BIOMECHANICAL AND NEUROMUSCULAR DIFFERENCES EXIST BETWEEN GENDERS FOR UNANTICIPATED RUNNING AND CUTTING MANEUVERS IN ADOLESCENT SOCCER PLAYERS: RELEVANCE TO THE ACL

by

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This thesis is dedicated to my parents,

Chriss and Charlie Landry

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Abstract

The anterior cruciate ligament (ACL) is an important contributor to knee joint stability during athletic maneuvers such as cutting to change directions. Approximately 70-80% of all ACL injuries are non-contact in nature and the injury rate is 2-8 times greater in females compared to males. This study measured quadriceps, hamstrings and gastrocnemii activation patterns and biomechanical features at the hip, knee and ankle in 21 male and 21 female adolescent soccer players while performing an unanticipated straight run, cross-cut and side-cut. It was hypothesized that differences between genders and medial-lateral muscle sites would be identified and related to non-contact ACL injury risk factors.

Kinematic differences during the stance phase of the maneuvers were captured at the hip and ankle, with the most notable gender difference being a reduced hip flexion angle in females for the 2 cutting maneuvers. Several joint moment differences were also identified, particularly during the first 20% of stance and at the hip. In comparison to females, males generated a greater hip flexion moment for all 3 maneuvers, suggesting that hip biomechanics may have a significant role towards to the gender bias of non-contact ACL injuries.

Neuromuscular differences were captured for the entire stance phase, the 100 msec pre-contact phase and early (0-20%) stance phase. Rectus femoris and lateral gastrocnemius activity was greater in females for all 3 maneuvers. Females also had a medial-lateral gastrocnemii activation imbalance that was not present in males. Throughout stance and compared to males, females also demonstrated reduced hamstring activity during the cross-cut and straight run and increased vastus medialis and lateralis activity during the straight run. The combination of these gender differences and medial-lateral imbalances could be placing the female ACL at greater risk of being injured. Pre-contact differences in the magnitude and shape of the hamstring, gastrocnemii and rectus femoris activation patterns also suggest that females may be using different neuromuscular control strategies as they prepare to execute unanticipated cutting maneuvers.

The neuromuscular and biomechanical differences were related to non-contact ACL injury risk factors and some of these potentially modifiable features could help improve current ACL preventative training programs.

List of Abbreviations and Symbols Used

ACL	anterior cruciate ligament
AM	anteromedial
ANOVA	analysis of variance
ASIS	anterior superior iliac spine
dB	decibel
CMRR	common mode rejection ratio
EMG	electromyography
GΩ, KΩ	giga-ohms, kilo-ohms
Hz	hertz
kg	kilo-gram
LG	lateral gastrocnemius
LH	lateral hamstring
MG	medial gastrocnemius
MH	medial hamstring
mm	millimeters
msec	millisecond
MVC, MVIC	maximal voluntary (isometric) contraction
MVC	maximal voluntary contraction
m/s	meters/second
N	Newton
Nm	Newton-meter
PC	principal component
PCA	principal component analysis
PL	posterolateral
RF	rectus femoris
sec	seconds
μV	micro-volts
VL	vastus lateralis
VM	vastus medialis
yrs	years

Acknowledgements

While I may be the primary author of this thesis, there are so many friends, family and colleagues that deserve co-authorship on this thesis in one way or another. What will be remembered most about my 15 years at Acadia and Dalhousie are the fun times and wonderful people I have gotten to know throughout this journey. It is impossible to express in only a couple of pages just how grateful I am to you all for your friendship and support over the years.

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I can say this without a doubt, that I had the best mentors a graduate student could ever wish for. Dr. Stanish, you believed in me from the start and every minute I got to spend with you, was an opportunity to learn and grow. You took me under your wing and provided me with so many wonderful opportunities that not every graduate student is as fortunate to experience. You taught me so much about life, about medicine and exposed me to so many fascinating areas that I never imagined would be attainable. You will without a doubt be one of the most special and caring individuals to ever come into my life and I look forward to an ever lasting friendship, particularly when I make my return to Halifax sometime in the future.

