving animals that are not primates is questionable due to not undergoing a menstrual cycle.[101] Furthermore, receptor sites for estrogen and progesterone are present on human ACL.[102, 103] This finding lends support to the supposition that tensile properties of the ACL are influenced by female sex hormones.

Due to the preceding potential harmful effects, the link between hormonal fluctuations and ACL injury during the menstrual cycle represents a rich source of interest for research. Due to fluctuations in serum concentrations of female sex hormones, researchers have hypothesized that a specific phase of the menstrual cycle would coincide with an increased risk of injury in female athletes. Although plausible that the risk of an ACL injury occurring varies throughout the cycle, evidence has been conflicting. The follicular phase was reported to be the phase when female athletes were most at risk of suffering an ACL tear.[7, 100] Also, the ovulatory phase was reported to have an increased risk of injury.[104-106] Conversely, evidence for the ovulatory phase having fewer injuries has been published.[7, 89]

Previous research had some limitations. First, some studies relied on self-reported questionnaires to determine the phase of the menstrual cycle of the participants. The reliability of questionnaires is uncertain at best. Questionnaires were reported to be unreliable when compared to urine assays.[105] Also, the validity of serum or saliva testing is controversial.[100, 107] Second, pinpointing the exact date of laxity due to oscillating hormone levels is difficult due to the possibility of measurable changes in joint laxity arising several days after changes in hormone levels.[93] Next, many studies are based on the cycle lasting the standard 28 days, but cycles can last from 25 to 35 days.[108] Finally, some of the participants were taking oral contraceptives. This would give a much different hormone profile than participants who were not ingesting oral contraceptives.[90] Furthermore, athletes who are taking oral contraceptives have a lower overall injury rate and a decreased risk of ACL injury.[105, 109]

**Neuromuscular Factors**

Representing the most modifiable of the factors influencing ACL injury, neuromuscular factors include altered movement and recruitment patterns employed during activity. For the majority of neuromuscular factors, improvement to a more secure pattern of movement seems plausible. However, many studies performed to elucidate differences in movement and recruitment patterns have occurred in a controlled laboratory setting. Although controlled laboratory research is necessary to further advance the knowledge base of the prevention of ACL injuries, the limitations inherent to this form of research prevent our understanding of the role of interaction that different factors play by treating each factor as a discrete entity. Although the continued accumulation of advanced research further aids in clarifying the association between neuromuscular factors and injury rates, further research encompassing a more holistic and prospective nature should be undertaken. Furthermore, these factors exist on a continuum and vary between genders and within each gender. Therefore, researchers should not assume that the average movement strategy for males is a successful strategy for avoiding ACL injury. How complex factor interactions affect at risk individuals of both genders must be better understood if the risk of ACL injury is ever to decrease.

Several potentially dangerous movement imbalances such as leg dominance, ligament dominance, and quadriceps dominance are frequently observed in female athletes. These imbalances may lead to a decreased neuromuscular control of the joint and stress the passive ligament structures, exceeding the failure strength of the ligament. Leg dominance is classified by significant strength and flexibility differences between legs. Potentially dangerous to both legs, the nondominant leg is unable to absorb potentially hazardous forces to the knee. Furthermore, a greater dependence on the dominant leg to absorb the forces of movement may produce excessive damage. Female athletes have significant differences in contralateral leg strength and flexibility.[110, 111] Athletes with significant strength and flexibility imbalances between legs incurred higher injury rates.[112] In a prospective study, athletes who suffered an ACL injury had a dominant knee abduction moment 6.4 times greater than the nondominant leg.[21]

Quadriceps dominance is exemplified by an imbalance between the quadriceps and hamstring strength, recruitment, and coordination. The hamstrings, an ACL agonist, are most influential at 15° and 30° of knee flexion.[113] The quadriceps, an ACL antagonist, is capable of loading the ACL throughout the entire range of motion.[114] However, quadriceps activity decreases with increased hip flexion. Others have reported that the highest strain of the ACL produced by quadriceps contraction occurs at 15° of knee flexion.[113, 115] Also, the hamstring is unable to aid the ACL in preventing anterior translation of the tibia at low knee flexion angles.[116] Females recruit their hamstrings less effectively at knee flexion angles between 15° and 25° when compared to males.[117] This supports the assertion that noncontact ACL injuries are likely to occur with the knee near full extension.

Contraction of the quadriceps without cocontraction of the hamstrings can lead to greater loads on the ACL. An eccentric quadriceps contraction can generate up to 6000 newtons (N).[118] This far exceeds the tensile strength of the ACL at 2100 N.[119] When these forces are coupled with tibial rotation, an impingement of the ACL in the femoral notch could result.[120] Other factors also contribute to an increased rate of injury of women. Female athletes are predisposed to an increased extensor moment about the knee.[70] Hewett et al.[110] reported a peak knee flexion moment that was three times greater in male athletes compared to females. During running and cutting movements, women tend to recruit the quadriceps more and the hamstrings less while utilizing a decreased knee flexion.[121, 122] Also, the ratio of the strength of flexion to the strength of extension (H/Q ratio) has been found to influence injury rates. Women have less quadriceps and hamstring strength after normalizing for body weight.[123, 124] Also, co-contraction of the muscles surrounding the knee was more effective in protecting the ligaments in males than in females.[125]

Recently, the gastrocnemius has been recognized as an antagonist to the ACL. The gastrocnemius is capable of loading the ACL at decreased knee flexion angles. Fleming et al.[126] documented a significantly increased loading of the ACL by the gastrocnemius at knee flexion angles of 5° and 15° when compared to knee flexion angles of 30° and 45°. O'Connor[127] postulated that a cocontraction of the quadriceps and gastrocnemius produces an increased loading of the ACL during movements performed utilizing low knee flexion angles. This was confirmed by Fleming et al.,[126] who reported that a cocontraction of the gastrocnemius and quadriceps produced more loading on the ACL than the addition of separate contractions. Similar to quadriceps loading, the hamstring proved an adequate agonist to gastrocnemius loading of the ACL at knee flexion angles of 30° and 45°.[126]

As was stated previously, most injuries to the ACL fall under one of three categories: pivoting, landings with an erect posture, and rapid decelerations. During landing from a jump, ground reaction forces (GRF) can be three to 14 times body weight.[128] Minimizing GRF is vital to ACL injury prevention due to ACL strain peaking at the maximum GRF.[129] Increased GRF correlated with an increased anterior shear force and greater knee abduction torques.[21, 130] During a jump landing, decreased degrees of knee flexion angle are associated with increased GRF. Therefore, decreasing landing GRF would translate to a decrease in forces at the joints of the lower extremity. A plethora of research documenting gender differences during jump landings exists. Women tend to land with a greater extension of the knee and hip when compared to men.[49, 131, 132] In addition, female athletes display an increased valgus angle at ground contact when compared to men. [111, 123, 133, 134]

Athletes with high valgus moments at the knee have been referred to as being ligament dominant.[135] During high risk movements, the forces of movement represent greater loads than the musculature of the athlete can safely absorb. Therefore, the knee ligaments are utilized to absorb landing forces rather than the surrounding musculature. This tends to increase valgus knee moment and GRF through an increase of medial knee motion.[111] According to Dugan,[136] ligament dominance is characterized by "the inability of the leg musculature to control motion results in high strains across the ACL as it acts to limit valgus force." This can lead to the previously mentioned "position of no return." Female athletes tend to suffer from this imbalance at a greater rate than their male counterparts.[110, 111, 137] This is important because a valgus load of 5° on the ACL can produce up to 6 times the force of the knee in normal alignment.[138] Furthermore, an increased knee valgus can predict individuals who are more susceptible to ACL injury.[21] However, Fagenbaum et al.[139] reported that women landed with 10 ° to 14 ° greater knee flexion than men. However, the authors stated this could be from the small sample being comprised of varsity basketball players who were instructed in correct landing technique. Urabe et al.[117] reported no significant differences in knee flexion angle between genders during a one leg landing from a maximum vertical jump, but did find that female athletes recruited their quadriceps more than male athletes. This can lead to a greater net extensor torque at the knee.

Presently, investigations of the effect of ankle kinetics and kinematics on ACL injury rates are becoming more prevalent. However, results conflict due to differences in the investigated task. During a jump stop and cut movement, females displayed a greater amount of peak ankle eversion.[35, 140] Also, females have produced a greater range of movement at the ankle, which may act as a different program for force absorption.[35, 141] During jump landings, females have shown greater peak dorsiflexion, peak pronation, and greater plantarflexion at initial contact.[133, 142] During side step cutting, females showed increased peak pronation angles at the ankle and more inversion throughout stance.[42, 143] Results from other studies have produced no differences at the ankle between genders.[132, 144]

Similarly, movement at the hip influences control of the knee.[145, 146] Hip adduction positively correlated with knee abduction angles in women, which places the athlete in a potentially dangerous position for ACL injuries.[21] During drop landings, females landed with a decreased peak hip flexion angle.[132] This places females in a more erect posture during landing that can place more stress on the ACL as the hamstrings are unable to more effectively prevent loading. Conversely, similarities to males have also been documented as no differences in peak hip flexion angle, peak hip extension moments, or EMG activation levels were produced.[133, 147] Although results may have been affected by the training level of each sample, the previously reported differences occurred during studies using samples composed of Division I athletes.

Other athletic movements implicated for producing high risk motions include running, side cutting, and crossover cutting. During running, female recreational athletes had greater internal rotation and greater adduction of the hip when compared to male recreational athletes.[148, 149] During a cutting maneuver, female recreational athletes produced decreased hip flexion and increased hip adduction when compared to male recreational athletes.[42] Similarly, Division I soccer athletes produced greater internal rotation angles and decreased flexion angles at the hip and increased adduction moment, decreased extension moment and internal rotation moment at the hip.[145, 150] Displaying such potentially dangerous positions is troubling due to these movements occurring in experienced athletes. Conversely, a random cutting trial displayed a decrease in peak hip adduction compared to their male counterparts during early stance phase.[151] Although there was no anticipated condition upon which to compare these results, the results are surprising due to the unanticipated movement more closely resembling the conditions of competition.

Maturation influences overall injury rates in females.[152] Preceding puberty, boys and girls have similar neuromuscular characteristics as both genders perform landing in a safe manner.[153] However, maturation results in a divergence of performance between the genders differently. In boys maturation produces increases in strength and vertical jump height, but females lacked similar performance increases.[153-155] Similarly, the maturation of boys produced a valgus motion at the knee during a jump landing, but with maturation females displayed knee valgus during a jump landing.[130] Similarly, prepubescent females landed with an increased knee flexion from a drop jump when compared to female adults.[156] Hewett et al.[153] postulates that the maturation of girls is not accompanied by a “neuromuscular spurt” which has been documented during the maturation of boys. Due to lacking this spurt, neuromuscular training represents a vital role in the injury prevention plan for females.

Neuromuscular training is a promising endeavor that has displayed a great potential to decrease the risk of ACL injury due to the possible modification of neuromuscular control during high risk athletic maneuvers. Of the published studies, the effectiveness of the prevention program is assessed through monitoring injury rates for a specific amount of time or through changing biomechanical measurements. Therefore, changes in many neuromuscular measures and decreased injury rates have been documented utilizing protocols of varying forms and durations. Focus on improvement of movement with a more neutral lower extremity alignment and softer landings are the cornerstones of many successful programs. Other components of successful programs include stretching, resistance training, and plyometrics. Studies that included stretching, strengthening, plyometrics and agility training were consistently able to decrease injuries in the intervention groups.[124, 157, 158] Also, decreases in knee varus and valgus, increasing the H/Q ratio, increased hip abduction, and decreased hip internal rotation were also produced.[110, 159, 160] A six week intervention of strength training involving medicine balls and core strengthening with college athletes decreased peak knee flexion angle and at initial contact during a drop jump.[161] Interestingly, this protocol showed a trend towards increasing knee valgus and internal rotation at initial contact. Although not statistically significant, this development is troubling as valgus and internal rotation of the knee being motions the program was attempting to decrease. An intervention program using weight training and balance training on a BOSU ball decreased peak knee frontal angles during the performance of a high risk maneuver.[162]

Although few examples of ineffective training programs exist, some protocols were unable to decrease injury rates or improve biomechanical variables. Herman et al.[163] utilized elastic band training during single joint movements and did not alter the kinetics of an athletic movement. The protocol may have proven ineffective due to a lack of carryover from training single joint open kinetic chain movements to a multiple joint close kinetic chain movement. Wobble board and balance mat training did not elicit significant changes in hip and knee angles during cutting and landing movements.[164] Similarly, wobble board training and landing technique training did not decrease injuries.[62, 165] However, one study incurred a 37% decrease in sample size due to decreased participation.[62] Heidt et al.[166] utilized a customized exercise protocol that did not decrease ACL injuries. However, the specific protocol used in the intervention program was not documented in the article.[166]

Although results look promising, there have been several limitations. When a specific category of training such as balance or core training was unable to produce a decrease in ACL injury or a measurable alteration in biomechanical variables, the entire category of training need not be discounted. The reason for unsatisfactory results more likely originates with the researcher's specific application of training within the category. Therefore, the entire training category does not warrant a dismissal. Similarly, the mode of training was provided without specifics details. Since each category of training contains multiple facets, more descriptive measures of each category are needed to advance thinking and research. For example, weight training was included in many studies. Yet, lifting with a low intensity and high volume provides vastly different adaptations than lifting with a high intensity at a low volume.

Furthermore, many studies applied a diverse training protocol composed of many methods. Though a variety of methods intuitively seems the best option for a prevention program, training diversity provides confounding factors due to being unable to separate specific causes and effects of a certain modality. On the other hand, the reason that training results have been positive may be due to the decreased baseline of conditioning seen in female athletes.[167] Due to such a low level of preparation, any intervention would produce positive results. Also, a limiting factor of some prospective studies is the sample size.[124, 158, 168] Although significant differences were found between the intervention and control groups, no noncontact ACL injuries were documented in one study.[124] Therefore, sample sizes in future studies should be increased to gain a more accurate assessment. In addition, the measurement upon which prospective studies are based is athlete exposures. However, variations exist in measuring exposures as some factor in the number of hours of participation and others count each practice or game as one exposure regardless of time engaging in actual participation. Therefore, study comparisons are difficult to make.