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Kelly McKean, how can I not cherish all the great laughs and adventures we had in room 5200, at Curry Village and throughout all the wonderful places in North American that we got to visit while attending the various conferences over the years. That San Francisco trip will forever be in the record books… oh how will we ever forget those yellow puma shoes, well we won't actually!! Donna, Pat, Sheila, Anne, Claudia and the rest of SMC ladies, thank you thank you and thank you some more! You are such a special group of girls and your energy, friendship and ability to always make Kelly and I smile, as well as all your hard work with helping our research group conduct studies with Dr. Stanish will forever be appreciated!!

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graduate degree. And Trevor, thank you for always making me believe that a PhD was attainable and that we were doing the right thing entering the academic world, ha ha!

When the time comes to reflect back on the past 7 years, it won't be the countless nights in the office or the long days spent in the laboratory that I will remember most, but rather it will be memorable moments I spent with my roommates, my friends from Acadia, Halifax, Pictou County and my Axemen Soccer Boys. I have made 3 of the best friends a person could ever imagine having during my degrees, with the likes of Jeff, Sue and Mike. Getting the opportunity to coach and coach against so many wonderful people throughout Nova Scotia will be something I will forever cherish and I owe that all to you Jeff, you are the greatest! To all my soccer girls that I coached at DU and DHS, you have a special place in my heart and I will truly miss the fun times we had over the past 6 years. And finally, an acknowledgement to Mike for the many years of entertainment and friendship. Thank you for all the laughs and great experiences that will be remembered for a lifetime, from back in the sandbox. days to the current Trailer Park days with Robb, JP and the rest of the crew, it's been a blast!

So everyone, this thesis and PhD is as much yours as it is mine, thank you for making my life so great!!

Chapter 1 - Introduction

1.1 Statement of the Problem

The anterior cruciate ligament (ACL) is a commonly injured knee ligament that continues to receive widespread attention throughout the medical and sporting communities. This attention is a result of the severity and potentially long-term effects associated with the injury, the manner in which the injury commonly occurs and the greater injury rate observed in females compared to males. Most ACL injuries occur during sporting activities and while a contacting blow to the knee or body can injure the ACL, it has been reported that approximately 70-80% of all ACL injuries are non-contact in nature and usually involve a sudden deceleration, an abrupt change in direction or a single leg landing during sports such as soccer, basketball, volleyball and handball.[21,99,153,160] The ACL provides important rotational and translational stability to the knee joint[130] and injury to this ligament is one of the most traumatic injuries in sport. An injured ACL most often results in knee joint instabilities and "giving way" episodes,[12,76] requires both an invasive surgical procedure to replace the ligament and intensive rehabilitation before returning to athletic related activities and generally leads to the early onset of knee osteoarthritis.[64,124,147,213]

Although there have been significant advances in the surgical techniques and rehabilitation protocols for ACL injuries in recent years, many questions and unknowns remain with respect to the mechanisms, risk factors and gender bias associated with non-contact ACL injuries. The cutting maneuver (running forward and quickly turning to the side) has been reported to be one of the single most hazardous mechanisms causing non-contact ACL injuries,[6] with the highest incidence of injuries occurring in individuals between the ages of 15 to 25 years of age.[72] It was estimated for the United States in 1985 that 50,000 ACL reconstructions were performed[100] but with the recent increase in sports participation, it is currently estimated that anywhere between 100,000 to 175,000 ACL reconstructions are being carried out in the United States each year[72,95,225] with a cost for the surgical procedures alone in access of 2 billion dollars.[68] Unfortunately for females, the number of ACL injuries they experience has increased drastically over the past 3 decades and this can partly be attributed to 3 main factors: i) the enactment of Title IX of the United States Educational Amendments Act in 1972 and similar regulatory guidelines in other countries which mandated increased institutional support for female participation in athletics, ii) the overall increase in participation rates seen throughout society for physical activities and organized sports and iii) the 2-8 times greater non-contact ACL injury rate observed in females over males, particularly during landing and cutting-related sports.[1,8,128]

Most studies attempting to understand the mechanisms of injury or identify injury risk factors have focused on comparing various characteristics between males and females. Anatomical comparisons between genders have been made in a number of studies and measures such as static alignment (Q-angle),[85,207] intercondylar notch width,[187,208] joint laxity[176] and foot pronation[13] have all been addressed specifically as being potential risk factors for ACL injury. The effect hormones and the different stages of the menstrual cycle have on athletic performance, ligamentous laxity and ACL injury incidence has also been studied in females;[118,143,146,168,219] however, the findings across these studies are contradictory and therefore making recommendations based on these studies has been difficult.