Fatigue, a reduction in performance due to exercise, may adversely modify neuromuscular control of the lower extremity and decrease the ability of soft tissue to stabilize joints.[169] Evidence of fatigue affecting the body's ability to control movement is produced by injuries occurring more frequently during latter stages of periods during games and more frequently in the second half compared to the first half.[87] Fatigue stems from multiple sources and can be characterized as peripheral fatigue or central fatigue.[169] Peripheral fatigue occurs at or distal to the neuromuscular junction or sarcolemma. Also, peripheral fatigue may be characterized by occurring during electrochemical coupling, cross-bridge release during ATP hydrolysis, or from lacking nutrients. Central fatigue occurs when the body is unable to voluntarily activate motor neurons.[169] Previously, many local fatigue models involving mainly one muscle group were employed.[170-173] However, more general fatigue models have been employed in order to more closely simulate realistic sports situations through the production of fatigue at the local and central level.[174] Therefore, contrasting results from studies may be attributable to dissimilar fatigue protocols and analysis of different movements.[175, 176]

Local and general fatigue protocols differ with the type of fatigue elicited. Local programs produce peripheral fatigue and general protocols produce peripheral and central fatigue.[169] The use of local fatigue protocols have been shown to demonstrate a decrease in proprioception of the knee, delayed muscle response, and decreased isokinetic torque of the knee flexors, and decrease in the ability of the muscle to absorb energy.[170-173] General fatigue programs have been shown to decrease peak isokinetic strength of the knee extensors and flexors, decrease the ability of the muscle to absorb energy, and decrease mental performance.[173, 177, 178] The influence of general fatigue on high risk movements such as landing and cutting have been investigated. Fatigue influences the lower extremity during high risk movements through increasing hip internal rotation, decreasing hip flexion angles, increased knee abduction and internal rotation, and increased external rotation of the ankle.[176, 179, 180] Conversely, fatigue did not influence knee varus/valgus angles in men or women.[179] Also, a lack of eccentric control of the hip and knee was noticed. Eccentric control is very important during sudden direction changes to insure safety during movements.[171]

Gender differences exist in the techniques used to plant and change direction. A side cut involves planting the foot opposite the direction of movement, while a crossover cut involves planting the foot on the same side of the new direction of movement.[181] These dangerous movements double knee valgus moments when compared to running.[24] Female athletes perform cutting maneuvers with a decreased knee flexion angle which may prevent the agonistic hamstrings from protecting the ACL.[42, 121, 182] Also, women tend to increase knee valgus angles during a cutting maneuver.[35, 42, 121, 183] However, the tasks performed during the previous studies were preplanned and may not accurately represent measurement of the kinetics and kinematics utilized during competition.[184] During competition, cutting maneuvers are not preplanned and can be performed at 5.0 to 7.0 meters per second.[185]

Recognizing the limitations of extrapolating results from anticipated movements during controlled laboratory studies to competition situations, researchers have identified the need for gender comparisons during experiments that more closely simulate game conditions. McLean et al.[42] compared side cutting with and without a defensive opponent. The addition of a defensive opponent caused females to utilize a more erect posture, a greater knee valgus, and increased foot pronation. Under unanticipated conditions, Ford et al.[111] reported that females had greater knee abduction at initial contact and greater ankle eversion and inversion during a cutting maneuver. Under similar conditions, Pollard et al.[151] reported significant gender differences in peak hip abduction over the first 40° of knee flexion during unanticipated cutting maneuvers. However, no gender differences in kinetics or kinematics of the knee were reported. Also, the two previous studies lacked a preplanned condition to compare with the unanticipated data and did not investigate the entire lower extremity.

While research is available that has focused upon gender differences during unanticipated movements, few groups have simultaneously investigated the influence of gender under anticipated and unanticipated conditions on loading of the entire lower extremity. Besier et al.[184] investigated loading at the knee under preplanned (PP) and unanticipated (UN) conditions. The researchers reported external flexion/extension moments at the knee joint were similar between

PP and UN conditions. However, movements performed during UN conditions can double varus/valgus moments and internal/external rotation moments at the knee [184]. Although these results are compelling, the sample of the previous study consisted only of males. Houck et al.[186] showed UN movements decreased hip abduction angles when compared to PP movements. However, the average speed of all tasks was 2.0 m/s. During competitions, an individual's speed before performing a side cut maneuver can be between 5.5 and 6.5 meters per second.[185] Extrapolating the results from this study to athletic movements in situations similar to games or practice is problematic at best. Furthermore, gender comparisons were not made. Sell et al.[187] compared PP and UN jump tasks to investigate how gender influences knee loading. Direction and reactivity can affect loading at the knee. However, a task that consisted of a low risk hop and cut was utilized. Also, data of the entire lower extremity were not provided, as only the kinetics and kinematics of the knee were reported. Finally, Borotikar et al.[174] investigated how fatigue and reaction influence lower extremity alignment during a high risk landing and response maneuver. The lack of planning prior to the unanticipated movements affected hip extension and internal rotation at initial contact and peak knee and ankle angles. However, gender comparisons were not made due to a sample composed of only females. Furthermore, kinetic data were not reported. Also, the examined task utilized a horizontal jump prior to the reactive movements. Although a high risk movement, the investigation of other tasks is important to provide a broader base of knowledge to discern the interaction of neuromuscular factors.

As was previously mentioned, noncontact ACL injury mainly occurs under three conditions: planting and cutting, landing with a more erect posture, and unilateral decelerations. The purpose of this study is to investigate the effects of gender on kinetics and kinematics of the entire lower extremity during anticipated and unanticipated planting and cutting maneuvers and relate these findings to the potential for ACL injury. Due to the plethora of previous studies utilizing anticipated movements, a comparison under both conditions would provide a link in the literature to better interpret movements performed under anticipated conditions and generate an improved understanding of lower extremity movement during conditions more specific to competition. The results from this study may help clarify gender differences in the response to unanticipated movements and improve future training methods for female athletes. Currently, most research implemented for neuromuscular training focuses on the improvement of technique from jump landings.[78, 188] However, ACL injuries occurring during planting and cutting constitute a larger percentage of the total noncontact injuries.[189, 190] Therefore, results from this study may be utilized to improve training programs that focus on technique improvements of a cutting maneuver [35]. Incorporation of the results from this study may improve prevention programs to aid in decreasing injury rates in males and females.

We hypothesized that females would perform the cutting maneuvers under anticipated conditions displaying kinematics and kinetics more closely resembling the common mechanism of ACL injury such as a more erect posture at the knee and hip, internal rotation of the knee and hip, hip adduction, knee abduction, and ankle eversion. Also, it is hypothesized that the unanticipated condition will exacerbate the alignment of the lower extremity in both genders to a more dangerous position compared to the anticipated condition. However, it is hypothesized that the unanticipated condition will have a more potentially deleterious effect on the lower extremity kinematics and kinetics of females with respect to ACL injury than males.

# CHAPTER 3
# METHODS

## Participants

Thirty healthy college-aged male and female individuals were recruited to participate in the study. Eligible individuals did not have any previous or existing injury to the lower extremity that required surgery. Before participating in the experiment, individuals were informed regarding the experimental protocol and read and signed an informed consent agreement under the established guidelines of the Institutional Review Board (IRB) of the University of Florida. Testing involved one session for each participant.

## Instrumentation

Three-dimensional motion analysis was performed using a Vicon MX system. The motion analysis system consisted of ten digital cameras (8 MX20 cameras and 2 MXF20 cameras, Oxford Metrics Ltd., Oxford, England) collected at 240 Hz. In addition, a Bertec force platform (Type 4060-10, Bertec Corporation, Columbus, OH) sampled at 2400 Hz was used to collect ground reaction force (GRF) data. To provide a digital video image of the participant, a Basler camera (A602FC Basler, Inc., Exton, PA) was located lateral to the force plate. A light signal system was created to signal the direction of the maneuver. The system consisted of a horizontal line of three light bulbs on a board connected to a switch box with one switch per each light, and was connected to the Vicon System to provide an analog signal to determine the elapsed time between the stimulus for the direction of movement and contact of the foot with the force plate. Nexus Software (Version 1.2) was used to obtain all kinetic and kinematic data. Also, Speedtrap 2 electrical timing gates (Brower Timing Systems, 2004, Draper, Utah) were employed to ensure the correct speed was maintained throughout all trials. Excel ® 2003 (Microsoft Corporation, Redmond, Washington) was used for data reduction. Statistical analyses of the loading on the lower extremity and GRF was performed using SPSS © 2008 (SPSS Incorporated, 2008, Chicago, Illinois).

## Procedure

All data collections occurred in the Biomechanics Lab at the University of Florida. Prior to the participant's arrival, calibration of the Vicon MX system occurred with acceptable calibration error rates less than .25 mm. Also, the force plates were calibrated to zero. Upon entering the laboratory, participants were provided an Informed Consent form to read and sign. After completion of the Informed Consent, the participants were asked with which leg they would prefer to kick a soccer ball. In order to guarantee correct performance of the movements, each maneuver and condition was described and demonstrated by the primary investigator.

Prior to performing the movements, anthropometric measurements were collected. Measurements included height, weight, bilateral knee and ankle widths, and bilateral length of the combined thigh and leg segments. Reflective markers were placed on the following lower extremity landmarks (left and right): posterior superior iliac spine, anterior superior iliac spine, thigh, lateral knee, shank, lateral malleolus, calcaneus, and 2$^{nd}$ metatarsal. Each participant wore shorts that did not cover the markers, a tight fitting shirt, and their own shoes. After application of the markers, a static trial was collected before any dynamic trials. Static trials involved the participant standing motionless on the force plate, allowing calculation of intermarker distances to be applied during dynamic movement.

Each maneuver was preceded by a run at a speed between 5.0 to 7.0 meters per second (m/s).[191] In order to ensure that speeds were maintained throughout each trial, electrical timing gates were placed at 0.1 m and 1.1 m before the force plate. In order to decrease the possibility of targeting, each participant was required to find a starting point that placed his or her right foot near the middle of the force plate during a natural stride. Participants were allowed as many trials as needed to locate their starting mark. Upon finding the starting point, participants were instructed to start at the mark and maintain the same speed for each trial. The runway length was 8 m.

Using their right foot to plant, the tasks performed by the participants were as follows: a cut to the left at an angle between 35° to 60°, continue to run straight, and a crossover step at 35° to 60° to the right.[160, 191] The tasks were performed under two conditions: anticipated and unanticipated. In order to differentiate between the categories, a light signal system was used. Prior to performing the anticipated condition, the participant was informed verbally by the primary investigator which movement to perform. During the run prior to the performance of the maneuver, the primary investigator pressed a switch to illuminate the corresponding light.

The timing of the signal was calibrated to each participant.[184] To decrease variability, the primary investigator determined the time to press the switch for each participant. To gauge the location of the participant, the primary investigator employed a live feed from a video camera connected to a separate computer. The digital camera was positioned on the wall 1.88 meters above the floor and orthogonal to the direction of movement. For the first attempt at calibration, the stimulus was displayed when the participant wass approximately 0.61 m prior to contact with the force plate. After each unsuccessful calibration, the distance from the force plate at which the stimulus was provided increased by approximately .305 m. Calibration ceased when the participant was able to consistently perform the correct movement.

For a trial to be analyzed, participants were required to approach the force plate at a speed between 5.0 to 7.0 m/s, cut at an angle of 35° to 60° using their right foot to plant, and perform the correct movement.[191] Infrared timing gates were used to ensure the speed was comparable among participants. Orange cones beginning at the center of the force plate and placed at the angles of 35° to 60° was placed on the floor to monitor the correct angle of movement during the side cut and crossover cut.[54] To decrease the effects of fatigue, participants were allowed as much time as needed between trials. Each movement was performed five times for a total of 30 trials. The order of the 30 trials was completely randomized prior to the arrival of the participant. Following the randomization, each trial order for the female participants was paired with a male participant.

## Data Analysis

Vicon Nexus software provided all calculations of lower extremity joint kinetics and kinematics. Coordinate data was filtered with a Woltering spline filter using a mean square error of 20 mm.[150] All kinetic data was calculated using standard inverse dynamic equations, and all results were normalized to body mass (Nm/kg). Vertical GRF surpassing and decreasing below 10 N for initial contact (IC) of the foot with the force plate to toe off, respectively, defined stance phase.[35]

Due to a majority of noncontact injuries occurring in the early decelerative phase of stance, this phase was the only portion analyzed.[12] For this study, the early decelerative phase was defined as IC to 20% of stance phase.[145] The variables of interest were the sagittal plane angles and moments, frontal plane angles and moments, and transverse plane angles and moments of the hip, knee, and ankle at IC and the peak value during the early decelerative phase of stance.

## Data Reduction

Excel was used to reduce each trial to stance phase. From this interval, values at IC and the peak during the early decelerative phase were identified and averaged for each trial and variable. These values were placed in a separate file. Each trial was time normalized to 100% of stance phase and be linear interpolated to 101 data points.

## Statistical Analysis

Separate 2:gender x 2: condition x 3: direction multivariate analyses of variance (MANOVA) on IC and the peak of the early decelerative phase with repeated measures on condition and direction of movement were performed in the three cardinal planes ($\alpha = .05$). For example, one MANOVA evaluated the effects of gender, condition, and direction on the peak and IC values of the sagittal plane (flexion/extension) angles of the hip, knee, and ankle.

# CHAPTER 4
# RESULTS

Preceding the description of the repeated measures MANOVA is a gender comparison of differences in age, anthropometrics, time separating the signal delivery till first contact, and the percentage of successful trials for each participant. The subsequent results are divided into sections containing kinematics and kinetics. Each of these two sections is further divided by plane of motion and contains the main effects of condition, gender, and direction. Furthermore, significant two way and three way interactions are reported.

## Participants

The 30 participants (15 males and 15 females) composed a sample of convenience that was recruited from undergraduate classes at the University of Florida. None of the participants had previously suffered from a lower leg injury that required surgery or were suffering from any minor injuries that may have impeded or altered performance. Of the participants, 97% reported their right leg as their dominant leg. Six independent t-tests were performed to compare gender for age, height, mass, signal calibration, and percentage of succesful trials. The averages of these tests are shown in Table 4-1. The average age of males and females did not differ significantly ($t = .989$; $P = .166$). However, there were gender differences for height ($t = 3.657$; $P = .001$) and mass ($t = 3.735$; $P < .001$), as the males were significantly taller and heavier than the females (Table 4-2). There were no significant gender differences for the calibration of the light signal ($t = 1.905$; $P = .097$). Gender differences were present for the percentage of analyzed trials ($t = 3.405$; $P = .045$). See Figure 4-1 for the failure rates of the genders.

## Kinematics

### Sagittal Plane

A 2 (gender) x 2 (condition) x 2 (direction) repeated measures MANOVA revealed a significant difference among joint angles when comparing levels of anticipation (Wilks' $\Lambda$ = 0.490, $F(6, 23) = 3.817$, $P = 0.009$). Univariate tests revealed that the unanticipated condition was performed with 2.2° greater hip flexion at IC ($P = .003$) and 2.4° at PEAK ($P = .001$). Sagittal plane kinematics of the lower extremity during the different anticipatory conditions are displayed in Table 4-2. No other significant main effects or interactions were observed. Joint angles of the hip, knee, and ankle for males and females are displayed in Table 4-3. See Table 4-4 for the kinematics of the joints of interest at IC and PEAK during the different cutting movements.

### Frontal Plane

A main effect did not exist for the condition of movement. However, a gender main effect was detected (Wilks' $\Lambda$ = 0.530, $F(6, 23) = 3.400$, $P = 0.015$). Univariate tests revealed that males performed the maneuvers with 5.7° and 5.6° greater hip abduction at IC ($P = .011$) and at PEAK ($P = .019$), respectively. Joint angles for males and females are shown in Table 4-5. A significant direction main effect was also observed (Wilks' $\Lambda$ = 0.110, $F(6, 22) = 30.930$, $P < 0.001$). Univariate tests showed that the hip was 7.5° more abducted at IC ($P < .001$) and 5.6° more abducted at PEAK ($P < .001$). Also, the ankle was 1.0° more supinated at IC during the side cut when compared to the crossover cut ($P = .027$). Frontal plane kinematics of the hip, knee, and ankle joints for the different directions appear in Table 4-6. No other main effects or interactions were detected. Angular data for the lower extremity joints under the different movement conditions are displayed in Table 4-7.

**Transverse Plane**

Direction of movement influenced joint angles at IC and PEAK (Wilks' $\Lambda = 0.371$, $F$ (6, 22) = 6.205, $P = 0.001$). At IC, the hip was internally rotated during the side cut and externally rotated during the crossover cut, which lead to a joint angle difference of 6.6° ($P < .001$). At PEAK, the hip was internally rotated during the side cut and externally rotated during the crossover cut yielding a difference of 9.9° ($P < .001$). Lower extremity kinematics comparing the different directions are reported in Table 4-8. No other significant main effects or interactions were documented. Joint angles of the lower extremity for the different levels of anticipation appear in Table 4-9 while joint angles for males and females are shown in Table 4-10.

## Kinetics

**Sagittal Plane**

Joint moments of portions of the lower extremity were affected by the direction of movement at IC and PEAK. Joint moments differed significantly for direction (Wilks' $\Lambda = .489$, $F$ (6, 23) = 4.004, $P = .007$). Univariate tests revealed that significant differences exist for the knee in cutting direction at PEAK and the ankle at IC. At PEAK ($P = 003$), the knee produced a .49 Nm/(kg*m) greater extensor moment when compared to the crossover cut ($P = .003$). At IC, the ankle produced a .02 Nm/(kg*m) larger plantarflexion moment during the side cut when compared to the crossover cut ($P = .003$). Sagittal plane moments of the hip, knee, and ankle joints are displayed for the different directions in Table 4-11. There were no other significant main effects or interactions. Lower extremity joint moments for males and females are shown in Table 4-12. Lower extremity joint moments of the different conditions are shown in Table 4-13.

## Frontal Plane

A direction x condition interaction was observed (Wilks' $\Lambda = 0.352$, $F(6, 23) = 7.052$, $P < 0.001$). Follow-up tests revealed significant differences for the hip at IC and knee at IC. For the hip, the side cut was performed under both conditions with an adduction moment at IC that was .051 Nm/(kg*m) greater during the anticipated condition. During the crossover cut, the anticipated movement was performed with an abduction moment, while the unanticipated movement was performed with an adduction moment that differed by .372 Nm/(kg*m) ($P < .001$). For the knee, the side cut was performed under both conditions with an adduction moment at IC that was .035 Nm/(kg*m) greater during the anticipated condition. During the crossover cut, the anticipated movement was performed with an abduction moment, and the unanticipated movement was performed with an adduction moment that differed by .084 Nm/(kg*m) ($P < .001$). The joint moments of males and females for the hip, knee, and ankle joints are shown in Table 4-16.

Several main effects and an interaction were detected at IC and PEAK. The repeated measures MANOVA revealed a main effect for condition (Wilks' $\Lambda = 0.589$, $F(6, 23) = 2.678$, $P = 0.040$). Univariate tests revealed that the joint moment of the hip for the unanticipated condition was .016 Nm/(kg*m) greater adduction moment than the anticipated condition ($P = .001$). Joint moments for the hip, knee, and ankle during the different conditions are shown in Table 4-14.

Also, there was a main effect for direction (Wilks' $\Lambda = 0.148$, $F(6, 23) = 22.010$, $P < 0.001$). Univariate tests revealed a significant difference at the hip at IC as an adduction moment occurred during the side cut and an abduction moment occurred during the crossover cut yielding a .22 Nm/(kg*m) difference IC ($P < .001$). At PEAK, the hip joint produced an abduction moment during the side cut and an adduction moment during the crossover cut yielding a 1.03

Nm/(kg*m) difference ($P < .001$). At IC, the knee joint moment for the side cut differed from the crossover cut by .06 Nm/(kg*m) due to a varus moment during the side cut and a valgus moment during the crossover cut ($P < .001$). At PEAK, the ankle joint produced a supination moment during the side cut and a pronation moment during the crossover cut giving a difference of .5 Nm/(kg*m) ($P < .001$). There were no other significant main effects or interactions. Frontal plane moments of the hip, knee, and ankle joints for the different directions are located in Table 4-15.

**Transverse Plane**

Main effects were present during IC and PEAK. A direction main effect was detected (Wilks' $\Lambda = 0.518$, $F(6, 23) = 3.570$, $P = 0.012$). Univariate tests revealed that the hip was .1 Nm/(kg*m) more externally rotated during the crossover cut when compared to the side cut at PEAK ($P < .049$). At IC, the knee produced an internal rotation moment during the side cut and an external rotation moment during the crossover cut to create a difference of .02 Nm/(kg*m) ($P < .010$). Furthermore, the moments of the ankle differed by .01 Nm/(kg*m) at IC as a near neutral moment was displayed during the side cut and a external rotation moment was displayed during the crossover cut ($P < .024$). Joint moments for the lower extremity during the different conditions are shown in Table 4-17. There were no other significant main effects or interactions. Transverse plane moments of the lower extremity joints across gender are located in Table 4-18. Joint moments for the different movement conditions are shown in Table 4-19.

Table 4-1. The average age, height (m), mass (kg), time between the signal and IC, and the percentage of successful trials for males and females [* denotes significant difference at $P < .05$]. Data are displayed as mean ± SD.

| Gender | Age | Height (m)* | Mass (kg)* | Time (s) | % of successful trials (%)* |
|---|---|---|---|---|---|
| Males (N=15) | 22.4 ± 2.9 | 1.77 ± .08 | 76.0 ± 9.2 | 0.61 ± 0.11 | 48 ± 12 |
| Females | 21.5 ± 1.7 | 1.66 ± .08 | 63.8 ± 8.8 | 0.68 ± 0.11 | 35 ± 20 |

| (N=15) |
|---|

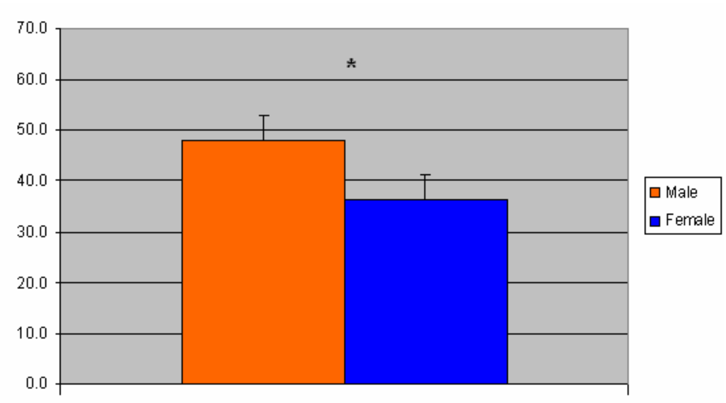


Figure 4-1. The percentage of successful trials for male and female participants

Table 4-2. Sagittal plane joint angles (degrees ± SD) for preplanned (PP) and unanticipated (UN) conditions (* denotes significant difference at P < .05 for IC).

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | 48.8 ± 7.3* | 49.5 ± 7.1 |
| | UN | 51.0 ± 7.3* | 51.9 ± 7.4 |
| Knee | PP | 17.9 ± 6.6 | 35.7 ± 8.1 |
| | UN | 19.0 ± 7.5 | 37.2 ± 8.4 |
| Ankle | PP | 2.3 ± 10.4 | 1.1 ± 12.1 |
| | UN | 2.6 ± 11.0 | -1.2 ± 13.1 |

Table 4-3. Sagittal plane joint angles (degrees ± SD) for males and females

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | 51.8 ± 6.4 | 52.7 ± 6.0 |
| | Females | 48.2 ± 7.7 | 48.6 ± 8.0 |
| Knee | Males | 19.5 ± 8.0 | 37.8 ± 9.6 |
| | Females | 17.5 ± 6.0 | 35.2 ± 6.8 |
| Ankle | Males | 0.8 ± 11.2 | -1.9 ± 13.9 |
| | Females | 3.9 ± 10.4 | 2.6 ± 10.8 |

Table 4-4. Sagittal plane joint angles (degrees ± SD) for the side cut (Left) and crossover cut (Right)

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | 50.1 ± 7.3 | 51.0 ± 7.5 |
| | Right | 49.7 ± 7.3 | 50.4 ± 7.1 |
| Knee | Left | 17.7 ± 6.1 | 37.0 ± 6.1 |
| | Right | 19.2 ± 8.0 | 35.9 ± 8.0 |
| Ankle | Left | 3.5 ± 10.8 | 1.3 ± 12.6 |
| | Right | 1.4 ± 10.6 | -1.3 ± 12.7 |

Table 4-5. Frontal plane joint angles (degrees ± SD) for males and females (* denotes significant difference at P < .05 for IC, † denotes significant difference at P < .05 for PEAK).

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | -7.3 ± 5.9* | -6.6 ± 7.5† |
| | Females | -1.6 ± 5.8* | -1.0 ± 6.8† |
| Knee | Males | 5.0 ± 6.7 | 10.5 ± 12.5 |
| | Females | 0.9 ± 7.3 | 4.2 ± 11.6 |
| Ankle | Males | 2.0 ± 5.5 | 4.9 ± 8.1 |
| | Females | 0.3 ± 4.7 | 4.7 ± 7.0 |

Table 4-6. Frontal plane joint angles (degrees ± SD) for the side cut (Left) and crossover cut (Right) (* denotes significant difference at P < .05 for IC, † denotes significant difference at P < .05 for PEAK).

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | -8.1 ± 6.0* | -8.6 ± 6.9† |
| | Right | -0.6 ± 6.7* | 1.2 ± 8.4† |
| Knee | Left | 1.9 ± 7.7 | 5.9 ± 7.7 |
| | Right | 3.9 ± 7.3 | 8.6 ± 6.8 |
| Ankle | Left | 1.6 ± 5.3* | 4.8 ± 7.3 |
| | Right | 0.6 ± 5.0* | 4.7 ± 7.6 |

Table 4-7. Frontal plane joint angles (degrees ± SD) for preplanned (PP) and unanticipated (UN)(* denotes significant difference at P < .05 for IC).

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | -4.2 ± 6.4 | -3.7 ± 7.5 |
| | UN | -4.5 ± 6.7 | -4.0 ± 7.8 |
| Knee | PP | 2.9 ± 7.0 | 7.1 ± 11.8 |
| | UN | 3.0 ± 7.4 | 7.3 ± 13.1 |
| Ankle | PP | 1.2 ± 5.1 | 4.9 ± 7.2 |
| | UN | 1.0 ± 5.2 | 5.0 ± 7.6 |

Table 4-8. Transverse plane joint angles (degrees ± SD) for the side cut (Left) and crossover cut (Right) (* denotes significant difference at P < .05 for IC, † denotes significant difference at P < .05 for PEAK).

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | 3.6 ± 7.2* | 9.3 ± 9.3† |
| | Right | -3.0 ± 9.6* | -0.6 ± 8.4† |
| Knee | Left | -2.9 ± 6.6 | 7.7 ± 6.6 |
| | Right | -2.6 ± 8.1 | 9.1 ± 8.1 |
| Ankle | Left | -6.7 ± 10.2 | -19.1 ± 9.6 |
| | Right | -3.8 ± 9.9 | -18.6 ± 9.5 |

Table 4-9. Transverse plane joint angles (degrees ± SD) for males and females

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | 2.2 ± 9.5 | 6.4 ± 9.2 |
| | Females | -1.4 ± 7.6 | 2.5 ± 9.6 |
| Knee | Males | -2.9 ± 7.4 | 3.6 ± 9.3 |
| | Females | -2.6 ± 7.5 | 12.9 ± 9.6 |
| Ankle | Males | -7.6 ± 8.9 | -17.4 ± 8.2 |
| | Females | -3.0 ± 9.1 | -20.2 ± 9.1 |

Table 4-10. Transverse plane joint angles (degrees ± SD) for preplanned (PP) and unanticipated (UN) conditions

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | -0.3 ± 8.7 | 4.0 ± 8.1 |
| | UN | 0.9 ± 9.7 | 4.8 ± 9.6 |
| Knee | PP | -2.7 ± 7.0 | 8.3 ± 7.4 |
| | UN | -2.8 ± 7.6 | 8.4 ± 7.6 |
| Ankle | PP | -5.3 ± 9.0 | -19.0 ± 8.4 |
| | UN | -5.1 ± 9.1 | -18.7 ± 8.3 |

Table 4-11. Sagittal plane joint moments (Nm/(kg*m) ± SD) for the side cut (Left) and crossover cut (Right) (* denotes significant difference at $P < .05$ for IC, † denotes significant difference at $P < .05$ for PEAK).

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | 1.26 ± 0.64 | 2.31 ± 0.86 |
| | Right | 1.33 ± 0.45 | 2.19 ± 0.72 |
| Knee | Left | -0.54 ± 0.30 | 0.58 ± 0.30† |
| | Right | -0.58 ± 0.28 | 0.09 ± 0.29† |
| Ankle | Left | 0.04 ± 0.08* | 0.52 ± 0.60 |
| | Right | 0.02 ± 0.08* | 0.47 ± 0.48 |

Table 4-12. Sagittal plane joint moments (Nm/(kg*m) ± SD) for males and females

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | 1.27 ± 0.54 | 2.41 ± 0.66 |
| | Females | 1.32 ± 0.52 | 2.09 ± 0.70 |
| Knee | Males | -0.61 ± 0.30 | 0.63 ± 0.35 |
| | Females | -0.51 ± 0.29 | 0.59 ± 0.38 |
| Ankle | Males | 0.04 ± 0.10 | 0.51 ± 0.57 |
| | Females | 0.02 ± 0.04 | 0.46 ± 0.50 |

Table 4-13. Sagittal plane joint moments (Nm/(kg*m) ± SD) for preplanned (PP) and unanticipated (UN) conditions.

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | 1.24 ± 0.43 | 2.25 ± 0.80 |
| | UN | 1.35 ± 0.52 | 2.22 ± 0.85 |
| Knee | PP | -0.56 ± 0.25 | 0.37 ± 0.46 |
| | UN | -0.56 ± 0.33 | 0.35 ± 0.52 |

| | | | |
|---|---|---|---|
| Ankle | PP | 0.02 ± 0.07 | 0.49 ± 0.51 |
| | UN | 0.04 ± 0.08 | 0.48 ± 0.57 |

Table 4-14. Frontal plane joint moments (Nm/(kg*m) ± SD) for preplanned (PP) and unanticipated (UN) conditions (* denotes significant difference at P < .05 for IC).

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | 0.01 ± 0.43* | 0.21 ± 0.35 |
| | UN | 0.17 ± 0.48* | 0.24 ± 0.31 |
| Knee | PP | -0.01 ± 0.17 | 0.62 ± 0.45 |
| | UN | 0.02 ± 0.16 | 0.62 ± 0.46 |
| Ankle | PP | 0.01 ± 0.03 | 0.10 ± 0.20 |
| | UN | 0.01 ± 0.02 | 0.11 ± 0.21 |

Table 4-15. Frontal plane joint moments (Nm/(kg*m) ± SD) for the side cut (Left) and crossover cut (Right) (* denotes significant difference at P < .05 for IC, † denotes significant difference at P < .05 for PEAK).

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | 0.19 ± 0.45* | -0.34 ± 0.49† |
| | Right | -0.03 ± 0.50* | 0.69 ± 0.54† |
| Knee | Left | 0.04 ± 0.15* | 0.49 ± 0.15 |
| | Right | -0.02 ± 0.17* | 0.75 ± 0.17 |
| Ankle | Left | 0.01 ± 0.02 | 0.35 ± 0.12† |
| | Right | 0.01 ± 0.03 | -0.15 ± 0.19† |

Table 4-16. Frontal plane joint moments (Nm/(kg*m) ± SD) for males and females.