While the categorization of risk factors varies throughout the literature, risk factors that are potentially modifiable offer the greatest opportunity for helping to develop ways to prevent and reduce the incidence of ACL injuries, particularly in females. Many laboratory studies have compared the biomechanics and/or neuromuscular control strategies of the lower limb between genders while landing from a jump[32,40,43,56,59,176,181,211,226,227] or cutting to change directions[60,127,138-140,167,191] and it has been suggested that some of these measures are potentially modifiable. The majority of these motion studies have either focused on identifying gender differences in knee joint angles and moments and/or in quadriceps and hamstring activation patterns.

Video analysis of non-contact ACL injuries has shown that many of these injuries arise from an unanticipated movement or slight perturbation just prior to the injury occuring.[21,160] Often the injured individual is making a last second decision to change directions in order to avoid a defender, to avoid a collision or to avoid going out of bounds. To more closely approximate a true-game like scenario where the ACL can be injured by an unanticipated non-contact cutting maneuver, recent studies have also started to incorporate light guiding systems in the laboratory to force subjects to make last second decisions as to what direction to cut.[16,17,60,167] The studies by Pollard et al.[167] and

Ford et al.[60] are the only studies to compare joint biomechanics between genders during unanticipated cutting.

There are only 2 biomechanical laboratory studies in the literature that have made gender comparisons for unanticipated cutting maneuvers. These studies have the potential to provide knowledge on non-contact ACL injury risk factors and help with the understanding of the gender bias associated with this injury. It is apparent that there is a need for the development of a comprehensive gender comparative study that simultaneously measures and compares lower limb biomechanics and the neuromuscular response during unanticipated cutting maneuvers in the laboratory, with the goal of improving upon the current understanding of non-contact ACL injuries.

1.2 Rationale

This study was designed to address 5 main areas that were identified through a critical review of the existing literature on non-contact ACL injuries and athletic maneuvers such as side-cutting and cross-cutting. The 5 areas that will be discussed in the following sections include i) adolescent athletes, ii) simultaneous comparison of lower limb biomechanics (hip, knee and ankle) and neuromuscular control patterns of the muscles surrounding the knee, iii) emphasis on the role of the gastrocnemii muscle group in protecting the knee, iv) medial-lateral muscle site comparisons within the quadriceps, hamstrings and gastrocnemii muscle groups and v) unanticipated running and cutting maneuvers.

1.2.1 Adolescent Athletes

Although no gender disparity in ACL injury rates has been reported in prepubescent athletes,[7,134] females have been shown to have greater injury rates than their male counterparts at both the high school[169] and collegiate level.[1,8] The larger high school athletic population also indicates that more ACL injuries are occurring at the high school level in comparison to the collegiate level.[95] The importance of studying teenage or adolescent athletes with respect to ACL injuries has also been emphasized locally in Nova Scotia where during the 2.5 years leading up to the final selection of the 2005 Nova Scotia Canada Game's female and male soccer teams, 9 females from the player selection pool sustained a complete or partial rupture of the ACL, in comparison to only 1 partial tear in the males from the same selection pool.

1.2.2 Simultaneous Neuromuscular and Biomechanical Comparisons of Lower Limb

Non-contact ACL injuries account for the majority of all ACL injuries and frequently it is the side-cut or cross-cut maneuver that is being performed by the athlete when this ligament is damaged.[21,141,160] Analyzing cutting-related maneuvers in the laboratory and comparing various biomechanical and/or neuromuscular features between genders can provide important information related to ACL injury risk factors and the mechanisms associated with this devastating injury. There have been several cutting studies addressing the gender bias of this injury; however, no study to date has done an analysis that has included a simultaneous comparison between genders of hip, knee and ankle joint angles and moments along with the neuromuscular activation patterns of the hamstrings, quadriceps and gastrocnemii muscles during cutting maneuvers. The importance of including the hip and ankle in ACL research is supported by various biomechanical studies, which have been summarized in a comprehensive review article by Hewett et al.[80] Excessive pronation at the ankle has been proposed as a potential risk factor related to the gender disparity in ACL injury rates.[125] Greater external hip flexion moments while landing have also been observed in athletes who have sustained an ACL injury in comparison to uninjured athletes.[81] Including an analysis of the neuromuscular activation patterns not only provides important information on muscle function but also helps with interpreting hip, knee and ankle biomechanics and gender differences for the athletic maneuvers.

1.2.3 Gastrocnemii Role in Protecting the Knee

Most cutting studies addressing gender differences in neuromuscular activity have focused on the quadriceps and hamstrings,[127,191] with almost no emphasis on the gastrocnemii muscles. Contraction of the quadriceps at small knee flexion angles can load the ACL through anterior pull of the tibia by the patellar tendon.[9,131] Contraction of the hamstrings, on the other hand, can unload the ACL through the posterior attachment of this muscle group to the tibia.[144,174] Joint stability can also be enhanced by increasing joint stiffness through the contraction of the 3 main muscle groups crossing the knee.[36,193] Contracting the gastrocnemii, however, has also been shown to increase the strain on the

ACL,[58,157] therefore making it important that this muscle group be considered when attempting to identify risk factors associated with ACL injuries.

1.2.4 Medial-Lateral Muscle Site Comparisons for the Three Main Muscle Groups Surrounding the Knee

No cutting-related studies have simultaneously compared muscle activation patterns between genders and between medial-lateral muscle sites of the same muscle group. Zhang and Wang[229] were able to show that selective recruitment of medial and lateral muscle sites could control net abduction and adduction moments. Medial and lateral muscle imbalances for the quadriceps, hamstrings and/or gastrocnemii while performing cutting maneuvers may place the knee at greater risk of ACL injury and this supports the need to compare medial and lateral muscle sites with respect to enhancing dynamic joint stability and preventing injury.

1.2.5 Unanticipated Running and Cutting Maneuvers

Unanticipated maneuvers using light guiding systems in the laboratory are thought to more closely replicate a true game-like scenario where the ACL can be injured. It has been shown that unanticipated maneuvers generate greater loads at the knee and higher muscle activation magnitudes compared to preplanned maneuvers.[16,17] Only two laboratory studies have compared male and female athletes during unanticipated cutting maneuvers, with one study focusing on knee and ankle kinematics during an unanticipated side-cut[60] and the other study focusing on hip and knee joint kinematics and kinetics.[167] No study to our knowledge has compared muscle activation patterns between male and female athletes for unanticipated cutting maneuvers.

1.2.6 Summary of Rationale

It is apparent, based on the 5 points discussed above, that there is a need for a study that focuses on the biomechanics and neuromuscular response patterns of elite adolescent male and female athletes during unanticipated running and cutting maneuvers. It would be beneficial to the understanding of non-contact ACL injuries if the biomechanics of the hip, knee and ankle were simultaneously compared between genders, along with also comparing the neuromuscular response patterns of the quadriceps, hamstrings and gastrocnemii between genders and between medial-lateral muscle sites.

1.3 Purpose

The purpose of this study was to perform a comprehensive biomechanical and neuromuscular analysis of male and female elite adolescent soccer players as they completed an unanticipated straight run, running cross-cut and running side-cut in the motion laboratory. The purpose was to also i) identify differences between genders for three dimensional joint angles and moments at the hip, knee and ankle, ii) identify differences between genders and/or medial lateral muscle sites for the EMG activation patterns of the quadriceps, hamstrings and gastrocnemii muscle groups and iii) to use these differences to help propose, understand and describe non-contact ACL injury risk factors and the gender bias associated with this injury. A further goal for this study was to measure and compare the isometric strength for knee flexion, knee extension and ankle plantar-flexion between the male and female athletes.

1.4 Objectives

The objectives of this study were:

1) To have elite adolescent soccer players perform running and cutting maneuvers in an unanticipated manner by developing and using a light guiding system in the laboratory for the purpose of simulating a scenario that more closely resembles a true game-like situation where the ACL is most likely to be injured by a non-contact injury mechanism.

2) To determine if biomechanical differences in joint angles and moments of force at the hip, knee and ankle exist between male and female elite adolescent soccer players during the stance phase of unanticipated running and cutting maneuvers.

3) To determine if differences in the neuromuscular response of the quadriceps, hamstrings and gastrocnemii exist between genders and between the medial-lateral muscle sites for each of the 3 muscle groups during the entire stance phase, early stance phase and pre-contact phase of the unanticipated maneuvers.

4) To determine if strength differences exist between the male and female soccer players during isometric knee extension, knee flexion and ankle plantar-flexion exercises and to also determine if gender differences exist in the ratio of these strength measures.