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | -0.04 ± 0.43 | -0.18 ± 0.56 |
| | Females | 0.20 ± 0.45 | 0.53 ± 0.59 |
| Knee | Males | 0.03 ± 0.17 | 0.45 ± 0.38 |
| | Females | 0.05 ± 0.15 | 0.79 ± 0.39 |
| Ankle | Males | 0.01 ± 0.03 | 0.08 ± 0.15 |
| | Females | 0.01 ± 0.01 | 0.14 ± 0.23 |

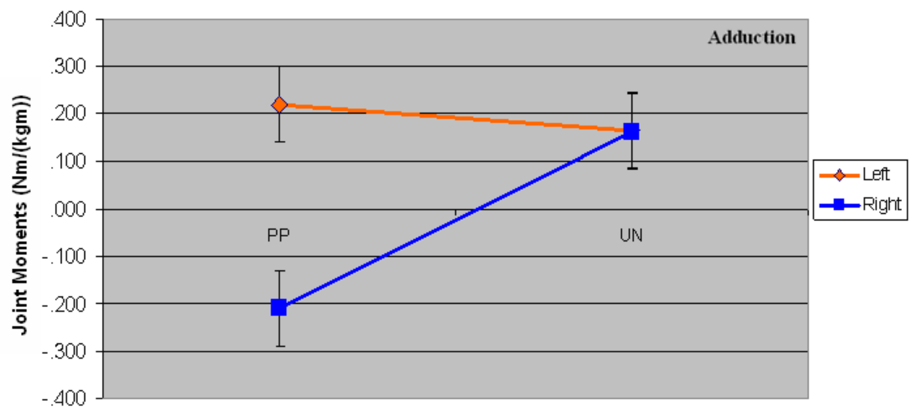


Figure 4-2. Direction x condition interaction for hip joint moments at IC

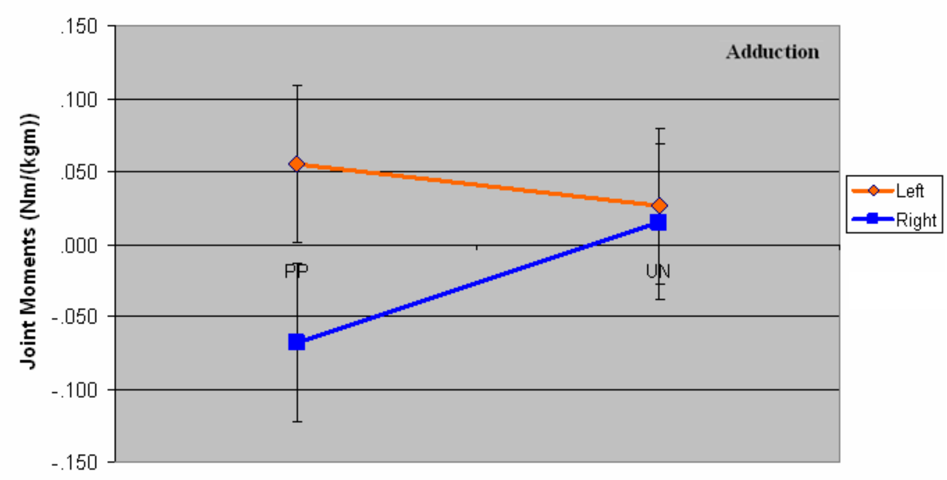


Figure 4-3. Direction x condition interaction for knee joint moments at IC

Table 4-17. Transverse plane moments (Nm/(kg*m) ± SD) for preplanned (PP) and unanticipated (UN) conditions (* denotes significant difference at P < .05 for IC, † denotes significant difference at P < .05 for PEAK).

| Joint | Direction | IC | PEAK |
|---|---|---|---|
| Hip | Left | -0.01 ± 0.04 | -0.10 ± 0.02† |
| | Right | -0.01 ± 0.01 | -0.20 ± 0.06† |
| Knee | Left | 0.01 ± 0.03* | 0.05 ± 0.03 |
| | Right | -0.01 ± 0.03* | 0.09 ± 0.03 |
| Ankle | Left | 0.00 ± 0.03* | -0.07 ± 0.05 |
| | Right | -0.01 ± 0.03* | -0.03 ± 0.09 |

Table 4-18. Transverse plane joint moments (Nm/(kg*m) ± SD) for males and females.

| Joint | Gender | IC | PEAK |
|---|---|---|---|
| Hip | Males | -0.02 ± 0.04 | -0.12 ± 0.17 |
| | Females | -0.01 ± 0.04 | -0.18 ± 0.15 |
| Knee | Males | -0.01 ± 0.03 | 0.07 ± 0.13 |
| | Females | 0.01 ± 0.02 | 0.07 ± 0.11 |
| Ankle | Males | -0.01 ± 0.03 | -0.05 ± 0.15 |
| | Females | 0.00 ± 0.02 | -0.04 ± 0.12 |

Table 4-19. Transverse plane joint moments (Nm/(kg*m) ± SD) for preplanned (PP) and unanticipated (UN) conditions.

| Joint | Condition | IC | PEAK |
|---|---|---|---|
| Hip | PP | -0.02 ± 0.04 | -0.16 ± 0.16 |
| | UN | -0.01 ± 0.05 | -0.13 ± 0.15 |
| Knee | PP | 0.00 ± 0.03 | 0.07 ± 0.12 |
| | UN | 0.00 ± 0.02 | 0.07 ± 0.12 |
| Ankle | PP | -0.01 ± 0.03 | -0.05 ± 0.14 |
| | UN | 0.00 ± 0.03 | -0.04 ± 0.16 |

# CHAPTER 5
# DISCUSSION

Females are four to six times more likely to suffer an ACL injury than men when playing the same sports.[5-8] Gender differences during anticipated cutting are well documented.[35, 42, 121, 183] Due to the limitations of extrapolating data collected during anticipated movements to competition, more researchers have utilized unanticipated movements in their research. Although some comparisons between anticipated movements and unanticipated movements have been reported, cutting movements have not been compared under anticipated and unanticipated conditions with a sample composed of both males and females. Therefore, the purpose of this study was to investigate the effects of anticipation and gender on the lower extremity during high risk cutting movements.

Although the statistical tests used in this study were delineated by cardinal plane and biomechanical measure, the interaction of the lower extremity joints in all planes of movement seems to produce the most deleterious effects with respect to ACL injury rates.[192] Therefore, comparisons of cutting condition, gender, and the different movement directions will be detailed in separate sections. Condition comparisons will be emphasized due to the dearth of published research relating condition effects on males and females. Although the relationship among drop jumps and cutting tasks utilized in laboratory research is not well understood, [127, 183] condition comparisons of drop jumps will be included due to the lack of research comparing anticipated and unanticipated conditions while utilizing cutting movements.

## Participants

The participants were college aged undergraduate students who composed a sample of convenience. The height and mass of the participants[41, 142] and the sample size was similar to other previously reported samples of convenience.[42, 54, 160, 174, 193] Due to significant gender differences in height and mass, joint moments were normalized to the height and mass of each subject.

In order to ensure that trials for each condition and direction could be analyzed, many of the participants attempted more than the required 30 trials. Although the number of analyzed trials did not differ significantly between genders, the percentage of successful trials was significantly different due to the males requiring less trials to acquire a similar number of analyzed trials as the females. Although the males were more adept at performing the cutting movements, both groups had a failure rate of more than 50%. The high failure rates are likely a combination of the relatively low skill inherent with samples of convenience and the difficulty of performing the cutting movements with the required approach speed. A trade off between speed and accuracy occurred as many participants were unable to consistently accelerate to the proper speed and cleanly plant on the force plate. Due to most researchers not reporting the number of analyzed trials, difficulty exists when comparing our number of succesful trials to previously published literature.

## Condition

### Sagittal

Noncontact ACL injuries purportedly occur during movements with decreased flexion at the hip and knee.[12, 13] Performance of sporting activities with decreased hip and knee flexion may prevent the hamstring from aiding the ACL in resisting anterior movement of the tibia relative to the femur.[121, 182] Due to less than optimal spatial orientation prior to performance of the athletic movement and a decreased time to appropriately position the body, an unanticipated movement would be more likely to produce an alignment which is less safe for ACL injury.[136] Similarly, Besier et al.[184] reported increased knee flexion angles for the unanticipated condition. Counter to our hypothesis, unanticipated movements were performed with an increased hip flexion at IC and at PEAK when compared to the anticipated condition. Compensation for unanticipated movements in a controllable lab setting may occur through lowering the COM height and producing a less dangerous movement pattern. An increased chance of injury may arise when compensation is unattainable due to temporal restrictions.[184]

**Frontal**

Since greater knee valgus moments and GRFs occur through an increase in medial knee motion, frontal plane biomechanical measures are extremely important.[111] Furthermore, frontal plane knee joint angles have been used to predict future ACL injuries, and continuous performance of athletic movements with increased frontal plane movements may increase the possibility of ACL injury.[12, 21] Direction x condition interactions were revealed for the hip and knee in the frontal plane. The side cut was performed with hip and knee adduction moments under both conditions, while the crossover cut was performed with hip and knee abduction moments during the preplanned condition and hip and knee adduction moments during the unanticipated condition. In order to perform the movements during the unplanned condition, participants used hip and knee adduction moments during the unanticipated movements. Due to similar moments used during the different directions under unanticipated conditions, participants were unable to accommodate to the unanticipated movements in the frontal plane.

Although no significant differences were found for the influence of anticipation on frontal plane kinematics, significant differences in joint moments were present at IC for the hip. Unanticipated movements were performed with greater hip adduction moments. Hip adduction is a primary component of dynamic valgus and previously correlated with knee valgus during drop landings.[21] Knee abduction was not revealed in our results. Thus, the predictive nature of knee abduction during drop jumps may not apply to cutting movements. Besier et al.[184] reported knee valgus moments increased when comparing anticipated movements to unanticipated movements. Frontal plane hip and knee joint differences have been published during cutting movements, as unanticipated movements were performed with increased knee abduction angles.[174, 194] Also, a visual inspection of the Borotikar study revealed that 58% more knee abduction occurred in the joint angles of the nondominant leg when comparing unanticipated movements to anticipated movement. In our sample, 97% of the participants performed the cutting movements using their dominant leg, which may help to explain the disparity among the studies.

**Transverse**

Increased hip internal rotation potentially places the lower extremity in an alignment that is less safe.[151] Furthermore, increased rotation and adduction at the hip when coupled with decreased glute medius strength may produce increased knee valgus angles.[195] However, no significant differences were found in the kinetics or kinematics of the lower extremity when comparing conditions in the transverse plane. Brown et al.[194] did not find significant differences in the kinematics of the knee and hip, but showed that unanticipated movements resulted in increased internal rotation moments of the hip and knee. In addition, Borotikar et al.[174] showed that the condition of movement can modify transverse plane kinematics at the hip and knee, as the dominant and nondominant leg became more internally rotated at the hip and ankle. Performance of an unanticipated side cut increased the internal rotation moment of the knee in early stance phase.[184] Differences among studies may be due to our sample being the least skilled, yet performing one of the more difficult tasks to consistently execute due to such a high approach speed.

Although unanticipated movements are increasingly being incorporated into controlled research, differences exist between the lab setting and competition. The present study incorporated acceleration towards a predetermine location followed by pivoting with the right leg and performance of one of the three movement options. In competition, athletes rarely change direction at a predetermined area with so few options regarding direction of movement and plant leg. Due to the vast differences in unpredictability between competition and lab settings, whether truly unanticipated movements were utilized in this study is questionable. However, the similar moments at the hip and knee for the unplanned conditions are an interesting finding suggesting that anticipation was prevented and a similar movement pattern was utilized. The success and ecological validity of future studies hinges upon improvement in techniques to prevent anticipation such as utilizing an increased number of movement options, delivery of the signal through more sophisticated means, or delivery of multiple signals during different phases of the gait cycle. Therefore, discrepancies among studies are an expected occurrence due to differing methods of anticipation prevention.

## Gender

### Sagittal

Females have been described as performing athletic movements with an internally rotated and adducted hip, decreased flexion and valgus at the knee, and ankle eversion. Gender differences exist during running, jump landings, and cutting maneuvers. Gender differences have been documented during various athletic movements with females using less hip and knee flexion when compared to males.[42, 121, 182] However, the present gender comparisons for kinematics and kinetics of the sagittal plane did not replicate the results of previous studies. Due to the plethora of gender difference data during various movements, our results are surprising. However, few researchers have utilized our approach speeds, and the ones that did recruited mostly college soccer players. [122, 145, 150, 151, 196] To our knowledge, this is the first study with a sample composed of recreational college undergraduates to perform cutting movements at approach speeds greater than 5.5 m/s. Furthermore, our participants did not reach the required speed until after the signal for the cutting movement. Although the process of performing a movement amidst accelerations and decelerations more closely simulates competition than anticipated cutting, the occurrence of this process at the required speed may have prevented variation in movement strategies due to venturing toward the limits of the sample's cutting ability.

**Frontal**

Previously, females consistently differed in frontal plane measures of the lower extremity. In the current study, females performed the cutting movements with less hip abduction at the hip at IC and at PEAK. Instead of relying on the sagittal plane for force dissipation, females tend to rely more on the frontal and transverse planes.[151] Decreased abduction may be due to lacking strength in the hip abductors such as the glute medius. Although no significant differences at the knee were present, increased knee valgus of females while performing cutting maneuvers is well documented.[42, 121, 134, 183] The results of the current study were very similar to a previous study which involved the investigation of a side cut, stop jump, and a run with analysis of stance phase across the first 40° of knee flexion.[151] Similarly, significant gender differences in peak hip abduction during the early decelerative phase of cutting maneuvers have been reported. [151]

**Transverse**

Increased hip internal rotation angles have been found for females during cutting movements.[145] Also, hip internal rotation at IC positively correlated with peak knee abduction.[183] Results for peak knee valgus in the current study were similar to the peak knee valgus moments of McLean et al.[183] However, the females in our sample performed cutting movements with external rotation at IC, not internal rotation. Differences exist between studies as their sample used slower approach speeds but was composed of more skilled college athletes. Increased approach speeds in the current study may be the reason for our increased knee valgus moments but would not explain why a less skilled sample performing a more difficult task utilized a safer alignment. As was noted previously, the relatively low skill of our sample performing the high risk movements at a greater speed may have prevented variation in cutting strategy due to the analysis of only the successful trials.

Direction changes during competition can occur at velocities ranging between 5.5 and 7 m/s.[191] For the current study, an approach speed of 5.5 to 7 m/s was selected to use the lab setting to test cutting movements at speeds encountered during competition. Although approach speeds similar to the current study have been previously employed during research, the majority of the samples used in those studies contained college athletes with the only sample not composed of college athletes being competitive high school athletes.[122, 145, 150, 151, 196] Therefore, the sample of convenience used in the current study was composed of relatively less skilled recreational college aged participants. Due to the stringent requirements necessary for the analysis of trials, a homogenizing effect on the data may have occurred. Theoretically, college athletes proficient at cutting would be more skilled performing the movements at higher speeds and may self select a greater approach speed than would a less skilled person. Naturally, the skilled athlete would be more proficient during change of direction and utilize a safer alignment at higher speeds. Therefore, the high approach speed necessary for analysis may have allowed for fewer acceptable cutting strategies for participants of either gender to complete the movements. Presumably, this may have negated any gender differences.

## Direction

### Sagittal

Change in direction occurs through foot placement lateral to the center of mass and opposite the direction of movement and incorporates a decrease in velocity over several gait cycles prior to cutting.[181] Previously, the side cut was documented as being more effective at producing changes in direction.[197] Although both movements in the current study were performed within the previously specified speed range, differences were present in sagittal plane moments for the knee at PEAK and ankle at IC. From a previous study, the vastus medialis, a knee extensor, and the gastrocnemius produced a greater activation during the side cut when compared to the crossover cut.[197] During early stance, lower extremity extensor moments absorb the force of movement.[42, 198] Therefore, greater extensor moments during early stance are due to increased momentum during the pivoting step of the side cut.