5) To use the biomechanical and neuromuscular differences during the athletic maneuvers for providing insight into i) non-contact ACL injury risk factors and ii) why females have a greater non-contact ACL injury rate compared to males.

1.5 Hypotheses

The hypotheses for this study were:

1) Biomechanical and neuromuscular differences exist between male and female elite adolescent soccer players throughout the stance phase of unanticipated running and cutting maneuvers.

2) Neuromuscular differences exist between genders and between medial-lateral muscle sites during the pre-contact and early stance phases of unanticipated running and cutting maneuvers.

3) Males will generate greater knee flexion, knee extension and ankle plantar-flexion torques than females and the ratio of knee flexion torques to knee extension torques will be greater in males compared to females.

4) Biomechanical differences between genders and neuromuscular differences between both genders and/or medial-lateral muscle sites will contribute to the current understanding of the gender bias associated with non-contact ACL injuries.

1.6 Structure of Thesis

Chapter 1 provides a brief overview on non-contact ACL injuries and the gender bias associated with the injury. Injury mechanisms and risk factors are introduced with an emphasis on risk factors related to the biomechanics and neuromuscular response of the lower limb during cutting-related maneuvers. The importance of analyzing unanticipated maneuvers is emphasized in the statement of the problem and rationale for the study. The purpose, objectives and hypotheses of the thesis are also clearly stated in this chapter.

Chapter 2 includes a comprehensive literature review on the anatomy of the knee and ACL, the functional role of the ACL and the injury mechanisms, gender bias and risk factors associated with this injury. Cutting-related studies are specifically addressed, with an emphasis on the biomechanical and neuromuscular response of the lower limb while performing these maneuvers. Gender related features of cutting maneuvers and a comparison of unanticipated and preplanned cutting maneuvers are also discussed. The chapter concludes with a review of principal component analysis (PCA) and a summary of the application of this analysis technique to various biomechanical and EMG waveforms.

Chapter 3 provides a detailed description of the methodology and analysis techniques used in this study. The subjects and recruitment of subjects are discussed as well as the motion analysis and EMG setup of the subjects for the testing procedures. The instrumentation and data acquisition equipment used in the study are described in addition to the running and cutting testing protocols and normalization procedures. Also presented in this chapter is a description of the how PCA was applied to all the joint angle, joint moment and EMG waveforms.

Chapters 4, 5 and 6 include the 3 manuscripts that have been written and submitted to 2 different journals. These 3 manuscripts discuss all the results of the thesis, along with detailed discussions of the findings in context with the literature on non-contact ACL injuries and cutting-related maneuvers. The Chapter 4 manuscript entitled "Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver" was accepted for publication in the *American Journal of Sports Medicine* on January 22, 2007. This manuscript was also presented at the 2006 Canadian Society of Biomechanics Conference (Waterloo, ON, Canada) and received first prize in the open category for the NDI New Investigator Award. Chapter 5 includes the second manuscript of the thesis that addresses the biomechanics and neuromuscular response of the lower limb during an unanticipated straight run and cross-cut maneuver. This manuscript was submitted to the

American Journal of Sports Medicine in January of 2007 under the title "Unanticipated running and cross-cutting maneuvers demonstrate neuromuscular and lower limb biomechanical differences between elite adolescent male and female soccer players." The final manuscript in Chapter 6 addresses the neuromuscular response of the lower limb during the pre-contact phase and early stance phase of the same 3 running and cutting maneuvers. This manuscript, entitled "Male and female adolescent soccer players demonstrate different neuromuscular patterns during the pre-contact and early stance phase of running and cutting maneuvers", was submitted to the *Journal of Electromyography and Kinesiology* in January of 2007. The 5 authors in these 3 manuscripts were involved in various stages throughout the course of this study; however, I was the primary investigator and was responsible for formulating the hypotheses, data analysis, writing and submission of all 3 manuscripts.

Chapter 7 concludes the thesis by first summarizing the findings of the study and then discussing the limitations and implications this work has on non-contact ACL injuries. Future recommendations are also made in this chapter.

Chapter 2 - Literature Review

2.1 General Anatomy of the Knee

It is imperative to have an understanding of the general anatomy of the knee and the stabilizing nature of this joint before the role of the ACL and the mechanism of injuring this ligament can be sufficiently understood. Unlike the hip joint that attains most of its stability from the relatively congruent fit of the pelvis's acetabulum with the head of the femur, the knee joint relies more on the surrounding structures of the knee for stability. The fit between the tibia and femur provides very little of the structural stability required to protect and avoid joint injury. The supporting structures of the knee include both passive and dynamic stabilizers, with the passive stabilizers being the ligaments, menisci and joint capsule and the active stabilizers being the muscles surrounding the knee joint. Instabilities, joint damage and abnormal movement patterns can result when an injury occurs to any one of these stabilizing structures. Also of importance towards adequate knee joint stability, is the ability of the neuromuscular control system to properly direct the timing in which the muscles contract and co-contract around the knee joint.

The two menisci at each knee joint absorb the impact from the external compressive loads, maintain the joint space between the tibia and femur and also increase the concavity of the tibial plateaus, thereby not only enhancing the congruency and stability of the joint but also decreasing the stresses on the articulating surfaces (Figure 2.1). Also enhancing joint stability is the passive joint capsule that wraps around the knee joint and attaches to the surrounding bones. Merging with the capsule are expansions from the vastus medialis, vastus lateralis and iliotibial band that also extend to the tibial plateaus and collateral ligaments of the knee. There are four main ligaments that provide passive joint stability and help guide the movement of the joint and they include the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL) and lateral collateral ligament (Figure 2.2). Acute or chronic instabilities often arise when one or more of these passive structures are damaged from a contact or non-contact injury mechanism.

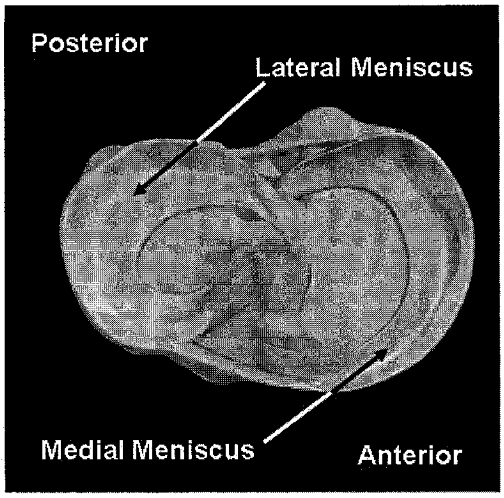

Figure 2.1. Superior view of right knee showing the lateral and medial menisci (Interactive Knee 1.1 © 2000 Primal Pictures Ltd.).

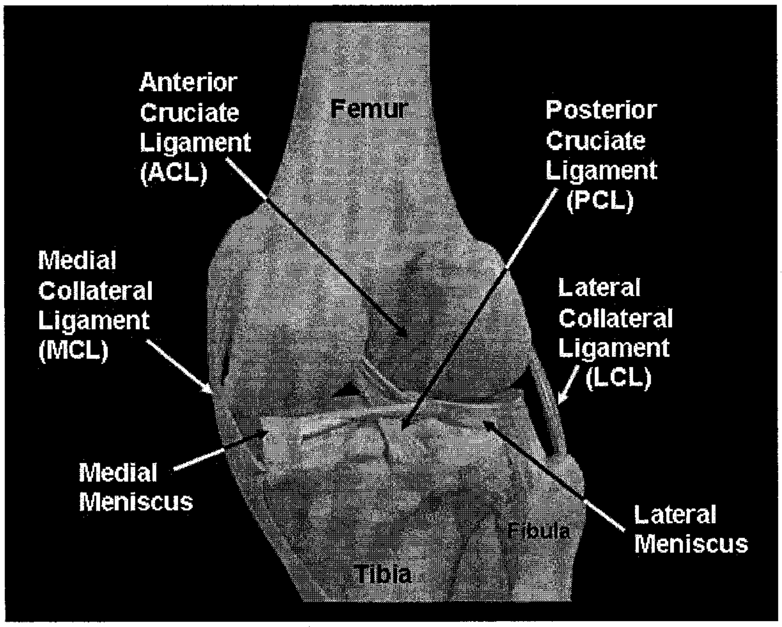

Figure 2.2. Posterior view of right knee showing the two menisci, four main ligaments and bones comprising the knee joint (Interactive Knee 1.1 © 2000 Primal Pictures Ltd.).