Based on subjective observation, accommodation for the crossover cut seemed to occur with the participants absorbing most of the momentum with the step preceding the crossover cut. In addition, many participants commented on the difficulty of performing the crossover cut at the required approach speed. Sagittal knee and ankle moment data corroborate our observations that participants required less force absorption during the crossover cut than the side cut. Performance of a crossover cut without the preceding step to safely decrease momentum may increase the possibility of an ACL injury as the alignment during a crossover cut more closely simulates the mechanism of valgus collapse seen during ACL injuries due to hip adduction required to propel the center of mass in the opposite direction of foot placement.[42]

Successful performance of the correct movement requires delivery of the stimulus to occur two steps prior to performing either cutting maneuver.[197] Due to our contention that the crossover cut was performed with a preceding side cut, the signal occurred less than two steps prior to changing directions. Our findings may be different than previous work because this is the first study to compare side cutting and crossover cutting at approach speeds over 5.5 m/s. Our protocol for calibrating the timing of the stimulus required participants to successfully perform both movements at that specified time, but we did not separately document the timing for each movement. Therefore, it is unknown whether differences in the timing of the signal exist for both movements. Requiring the signal to be two steps or more prior to contact with the force plate may have been due to limitations of performing the crossover cut and not the side cut. Although our results support the timing of the stimulus being two steps prior to IC, further investigation is required to locate the timing of the stimulus in relation to both the crossover cut and side cut.

**Frontal**

Frontal plane kinematics and kinetics differed during the side cut and the crossover cut. The dangerous frontal plane alignment for noncontact injuries usually contains hip adduction, knee valgus, and ankle eversion. Though neither direction completely coordinated with the deleterious alignment, the kinetics of the crossover cut seem to be more perilous due to hip adduction moment at PEAK, knee abduction moment at IC, and a pronation ankle moment at PEAK. When the kinetics are coupled with an adducted hip angle at PEAK, a crossover cut seems to produce a movement pattern more similar to the proposed ACL noncontact injury mechanism than the side cut.

**Transverse**

In the transverse plane, the more dangerous alignment for an ACL injury is an internal rotation angle at the hip. In the current study, the side cut was performed with internal rotation at the hip at IC and PEAK. Although an external rotation moment during the side cut does not seem to be injurious to the ACL, when coupled with an internal rotation moment at the knee, an increased chance of injury may exist due to the joints having moments in opposite directions. Conversely, the crosscut was performed with external rotation moments at all joints of the lower extremity. In the transverse plane, the side cut seems to be a more dangerous movement.

To change direction, lateral placement of the center of pressure (COP) to the center of mass (COM) is required.[199] The side cut has been documented as being more effective at change of direction due to retaining a greater velocity when compared to the crossover cut.[197] Our results confirm the effectiveness of the side cut over the crossover cut, as the performance of the crossover cut at high speeds seems to only be accomplished through decreasing momentum in the preceding step. Furthermore, the crossover cut seems to be more dangerous due to knee abduction and ankle pronation and the required hip adduction to perform the maneuver.

## Limitations

The purpose of this study was to use unanticipated movements to more closely simulate competition in order to provide an improved understanding of biomechanical measures in relation to ACL injury and compare this more realistic data to controlled research. Logically, unanticipated movements would seem to be more relatable to competition than anticipated movements. However, it is questionable just how similar to competition the laboratory setting is. During competition, athletes are constantly assessing the location and spatial orientation of members of both teams in addition to the ball while coordinating their own movements to perform a variety of accelerations and decelerations. Conversely, this study entailed only one movement from one stimulus during each trial. Although the participants did not know what specific direction to move, only three choices were available: cut left, straight, or cut right. Therefore, the level of relatedness of this study to cutting in actual competition encountered in soccer or basketball is debatable. However, utilization of unanticipated movements in laboratory studies is important to more closely simulate competition.

Similarly, the location and design of the light signal system may have proved a limiting factor. The exact location of the light signal system is often not provided in the literature. Few have reported exact distances, while most opt for an overhead picture of the entire lab space.

What influence the location of the light stimulus may have on the results is unclear. Also, the design of the light signal system may be not be conducive to recognizing the correct signal during sprint movements. Central processing must occur in order to see the cue, process the information, and employ the proper movement pattern. Therefore, the signal produced by our light system may not have been as easily recognized as the use of a runway lined with a string of lights or an approaching obstacle to be avoided. Furthermore, the lapse of time between the delivery of the signal and contact with the force plate is not reported for unanticipated movements. Therefore, difficulty exists for making comparisons within the literature for skill discrepancies pertaining to specific athletic tasks across samples.

Our analysis consisted only of successful trials with the correct speed, angle, movement, and successfully placing the right foot on the force plate. Our sample was composed of recreationally active undergraduate students, which lead to a range in skill levels and experience with the cutting movements. The success rates for males and females were over 60% and 74%, respectively. However, there was variability in the skill of the sample; six of the participants completed less than 50% of the trials. Due to this discrepancy in skill and stringent requirements for trials to be analyzed, the participants may have utilized similar movement patterns in the successful trials. Of the failed trails, 67% were not analyzed due to the improper placement of the entire foot on the force plate, and 16% were not analyzed due to performing the cutting maneuver out of the required range . It is unknown how the kinematics and kinetics of the unsuccessful trials compare to those of the successful trials.

Another potential limitation would be the relatively small percentage of stance utilized for analysis. For this project, data were analyzed at IC and the first 20% of stance. Early decelerative phase is the portion of stance for which most noncontact ACL injuries occur.[12]

However, it is unknown at exactly what percentage of stance most injuries occur, what interval of stance would contain most injuries, or at what percentage of stance for which the risk of injury dramatically decreases. Lacking a better understanding of the stance interval containing most injuries produced the investigation of a variety of measurements during different periods of stance. Variation in results among studies may be partially attributed to discrepancies in the portion investigated during stance. Therefore, further research is necessary to clarify the portion of stance which contains most injuries.

In this study, 97% of the participants performed the cutting movements with their dominant leg. Analysis of only one leg was undertaken to simplify the calculations of the reported biomechanical measures. Leg dominance, a significant strength and flexibility discrepancies between legs, is well documented in females, and athletes with significant strength and flexibility imbalances between legs have higher injury rates.[110-112] Previously, researchers showed greater knee abduction in the nondominant leg.[174, 194] Therefore, testing the dominant and nondominant leg may have provided a better understanding of how the effects of anticipation can alter biomechanical measures of the lower extremity.

According to Winter,[200] two strategies exist for changing direction during locomotion: control during swing phase of the COP through foot placement (swing strategy) or control during stance using hip and ankle musculature (stance strategy). Differentiation between COM and COP dictate the acceleration and direction of the movements. For example, performance of a side cut occurs through placing the COP farther to the right of the normal foot placement when running straight. Utilization of the stance strategy occurs through recruitment of hip and ankle musculature to change direction. Due to variety in the timing of stimuli during locomotion, the reliance on either strategy will exist on a continuum. In theory, utilization of the swing strategy would be more prevalent during preplanned movements. An individual would preplan the placement of the COP location. During unplanned movements, a greater reliance on stance strategy would be required due to temporal restrictions. Due to a combination of change of direction and braking, the forced reliance on stance strategy to change direction may prove to generate greater forces than the lower extremity can safely dissipate. This may help explain the gender differences in ACL injury rates since females have a lower baseline of strength due to focus on improved strength during prevention programs improving the gender differences in ACL injury rates.[124, 167]

## Conclusion

Investigation into causes of the gender discrepancy in ACL injury rates has garnered much attention with little improvement. This study represents the first attempt at investigating the anticipatory effects of cutting movements on the lower extremity using a sample composed of males and females. Also, this is the first project to use approach speeds greater than 5.5 m/s with a sample composed of college aged recreational athletes. Due to the combination of a relatively low skilled sample and difficult tasks, failure rates exceeded 50%. Unanticipated movements were performed with increased hip flexion angles and greater hip adduction moments. Similar to results from previous studies, participants accommodated for lacking the time to plan movements by utilizing a more versatile posture for cutting through decreasing the height of the COM and using similar moments at the hip and knee in the frontal plane. These accommodations show the difficulty of preventing anticipation in the lab setting. However, increased hip adduction moments were utilized during the unanticipated condition. Hip adduction is a component of dynamic valgus, the purported injury mechanism for ACL injury. Since recreational athletes possess the capacity to safely alter movement patterns during unanticipated conditions in the lab setting, two recommendations can be made. First, improvements for preventing anticipation in experiments are necessary to further understand how movements are controlled when lacking the time to preplan. Second, unanticipated movements should be incorporated into training programs with anticipated movements. The combination of using anticipated movements to teach correct alignment may provide a carryover affect into unanticipated movements. Although our results provide positive evidence for the incorporation of unanticipated movements into training programs, further investigation is required under more diverse conditions and utilizing different movements.

For the present study, gender differences were found only in the frontal plane hip kinematics. With the high failure rates, the possibility exists that we unintentionally biased our results due to only processing the successful trials. Although the stringent requirements may have pushed the sample to the limits of their capacity to successfully change direction, a successful performance may have necessitated a similar movement strategy for both genders. In order for a trial to be analyzed, the kinematics and kinetics employed by participants may have been required to be similar. Therefore, we recommend the incorporation of unsuccessful trails into the analysis of future studies.

Regarding ACL injury, the crossover cut seemed to produce a more deleterious alignment than the side cut due to increased knee abduction and ankle pronation. Similarly, the crossover cut seemed to have only been successfully performed by decreasing momentum through the performance of a preceding side cut. The ramifications of this development are twofold. First, ACL injury seems more likely to occur during a crossover cut that lacks a preceding side cut to safely decrease the momentum of movement. Second, these results would disagree with the assertion that a signal for movement must be displayed at least two steps prior to a change in direction. Although the crossover cut seems to be less safe due to performance with a preceding accommodation step at high speeds, the side cut seems to be a more popular choice for research as more examples exist of the side cut in previous studies. Therefore, we recommend more investigation of the crossover cut related to ACL injury.

APPENDIX A
MANOVA TABLES FOR NONSIGNIFICANT RESULTS

## Kinematics

### Sagittal

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Gender | 0.685 | 1.690 | 0.171 |
| Direction | 0.615 | 2.299 | 0.071 |
| Condition * Gender | 0.836 | 0.719 | 0.650 |
| Condition * Direction | 0.804 | 0.895 | 0.516 |
| Direction * Gender | 0.738 | 1.359 | 0.272 |
| Gender * Condition * Direction | 0.781 | 1.074 | 0.407 |

### Frontal

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Condition | 0.921 | 0.316 | 0.921 |
| Condition * Gender | 0.888 | 0.464 | 0.827 |
| Condition * Direction | 0.549 | 3.153 | 0.221 |
| Direction * Gender | 0.905 | 0.400 | 0.871 |
| Gender * Condition * Direction | 0.717 | 1.510 | 0.219 |

### Transverse

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Condition | 0.803 | 0.899 | 0.513 |
| Gender | 0.766 | 1.121 | 0.382 |
| Condition * Gender | 0.729 | 1.426 | 0.247 |
| Condition * Direction | 0.686 | 1.755 | 0.153 |
| Direction * Gender | 0.720 | 1.437 | 0.244 |
| Gender * Condition * Direction | 0.710 | 1.565 | 0.202 |

## Kinetics

### Sagittal

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Gender | 0.726 | 1.445 | 0.241 |
| Condition | 0.726 | 1.448 | 0.240 |
| Condition * Direction | 0.645 | 1.798 | 0.189 |

| | | | |
|---|---|---|---|
| Condition * Gender | 0.882 | 0.514 | 0.792 |
| Direction * Gender | 0.793 | 1.003 | 0.447 |
| Gender * Condition * Direction | 0.802 | 0.949 | 0.480 |

**Frontal**

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Gender | 0.662 | 1.956 | 0.114 |
| Condition * Gender | 0.898 | 0.436 | 0.847 |
| Direction * Gender | 0.823 | 0.827 | 0.561 |
| Gender * Condition * Direction | 0.654 | 2.025 | 0.103 |

**Transverse**

| Comparison | Wilks' Λ | F value | P value |
|---|---|---|---|
| Condition | 0.758 | 1.225 | 0.330 |
| Gender | 0.780 | 1.081 | 0.403 |
| Condition * Gender | 0.934 | 0.270 | 0.945 |
| Condition * Direction | 0.934 | 0.270 | 0.100 |
| Direction * Gender | 0.817 | 0.859 | 0.539 |
| Gender * Condition * Direction | 0.786 | 1.043 | 0.424 |

APPENDIX B
JOINT ANGLES AND MOMENTS

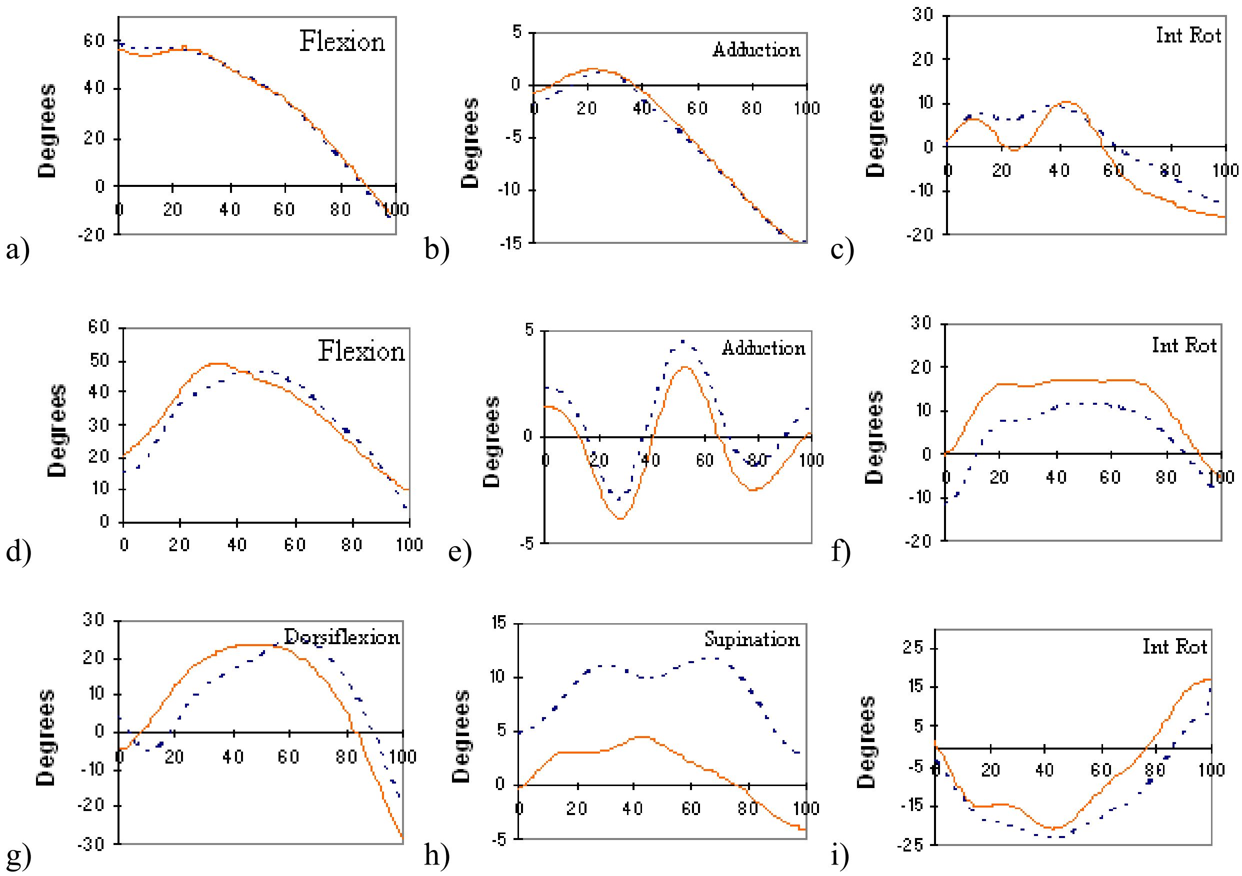


Figure B-1. Joint angles during stance phase for males (dotted, blue line) and females (solid, orange line) for a) hip sagittal plane b) hip frontal plane c) hip transverse plane d) knee sagittal plane e) knee frontal plane f) knee transverse plane g) ankle sagittal plane h) ankle frontal plane i) ankle transverse plane