The main dynamic stabilizers of the knee include the quadriceps, hamstrings and gastrocnemii (Figure 2.3) and contracting these muscle groups can increase joint stiffness[132] and enhance joint stability. With respect to the musculature surrounding the knee, both preparatory and reflexive neuromuscular control is required to properly coordinate the muscles for dynamic joint stability.[202] The loads experienced at the knee during athletic activities are greater than the loads that the passive structures can withstand; therefore it is important that the muscles be properly controlled by the neuromuscular control system in order to increase joint stiffness and avoid ligament damage.[190]

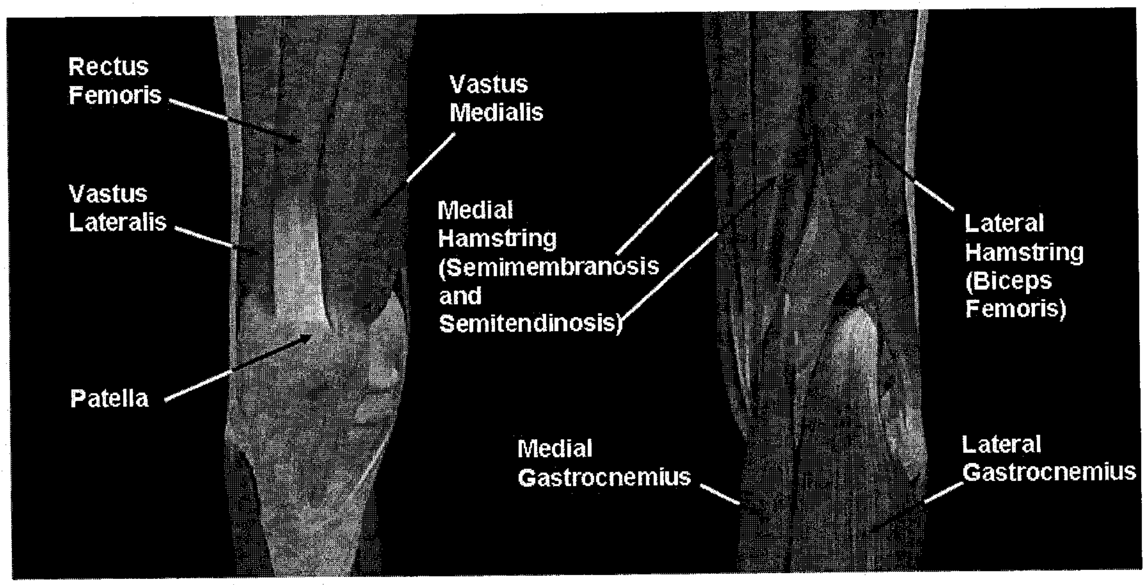

Figure 2.3. Main muscles surrounding the knee joint
Anterior view of knee located on left side and posterior view of knee located on right side (Interactive Knee 1.1 © 2000 Primal Pictures Ltd.).

2.2 ACL Anatomy

The ACL is a band-like structure of dense connective tissue located centrally within the knee and the reason for the name "cruciate" is because it forms an "X" with the posterior cruciate ligament, the other centrally located knee ligament. Although the ACL is completely intra-articular, it has its own synovial envelope that allows the ligament to be extrasynovial. The length of the ACL varies from 22 to 41 mm (mean, 32 mm) and the width of the ligament ranges from 5 to 12 mm (mean, 10 mm).[51,53,158] The ACL runs from a fossa on the posterior aspect of the medial surface of the lateral femoral condyle to a broader fossa on the tibia that is located slightly anterior and lateral to the medial tibial spine.

The orientation of the ACL and PCL as they cross within the knee joint is critical for properly constraining joint motion and providing adequate stability. The ACL, as it passes from the femur to the tibia, follows an anterior, medially and distal path. It crosses obliquely at a 25° angle from lateral to medial and its sagittal angle within the knee is approximately 45° when the knee is fully extended.[10] The orientation of the bony attachments also causes the ACL to rotate on itself in a slightly outward lateral spiral. Fibers that originate superiorly on the femur insert anteriorly on the tibia and the inferior fibers on the femur insert posteriorly on the tibia (Figure 2.4).[156]