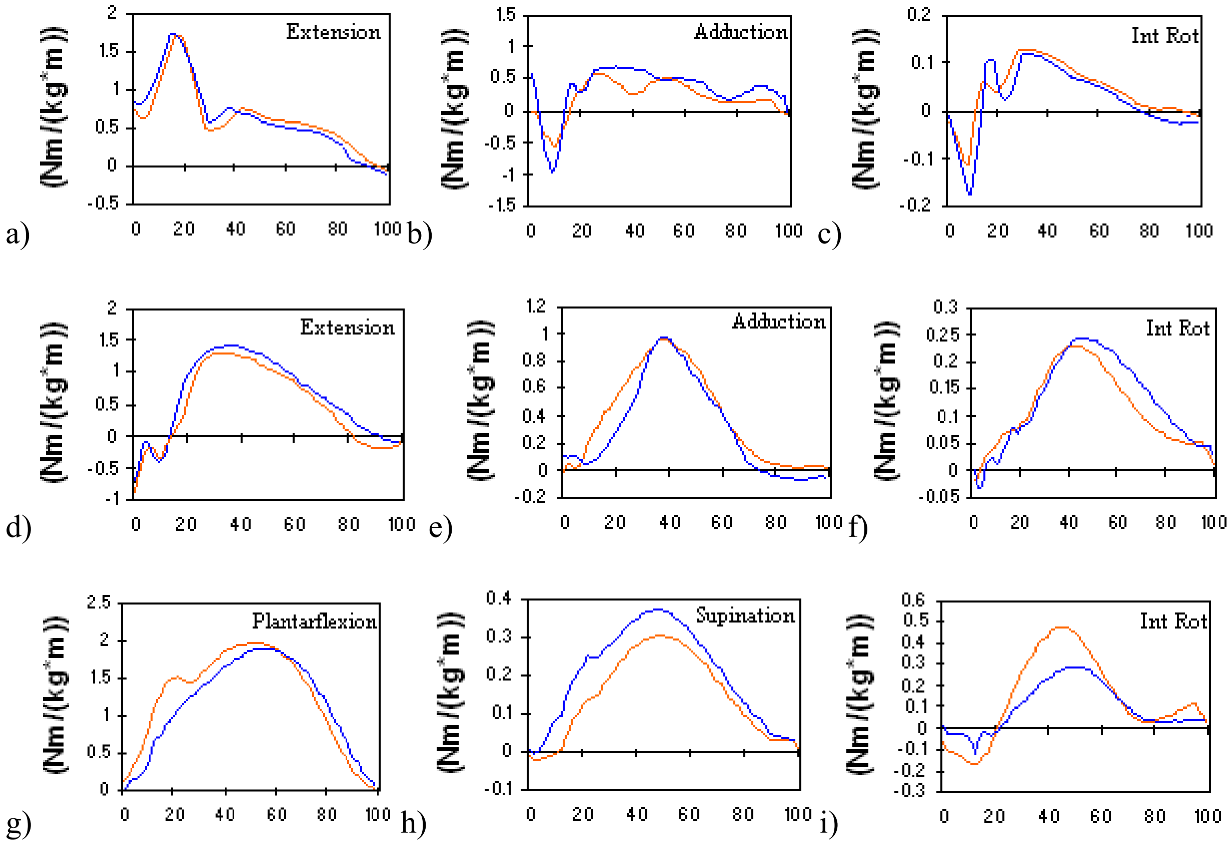


Figure B-2. Joint moments during stance phase for males (blue line) and females (orange line) for a) hip sagittal plane b) hip frontal plane c) hip transverse plane d) knee sagittal plane e) knee frontal plane f) knee transverse plane g) ankle sagittal plane h) ankle frontal plane i) ankle transverse plane

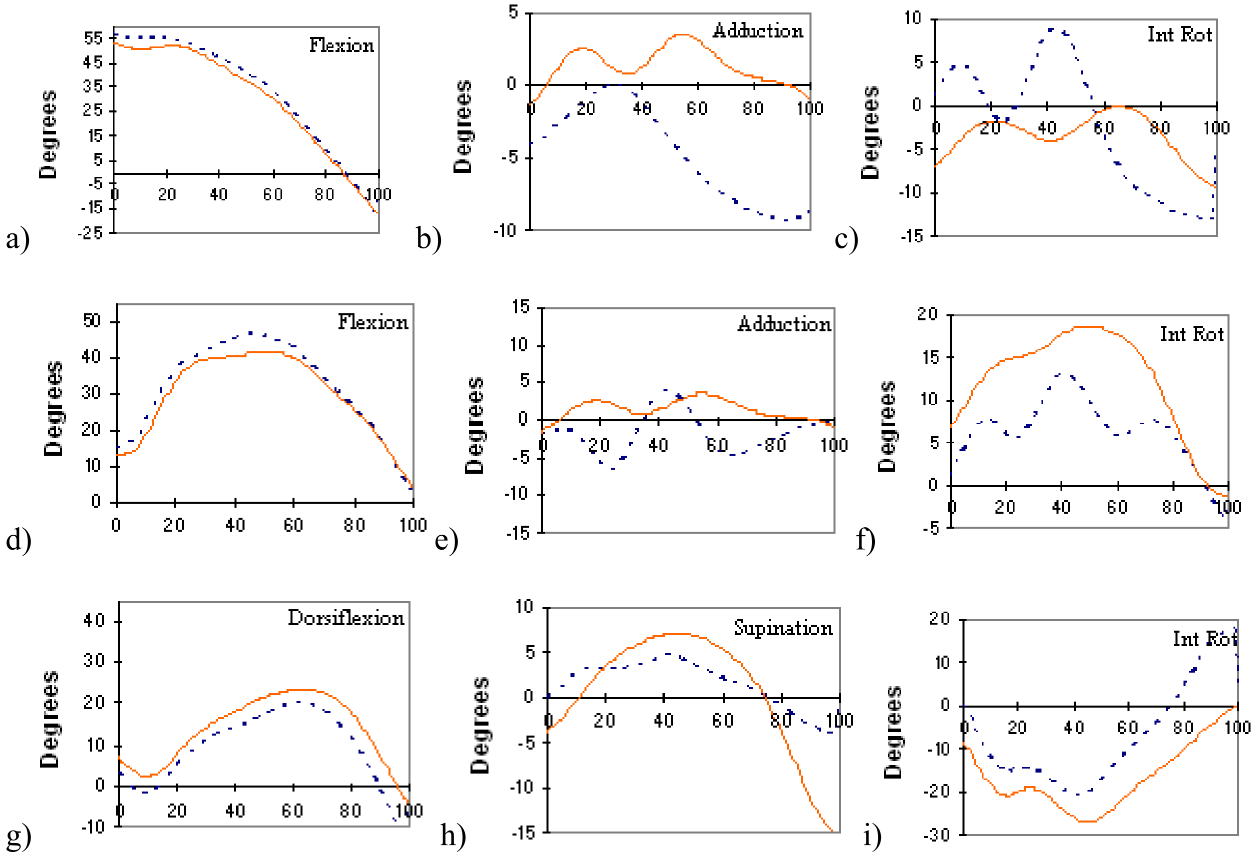


Figure B-3. Joint angles during stance phase for side cut (dotted, blue line) and crossover cut (solid, orange line) for a) hip sagittal plane b) hip frontal plane c) hip transverse plane d) knee sagittal plane e) knee frontal plane f) knee transverse plane g) ankle sagittal plane h) ankle frontal plane i) ankle transverse plane

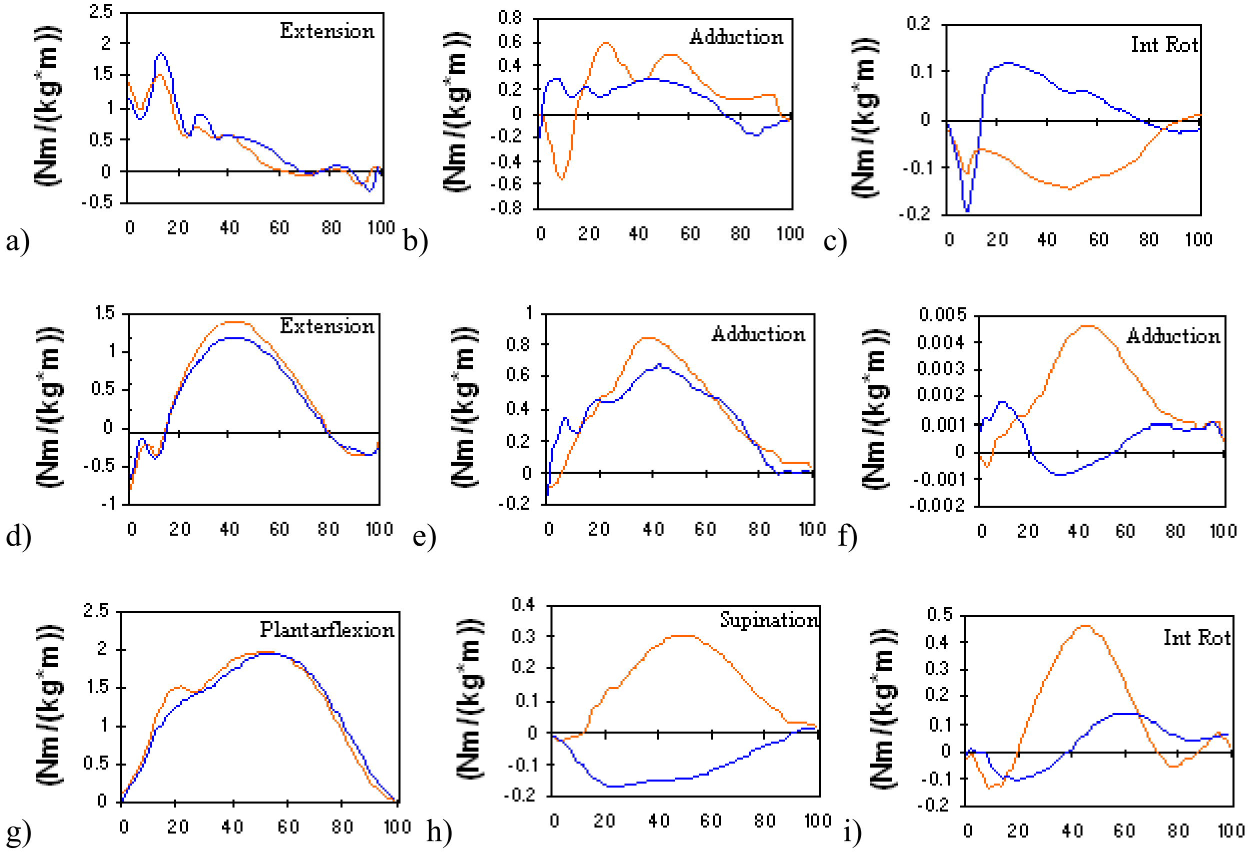


Figure B-4. Joint moments during stance phase for side cut (orange line) and crossover cut (blue line) for a) hip sagittal plane b) hip frontal plane c) hip transverse plane d) knee sagittal plane e) knee frontal plane f) knee transverse plane g) ankle sagittal plane h) ankle frontal plane i) ankle transverse plane

LIST OF REFERENCES


**1.** Girgis FG, Marshall JL, Monajem A. Cruciate Ligaments of Knee-Joint - Anatomical, Functional and Experimental Analysis. *Clinical Orthopaedics and Related Research.* 1975(106):216-231.

**2.** Butler DL, Noyes FR, Grood ES. Ligamentous Restraints to Anterior-Posterior Drawer in the Human Knee - Biomechanical Study. *Journal of Bone and Joint Surgery-American Volume.* 1980;62(2):259-270.

**3.** Amis AA, Dawkins GPC. Functional-Anatomy of the Anterior Cruciate Ligament - Fiber Bundle Actions Related to Ligament Replacements and Injuries. *Journal of Bone and Joint Surgery-British Volume.* Mar 1991;73(2):260-267.

**4.** Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8(3):141-150.

**5.** Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the Acl-Injured Patient - a Prospective Outcome Study. *American Journal of Sports Medicine.* 1994;22(5):632-644.

**6.** Huston LJ, Greenfield M, Wojtys EM. Anterior cruciate ligament injuries in the female athlete - Potential risk factors. *Clinical Orthopaedics and Related Research.* 2000(372):50-63.

**7.** Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *Journal of Athletic Training.* 1999;34(2):86-92.

**8.** Messina DF, Farney WC, DeLee JC. The incidence of injury in Texas high school basketball - A prospective study among male and female athletes. *American Journal of Sports Medicine.* 1999;27(3):294-299.

**9.** Goodman LRW, M. P. The female athlete and menstrual function. *Current Opinion in Obstetrics and Gynecology.* 2005;17:466–470.

**10.** Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes - Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *American Journal of Sports Medicine.* 2006;34(3):490-498.

**11.** Silvers HJ, Mandelbaum BR. Prevention of anterior cruciate ligament injury in the female athlete. *British Journal of Sports Medicine.* August 1, 2007 2007;41(suppl_1):i52-59.

**12.** Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* Jun 2000;23(6):573-578.

**13.** McNair PJ, Marshall RN, Matheson JA. Important Features Associated with Acute Anterior Cruciate Ligament Injury. *New Zealand Medical Journal.* 1990;103(901):537-539.

**14.** Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball a systematic video analysis. *American Journal of Sports Medicine.* 2004;32(4):1002-1012.

**15.** Ireland ML. Anterior cruciate ligament injury in female athletes: Epidemiology. *Journal of Athletic Training.* 1999;34(2):150-154.

**16.** Tillman MD, Hass CJ, Brunt D, Bennett GR. Jumping and landing techniques in elite women's volleyball. *Journal of Sports Science and Medicine.* 2004;3(1):30-36.

**17.** Hewett TE, Paterno, M. V., & Myer, G. D. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthopaedics and Related Research.* 2002;402:76-94.

**18.** Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *British Journal of Sports Medicine.* 2008;42(6):394-412.

**19.** Bonci CM. Assessment and evaluation of predisposing factors to anterior cruciate ligament injury. *Journal of Athletic Training.* 1999;34(2):155-164.

**20.** Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes - Part 1, mechanisms and risk factors. *American Journal of Sports Medicine.* 2006;34(2):299-311.

**21.** Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine.* 2005;33(4):492-501.

**22.** Hughes G, Watkins J. A risk-factor model for anterior cruciate ligament injury. *Sports Medicine.* 2006;36(5):411-428.

**23.** Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis and Rheumatism.* 2004;50(10):3145-3152.

**24.** Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise.* 2001;33(7):1168-1175.

**25.** Hamill J, Knutzen, K. M. *Bioimechanical Basis of Human Movement.* Philladelphia: Lippincott Williams & Wilkins; 2003.

**26.** Zantop T, Petersen W, Sekiya JK, Musahl V, Fu FH. Anterior cruciate ligament anatomy and function relating to anatomical reconstruction. *Knee Surgery Sports Traumatology Arthroscopy.* 2006;14(10):982-992.

**27.** Markolf KL, Mensch JS, Amstutz HC. Stiffness and Laxity of Knee - Contributions of Supporting Structures - Quantitative Invitro Study. *Journal of Bone and Joint Surgery-American Volume.* 1976;58(5):583-594.

**28.** Norwood LA, Cross MJ. The intercondylar shelf and the anterior cruciate ligament. *Am J Sports Med.* 1977;5(4):171-176.

**29.** Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Menetrey J. Anatomy of the anterior cruciate ligament. *Knee Surgery Sports Traumatology Arthroscopy.* 2006;14(3):204-213.

**30.** Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH. Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. *Journal of Bone and Joint Surgery-American Volume.* 2006;88A:2-10.

**31.** Xerogeanes JW, Takeda Y, Livesay GA, et al. Effect of knee flexion on the in situ force distribution in the human anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc.* 1995;3(1):9-13.

**32.** Hollis JM, Takai S, Adams DJ, Horibe S, Woo SLY. The Effects of Knee Motion and External Loading on the Length of the Anterior Cruciate Ligament (Acl) - a Kinematic Study. *Journal of Biomechanical Engineering-Transactions of the Asme.* 1991;113(2):208-214.

**33.** Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiou N. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *American Journal of Sports Medicine.* 2003;31(1):75-79.

**34.** Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SLY. Quantitative analysis of human cruciate ligament insertions. *Arthroscopy-the Journal of Arthroscopic and Related Surgery.* 1999;15(7):741-749.

**35.** Ford KR, Myer, G. D., Toms, H. E., & Hewett, T. E. Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine and Science in Sports and Exercise.* 2005;37:124-129.

**36.** Hurd WJ, Chmielewski TL, Axe MJ, Davis I, Snyder-Mackler L. Differences in normal and perturbed walking kinematics between male and female athletes. *Clinical Biomechanics.* 2004;19(5):465-472.

**37.** Chaudhari AM, Andriacchi TP. The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *Journal of Biomechanics.* 2006;39(2):330-338.

**38.** Bellchamber TL, van den Bogert AJ. Contributions of proximal and distal moments to axial tibial rotation during walking and running. *Journal of Biomechanics.* 2000;33(11):1397-1403.

**39.** Perry SD, Lafortune MA. Influences of Inversion Eversion of the Foot Upon Impact Loading During Locomotion. *Clinical Biomechanics.* 1995;10(5):253-257.

**40.** McClay I, Manal K. Coupling parameters in runners with normal and excessive pronation. *Journal of Applied Biomechanics.* 1997;13(1):109-124.

**41.** Nigg BM, Cole GK, Nachbauer W. Effects of Arch Height of the Foot on Angular Motion of the Lower-Extremities in Running. *Journal of Biomechanics.* 1993;26(8):909-916.

**42.** McLean SG, Lipfert SW, Van Den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Medicine and Science in Sports and Exercise.* 2004;36(6):1008-1016.

**43.** Krosshaug T, Nakamae A, Boden B, et al. Estimating 3D joint kinematics from video sequences of running and cutting maneuvers-assessing the accuracy of simple visual inspection. *Gait & Posture.* 2007;26:378-385.

**44.** Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC. Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 859 west point cadets (Vol 31, pg 831, 2003). *American Journal of Sports Medicine.* 2005;33(4):614-614.

**45.** Ostenberg A, Roos H. Injury risk factors in female European football. A prospective study of 123 players during one season. *Scandinavian Journal of Medicine & Science in Sports.* 2000;10(5):279-285.

**46.** Shambaugh JP, Klein A, Herbert JH. Structural Measures as Predictors of Injury in Basketball Players. *Medicine and Science in Sports and Exercise.* 1991;23(5):522-527.

**47.** Horton MG, Hall TL. Quadriceps Femoris Muscle Angle - Normal Values and Relationships with Gender and Selected Skeletal Measures. *Physical Therapy.* 1989;69(11):897-901.

**48.** Guerra JP, Arnold MJ, Gajdosik RL. Q-Angle - Effects of Isometric Quadriceps Contraction and Body Position. *Journal of Orthopaedic & Sports Physical Therapy.* 1994;19(4):200-204.

**49.** Huston LJ, Vibert B, Ashton-Miller JA, Wojtys EM. Gender differences in knee angle when landing from a drop-jump. *Am J Knee Surg.* 2001;14(4):215-219; discussion 219-220.

**50.** Herrington L, Nester C. Q-angle undervalued? The relationship between Q-angle and medio-lateral position of the patella. *Clinical Biomechanics.* 2004;19(10):1070-1073.

**51.** Tillman MD, Bauer JA, Cauraugh JH, Trimble MH. Differences in lower extremity alignment between males and females - Potential predisposing factors for knee injury. *Journal of Sports Medicine and Physical Fitness.* 2005;45(3):355-359.

**52.** Moul JL. Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA Division I collegiate basketball players. *Journal of Athletic Training.* 1998;33(2):118-121.

**53.** Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology.* 2005;15(2):181-189.

**54.** McLean SG, Walker KB, van den Bogert AJ. Effect of gender on lower extremity kinematics during rapid direction changes: An integrated analysis of three sports movements. *Journal of Science and Medicine in Sport.* 2005;8(4):411-422.

**55.** Palmer I. On the injuries to the ligaments of the knee joint: a clinical study. 1938. *Clin Orthop Relat Res.* 2007;454:17-22; discussion 14.

**56.** Anderson AF, Dome DC, Gautam S, Awh MH, Rennirt GW. Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *American Journal of Sports Medicine.* 2001;29(1):58-66.

**57.** Shelbourne KD, Davis TJ, Klootwyk TE. The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears - A prospective study. *American Journal of Sports Medicine.* 1998;26(3):402-408.

**58.** Souryal TO, Freeman TR, Daniel DM. Intercondylar Notch Size and Anterior Cruciate Ligament Injuries in Athletes - a Prospective-Study. *American Journal of Sports Medicine.* 1993;21(4):535-539.

**59.** Ireland ML, Ballantyne BT, Little K, McClay IS. A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. *Knee Surgery Sports Traumatology Arthroscopy.* 2001;9(4):200-205.

**60.** Fayad LM, Elan H. Rosenthal William B. Morrison John A. Carrino. Anterior cruciate ligament volume: Analysis of gender differences. *Journal of Magnetic Resonance Imaging.* 2008;27(1):218-223.

**61.** Tillman MD, Smith KR, Bauer JA, Cauraugh JH, Falsetti AB, Pattishall JL. Differences in three intercondylar notch geometry indices between males and females: a cadaver study. *Knee.* 2002;9(1):41-46.

**62.** Soderman K, Alfredson H, Pietila T, Werner S. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surgery Sports Traumatology Arthroscopy.* 2001;9(5):313-321.

**63.** Nicholas JA. Injuries to Knee Ligaments - Relationship to Looseness and Tightness in Football Players. *Journal of the American Medical Association.* 1970;212(13):2236-&.

**64.** Kalenak A, Morehouse CA. Knee Stability and Knee Ligament Injuries. *Jama-Journal of the American Medical Association.* 1975;234(11):1143-1145.

**65.** Woodford-Rogers B, Cyphert L, Denegar CR. Risk factors for anterior cruciate ligament injury in high school and college athletes. *Journal of Athletic Training.* 1994;29(4):343-346.

**66.** Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC. Risk factors associated with noncontact injury of the anterior cruciate ligament - A prospective four-year evaluation of 859 West Point cadets. *American Journal of Sports Medicine.* 2003;31(6):831-842.

**67.** Hsu WH, Fisk JA, Yamamoto Y, Debski RE, Woo SLY. Differences in torsional joint stiffness of the knee between genders - A human cadaveric study. *American Journal of Sports Medicine.* 2006;34(5):765-770.

**68.** Wojtys EM A-MJ, Huston LJ. A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *Journal of Bone and Joint Surgery.* 2002;84:10-16.

**69.** Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *Journal of Bone and Joint Surgery-American Volume.* 2003;85A(5):782-789.

**70.** Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *American Journal of Sports Medicine.* 1996;24(4):427-436.

**71.** Chandrashekar N, Mansouri H, Slauterbeck J, Hashemi J. Sex-based differences in the tensile properties of the human anterior cruciate ligament. *Journal of Biomechanics.* 2006;39(16):2943-2950.

**72.** Bates BT, Osternig LR, Mason B, James LS. Foot orthotic devices to modify selected aspects of lower extremity mechanics. *Am J Sports Med.* 1979;7(6):338-342.

**73.** Mueller MJ, Host JV, Norton BJ. Navicular Drop as a Composite Measure of Excessive Pronation. *Journal of the American Podiatric Medical Association.* 1993;83(4):198-202.

**74.** Allen MK, Glasoe WM. Metrecom measurement of navicular drop in subjects with anterior cruciate ligament injury. *Journal of Athletic Training.* Oct-Dec 2000;35(4):403-406.

**75.** Trimble MH, Bishop MD, Buckley BD, Fields LC, Rozea GD. The relationship between clinical measurements of lower extremity posture and tibial translation. *Clinical Biomechanics.* 2002;17(4):286-290.

**76.** Jenkins WL, Killian CB, Williams DS, Loudon J, Raedeke SG. Anterior cruciate ligament injury in female and male athletes - The relationship between foot structure and injury. *Journal of the American Podiatric Medical Association.* 2007;97:371-376.

**77.** Scranton PE, Whitesel JP, Powell JW, et al. A review of selected noncontact anterior cruciate ligament injuries in the National Football League. *Foot & Ankle International.* 1997;18(12):772-776.

**78.** Orchard J. Is there a relationship between ground and climatic conditions and injuries in football? *Sports Medicine.* 2002;32(7):419-432.

**79.** Orchard J, Seward H, McGivern J, Hood S. Rainfall, evaporation and the risk of non-contact anterior cruciate ligament injury in the Australian Football League. *Medical Journal of Australia.* 1999;170(7):304-306.

**80.** Backx FJG, Beijer HJM, Bol E, Erich WBM. Injuries in High-Risk Persons and High-Risk Sports - a Longitudinal-Study of 1818 School-Children. *American Journal of Sports Medicine.* 1991;19(2):124-130.

**81.** Lambson RB, Barhnill BS, Higgins RW. Football cleat design and its effect on anterior cruciate ligament injuries - A three-year prospective study. *American Journal of Sports Medicine.* 1996;24(2):155-159.

**82.** Ekstrand J, Timpka T, Hagglund M. Risk of injury in elite football played on artificial turf versus natural grass: a prospective two-cohort study. *British Journal of Sports Medicine.* 2006;40(12):975-980.

**83.** Fuller CW, Dick RW, Corlette J, Schmalz R. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: match injuries. *British Journal of Sports Medicine.* 2007;41:I20-I26.

**84.** Steffen K, Andersen TE, Bahr R. Risk of injury on artificial turf and natural grass in young female football players. *British Journal of Sports Medicine.* 2007;41:I33-I37.

**85.** Milburn PD, Barry EB. Shoe-surface interaction and the reduction of injury in rugby union. *Sports Medicine.* 1998;25(5):319-327.

**86.** Girard O, Eicher F, Fourchet F, Micallef JP, Millet GP. Effects of the playing surface on plantar pressures and potential injuries in tennis. *British Journal of Sports Medicine.* 2007;41.

**87.** Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: an audit of injuries in professional football. *British Journal of Sports Medicine.* 2001;35(1):43-47.

**88.** Delee JC, Farney WC. Incidence of Injury in Texas High-School Football. *American Journal of Sports Medicine.* 1992;20(5):575-580.

**89.** Myklebust G, Maehlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian Journal of Medicine & Science in Sports.* 1998;8(3):149-153.

**90.** Harmon KG, Ireland ML. Gender differences in noncontact anterior cruciate ligament injuries. *Clinics in Sports Medicine.* 2000;19(2):287-+.

**91.** Karageanes SJ, Blackburn K, Vangelos ZA. The association of the menstrual cycle with the laxity of the anterior cruciate ligament in adolescent female athletes. *Clinical Journal of Sport Medicine.* 2000;10(3):162-168.

**92.** Bani D. Relaxin: A pleiotropic hormone. *General Pharmacology.* 1997;28(1):13-22.

**93.** Shultz SJ, Kirk SE, Johnson ML, Sander TC, Perrin DH. Relationship between sex hormones and anterior knee laxity across the menstrual cycle. *Medicine and Science in Sports and Exercise.* 2004;36(7):1165-1174.

**94.** Heitz NA, Eisenman PA, Beck CL, Walker JA. Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. *Journal of Athletic Training.* 1999;34(2):144-149.

**95.** Shultz SJ, Sander TC, Kirk SE, Perrin DH. Sex differences in knee joint laxity change across the female menstrual cycle. *Journal of Sports Medicine and Physical Fitness.* 2005;45(4):594-603.

**96.** Deie M, Sakamaki Y, Sumen Y, Urabe Y, Ikuta Y. Anterior knee laxity in young women varies with their menstrual cycle. *International Orthopaedics.* 2002;26(3):154-156.

**97.** Sarwar R, Niclos BB, Rutherford OM. Changes in muscle strength, relaxation rate and fatiguability during the human menstrual cycle. *Journal of Physiology-London.* 1996;493(1):267-272.

**98.** Lebrun CM. The Effect of the Phase of the Menstrual-Cycle and the Birth-Control Pill on Athletic Performance. *Clinics in Sports Medicine.* 1994;13(2):419-441.

**99.** Posthuma BW, Bass MJ, Bull SB, Nisker JA. Detecting Changes in Functional Ability in Women with Premenstrual-Syndrome. *American Journal of Obstetrics and Gynecology.* Feb 1987;156(2):275-278.

**100.** Slauterbeck JR FS, Smith MP, Clark RJ, Xu K, Starch DW, Hardy DM. The Menstrual Cycle, Sex Hormones, and Anterior Cruciate Ligament Injury. *Journal of Athletic Training.* 2002;37:275-278.

**101.** Fox S. *Human Physiology*. Boston: McGraw and Hill; 1999.

**102.** Liu SH, AlShaikh R, Panossian V, et al. Primary immunolocalization of estrogen and progesterone target cells in the human anterior cruciate ligament. *Journal of Orthopaedic Research.* 1996;14(4):526-533.

**103.** Sciore P, Frank CB, Hart DA. Identification of sex hormone receptors in human and rabbit ligaments of the knee by reverse transcription-polymerase chain reaction: Evidence that receptors are present in tissue from both male and female subjects. *Journal of Orthopaedic Research.* 1998;16(5):604-610.

**104.** Wojtys EM, Huston LJ. Neuromuscular Performance in Normal and Anterior Cruciate Ligament-Deficient Lower-Extremities. *American Journal of Sports Medicine.* 1994;22(1):89-104.

**105.** Wojtys EM HL, Boynton MD, Spindler KP, Lindenfeld TN. The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *American Journal of Sports Medicine.* 2002;30(2):182-188.

**106.** Adachi N, Nawata K, Maeta M, Kurozawa Y. Relationship of the menstrual cycle phase to anterior cruciate ligament injuries in teenaged female athletes. *Archives of Orthopaedic and Trauma Surgery.* May 2008;128(5):473-478.

**107.** Shirtcliff EA, Granger DA, Schwartz EB, Curran MJ, Booth A, Overman WH. Assessing estradiol in biobehavioral studies using saliva and blood spots: Simple radioimmunoassay protocols, reliability, and comparative validity. *Hormones and Behavior.* 2000;38(2):137-147.

**108.** Baker FC, Driver HS. Circadian rhythms, sleep, and the menstrual cycle. *Sleep Medicine.* 2007;8:613-622.

**109.** Moller Nielsen JH, M. Sports injuries and oral contraceptives use. Is there a relationship? *Sports Medicine.* 1991;12(3):152-160.

**110.** Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes - Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine.* 1996;24(6):765-773.

**111.** Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise.* 2003;35(10):1745-1750.

**112.** Knapik JJ, Bauman CL, Jones BH, Harris JM, Vaughan L. Preseason Strength and Flexibility Imbalances Associated with Athletic Injuries in Female Collegiate Athletes. *American Journal of Sports Medicine.* 1991;19(1):76-81.

**113.** Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SLY. The importance of quadriceps and hamstring muscle loading on knee kinematics land in-situ forces in the ACL. *Journal of Biomechanics.* 1999;32(4):395-400.

**114.** Torzilli PA, Deng XH, Ramcharan M. Effect of compressive strain on cell viability in statically loaded articular cartilage. *Biomechanics and Modeling in Mechanobiology.* 2006;5(2-3):123-132.

**115.** Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension - A comparison of an open and a closed kinetic chain. *American Journal of Sports Medicine.* 1997;25(6):823-829.

**116.** Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *Journal of Biomechanics.* 1997;30(10):1015-1024.

**117.** Urabe Y, Kobayashi R, Sumida S, et al. Electromyographic analysis of the knee during jump landing in male and female athletes. *Knee.* 2005;12(2):129-134.

**118.** Barrett GR, Field LD. Comparison of Patella Tendon Versus Patella Tendon Kennedy Ligament Augmentation Device for Anterior Cruciate Ligament Reconstruction - Study of Results, Morbidity, and Complications. *Arthroscopy.* 1993;9(6):624-632.

**119.** Woo SLY, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile Properties of the Human Femur-Anterior Cruciate Ligament-Tibia Complex - the Effects of Specimen Age and Orientation. *American Journal of Sports Medicine.* 1991;19(3):217-225.

**120.** Ebstrup JF, Bojsen-Moller F. Anterior cruciate ligament injury in indoor ball games. *Scandinavian Journal of Medicine & Science in Sports.* 2000;10(2):114-116.

**121.** Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics.* 2001;16(5):438-445.

**122.** Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clinical Biomechanics.* 2006;21(1):41-48.

**123.** Lephart SM, Ferris, C. M., Riemann, B. L., Myers, J. B., Fu, F. H. Gender differences in strength and lower extremity kinematics during landing. . *Clinical Orthopaedics and Related Research.* 2002;401:162-169.

**124.** Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes - A prospective study. *American Journal of Sports Medicine.* 1999;27(6):699-706.

**125.** Wojtys EM, Huston LJ, Lindenfeld TN, Hewett TE, Greenfield M. Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *American Journal of Sports Medicine.* 1998;26(5):614-619.

**126.** Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics.* 2001;34(2):163-170.

**127.** O'Connor JJ. Can muscle co-contraction protect the knee ligaments after injury or repair? *Journal of Bone and Joint Surgery.* 1993;75:41-48.

**128.** Dufek JS, Bates BT. Biomechanical Factors Associated with Injury During Landing in Jump Sports. *Sports Medicine.* 1991;12(5):326-337.

**129.** Cerulli G, Benoit DL, Lamontagne M, Caraffa A, Liti A. In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. *Knee Surgery Sports Traumatology Arthroscopy.* 2003;11(5):307-311.

**130.** Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirkendall DT, Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *American Journal of Sports Medicine.* 2005;33(9):1356-1364.

**131.** Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *American Journal of Sports Medicine.* 2005;33(7):1022-1029.

**132.** Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. *Clinical Biomechanics.* 2004;19(6):622-628.

**133.** Kernozek TW, Torry MR, Van Hoof H, Cowley H, Tanner S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Medicine and Science in Sports and Exercise.* 2005;37(6):1003-1012.

**134.** Ford KR, Myer GD, Smith RL, Vianello RM, Seiwert SL, Hewett TE. A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clinical Biomechanics.* 2006;21(1):33-40.

**135.** Andrews JR, Axe MJ. The Classification of Knee Ligament Instability. *Orthopedic Clinics of North America.* 1985;16(1):69-82.

**136.** Dugan SA, Bhat KP. Biomechanics and analysis of running gait. *Physical Medicine and Rehabilitation Clinics of North America.* 2005;16:603-621.

**137.** Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *American Journal of Sports Medicine.* 2002;30:261-267.

**138.** Bendjaballah MZ, ShiraziAdl A, Zukor DJ. Finite element analysis of human knee joint in varus-valgus. *Clinical Biomechanics.* 1997;12(3):139-148.

**139.** Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *American Journal of Sports Medicine.* 2003;31(2):233-240.

**140.** Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *Journal of Strength and Conditioning Research.* 2005;19(2):394-399.

**141.** Zeller BL, McCrory JL, Ben Kibler W, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *American Journal of Sports Medicine.* 2003;31(3):449-456.

**142.** Decker MJ, Torry MR, Wyland DJ, Sterett WI, Steadman JR. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics.* 2003;18(7):662-669.

**143.** Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Unanticipated running and cross cutting maneuvers demonstrate neuromuscular and lower limb, biomechanical differences between elite adolescent male and female soccer players. *Journal of Biomechanics.* 2007;40(Supplement 2):S379-S379.

**144.** Sanna G, O'Connor KM. Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers. *Clinical Biomechanics.* 2008;23(7):946-954.

**145.** Pollard CD, Sigward SM, Powers CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clinical Journal of Sport Medicine.* 2007;17(1):38-42.

**146.** Hanson AM, Padua DA, Blackburn JT, Prentice WE, Hirth CJ. Muscle activation during side-step cutting maneuvers in male and female soccer athletes. *Journal of Athletic Training.* 2008;43(2):133-143.

**147.** Garrison JC, Hart JM, Palmieri RM, Kerrigan DC, Ingersoll CD. Lower extremity EMG in male and female college soccer players during single-leg landing. *Journal of Sport and Rehabilitation.* 2005;14:48-57.

**148.** Ferber R, Davis IM, Williams DS. Gender differences in lower extremity mechanics during running. *Clinical Biomechanics.* 2003;18(4):350-357.

**149.** Chumanov ES, Wall-Schefer C, Heiderscheit BC. Gender differences in walking and running on level and inclined surfaces. *Clinical Biomechanics.* 2008;23(10):1260-1268.

**150.** Sigward SM, Powers CM. Loading characteristics of females exhibiting excessive valgus moments during cutting. *Clinical Biomechanics.* 2007;22(7):827-833.

**151.** Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clinical Biomechanics.* 2004;19(10):1022-1031.

**152.** Michaud PA, Renaud A, Narring F. Sports activities related to injuries? A survey among 9-19 year olds in Switzerland. *Injury prevention : journal of the International Society for Child and Adolescent Injury Prevention.* 2001;7:41-45.

**153.** Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *Journal of Bone and Joint Surgery-American Volume.* 2004;86A(8):1601-1608.

**154.** Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Gender differences in hip adduction motion and torque during a single-leg agility maneuver. *Journal of Orthopaedic Research.* 2006;24(3):416-421.

**155.** Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation leads to gender differences in landing force and vertical jump performance - A longitudinal study. *American Journal of Sports Medicine.* 2006;34(5):806-813.

**156.** Hass CJ, Schick EA, Chow JW, Tillman MD, Brunt D, Cauraugh JH. Lower extremity biomechanics differ in prepubescent and postpubescent female athletes during stride jump landings. *Journal of Applied Biomechanics.* 2003;19(2):139-152.

**157.** Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes - 2-year follow-up. *American Journal of Sports Medicine.* 2005;33(7):1003-1010.

**158.** Gilchrist J, Mandelbaum BR, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior Cruciate ligament injury in female collegiate soccer players. *American Journal of Sports Medicine.* 2008;36(8):1476-1483.

**159.** Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *Journal of Strength and Conditioning Research.* 2005;19(1):51-60.

**160.** Pollard CD, Sigward SM, Ota S, Langford K, Powers CM. The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clinical Journal of Sport Medicine.* 2006;16(3):223-227.

**161.** Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *American Journal of Sports Medicine.* 2008;36(6):1081-1086.

**162.** Kato S, Urabe Y, Kawamura K. Alignment control exercise changes lower extremity movement during stop movements in female basketball players. *Knee.* 2008;15(4):299-304.

**163.** Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *American Journal of Sports Medicine.* 2008;36(4):733-740.

**164.** Zebis MK, Bencke J, Andersen LL, et al. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clinical Journal of Sport Medicine.* 2008;18(4):329-337.

**165.** Petersen W, Braun C, Bock W, et al. A controlled prospective case control study of a prevention training program in female team handball players: the German experience. *Archives of Orthopaedic and Trauma Surgery.* 2005;125(9):614-621.

**166.** Heidt RS, Sweeterman LM, Carlonas RL, Traub JA, Tekulve FX. Avoidance of soccer injuries with preseason conditioning. *American Journal of Sports Medicine.* 2000;28(5):659-662.

**167.** Kraemer WJ, Keuning M, Ratamess NA, et al. Resistance training combined with bench-step aerobics enhances women's health profile. *Medicine and Science in Sports and Exercise.* 2001;33(2):259-269.

**168.** Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular control training programs and noncontact anterior cruciate ligament injury rates in female athletes: A numbers-needed-to-treat analysis. *Journal of Athletic Training.* 2006;41(4):450-456.

**169.** Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews.* 2001;81(4):1725-1789.

**170.** Wojtys EM, Wylie BB, Huston LJ. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *American Journal of Sports Medicine.* 1996;24(5):615-621.

**171.** Nyland JA, Caborn DN, Shapiro R, Johnson DL. Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surg Sports Traumatol Arthrosc.* 1997;5(3):162-167.

**172.** Rozzi SL, Lephart SM, Fu FH. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *Journal of Athletic Training.* 1999;34(2):106-114.

**173.** Mercer TH, Gleeson NP, Wren K. Influence of prolonged intermittent high-intensity exercise on knee flexor strength in male and female soccer players. *European Journal of Applied Physiology.* 2003;89(5):506-508.

**174.** Borotikar BS, Newcomer R, Koppes R, McLean SG. Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk. *Clinical Biomechanics.* 2008;23(1):81-92.

**175.** Orlshimo KF, Kremenic IJ. Effect of fatigue on single-leg hop landing biomechanics. *Journal of Applied Biomechanics.* 2006;22(4):245-254.

**176.** Madigan ML, Pidcoe PE. Changes in landing biomechanics during a fatiguing landing activity. *Journal of Electromyography and Kinesiology.* 2003;13(5):491-498.

**177.** Rahnama N, Reilly T, Lees A, Graham-Smith P. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *Journal of Sports Sciences.* 2003;21(11):933-942.

**178.** Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, van Hoecke J. Evidence of neuromuscular fatigue after prolonged cycling exercise. *Medicine and Science in Sports and Exercise.* 2000;32(11):1880-1886.

**179.** Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *American Journal of Sports Medicine.* 2008;36(3):554-565.

**180.** McLean SG. The ACL injury enigma: We can't prevent what we don't understand. *Journal of Athletic Training.* 2008;43(5):538-540.

**181.** Andrews JR, McLeod WD, Ward T, Howard K. The cutting mechanism. *American Journal of Sports Medicine.* 1977;5(3):111-121.

**182.** James CR, Sizer PS, Starch DW, Lockhart TE, Slauterbeck J. Gender differences among sagittal plane knee kinematic and ground reaction force characteristics during a rapid sprint and cut maneuver. *Research Quarterly for Exercise and Sport.* 2004;75(1):31-38.

**183.** McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: Implications for ACL injury. *Clinical Biomechanics.* 2005;20(8):863-870.

**184.** Besier TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine and Science in Sports and Exercise.* 2001;33(7):1176-1181.

**185.** McLean SG, Myers PT, Neal RJ, Walters MR. A quantitative analysis of knee joint kinematics during the sidestep cutting maneuver. Implications for non-contact anterior cruciate ligament injury. *Bull Hosp Jt Dis.* 1998;57(1):30-38.

**186.** Houck JR, Duncan A, DeHaven KE. Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait & Posture.* 2005;24(3):314-322.

**187.** Sell TC, Ferris CM, Abt JP, et al. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *Journal of Orthopaedic Research.* 2007;25:1589-1597.

**188.** Cowling EJ, Steele JR, McNair PJ. Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing. *British Journal of Sports Medicine.* 2003;37(2):126-130.

**189.** Hutchinson MR, Ireland ML. Knee Injuries in Female Athletes. *Sports Medicine.* 1995;19(4):288-302.

**190.** Borowski LA, Yard EE, Fields SK, Comstock RD. The epidemiology of US high school basketball injuries, 2005-2007. *American Journal of Sports Medicine.* 2008;36(12):2328-2335.

**191.** McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Medicine and Science in Sports and Exercise.* 1999;31(7):959-968.

**192.** Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries - A review of the Hunt Valley II Meeting, January 2005. *American Journal of Sports Medicine.* 2006;34:1512-1532.

**193.** O'Connor KM, Monteiro SK, Hoelker IA. Comparison of Selected Lateral Cutting Activities Used to Assess ACL Injury Risk. *Journal of Applied Biomechanics.* 2009;25(1):9-21.

**194.** Brown TN, Palmieri-Smith RM, McLean SG. Differences between Sexes and Limbs in Hip and Knee Kinematics and Kinetics during Anticipated and Unanticipated Jump Landings: Implications for ACL injury. *British Journal of Sports Medicine.* 2009;Epub ahead of print.

**195.** Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *Journal of Motor Behavior.* 2005;37(2):111-125.

**196.** Pollard CD, Heiderscheit BC, van Emmerik REA, Hamill J. Gender differences in lower extremity coupling variability during an unanticipated cutting maneuver. *Journal of Applied Biomechanics.* 2005;21(2):143-152.

**197.** Rand MK, Ohtsuki T. EMG analysis of lower limb muscles in humans during quick change in running directions. *Gait & Posture.* 2000;12(2):169-183.

**198.** Novacheck TF. The biomechanics of running. *Gait & Posture.* 1998;7:77-98.

**199.** Patla AE, Adkin A, Ballard T. Online steering coordinatino and control of body center of mass, head and body reorientation. *Experimental Brain Research.* 1999;129(4):629-634.

**200.** Winter D. Anatomy, biomechanics, and control of balance during standing and walking. *Gait & Posture.* 1995;3:193-214.

# BIOGRAPHICAL SKETCH

Ryan Ashley Mizell was born in Georgia to Dr. Russ Mizell III, a professor of entomology, and Patricia Mizell, a teacher. The family moved to Monticello, Florida, where he resided until moving to Gainesville to attend the University of Florida. Ryan graduated with a bachelor's degree in exercise and sport science. He attended graduate school and attained a master's degree in biomechanics in 2009. Ryan has an older brother, Rusty, who attended the University of Florida and now lives in Tampa with his wife and son.