The fascicles that make up the ACL can be separated into two groups or bands, with each band having a different function throughout the range of flexion/extension (Figure 2.4). The anteromedial (AM) band inserts on the anteromedial aspect of the tibia and transverses up to the proximal aspect of the femoral attachment site when standing in full flexion. The posterolateral (PL) band, the largest portion of the ACL, inserts on the posterolateral aspect of the tibia and inserts on the distal portion of the femoral attachment site.[10,53,196] During knee extension, the fibers of the PL band have been shown to be taut and during knee flexion, the PL band tends to be more relaxed. In contrast, the AM band is most taut during knee flexion and is moderately relaxed when the knee is fully extended and not flexing.[10,53,156] Some authors have actually suggested that the ACL is made up of 3 bands[4,84] but the 2 band model is the most commonly accepted model for understanding ACL function.[51] The AM and PL bands move relative to each other as the knee is flexed and extended and this is a result of the orientation of the bony attachments of the 2 bands. During knee flexion, the ACL rotates slightly laterally as a whole around its longitudinal axis and the AM band starts to spiral around the remainder of the ligament.[51]

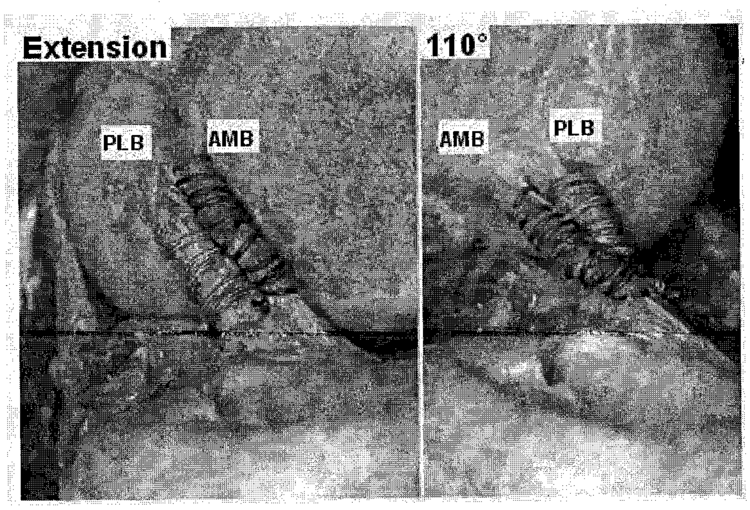

Figure 2.4. The AM and PL band of the ACL during knee flexion and extension
Medial view of left knee with knee extension shown on the left and 110° of knee flexion shown on right.[51]

In addition to the mechanical role that the ACL has at the knee, studies have also suggested that the ACL has a sensory role that helps control joint position, muscle tension and joint stiffness.[11,83,101] Mechanoreceptors have been identified throughout the ACL[109,183] and these receptor cells function as transducers by converting mechanical energy of physical deformation into electrical energy of a nerve action potential. Fast adapting mechanoreceptors are able to track acceleration at the initiation and termination of movement whereas slow adapting mechanoreceptors are capable of monitoring steady state information such as joint motion, position and angle of rotation.[11,83,184] The ACL mechanoreceptors are thought to be able to sense the limits of knee motion and as these limits are approached, the stretched receptor cells fire to initiate signals that can either inhibit agonist muscles such as the quadriceps and/or stimulate antagonist muscles such as the hamstrings.[199,209] It has also been noted that the receptors in the ACL can modify joint stiffness by influencing muscle tension[101] and that a person with an ACL injury has a diminished ability to detect joint motion.[61]

2.3 Functional Role of the ACL

The ACL has both primary and secondary functional roles for stabilizing and guiding the overall motion of the knee during dynamic tasks. Numerous biomechanical studies have been conducted on humans in vivo, on human cadavers and on animals to quantifiably determine both the loads experienced by the ACL throughout the knee's range of motion and the degree of stability the ACL is responsible for within the knee.

The main function of the ACL is as a primary restraint for limiting anterior displacement of the tibia with respect to the femur.[26,62,66,151,180,189] The ACL also functions as a secondary restraint to tibial internal rotation, helps prevent hyperextension and has a small role in resisting varus-valgus stresses. The ACL acts as a major secondary restraint to internal rotation, a minor secondary restraint to external rotation and its contribution in restraining these rotations about the longitudinal axis of the tibia is greater in full extension than in 20-30° of flexion.[62,98,130,151] The strength of the ACL has been assessed using cadavers and for cadavers between the ages of 22 and 35 years, the mean load that the ACL is capable of withstanding before failure is 2160 N.[221] It has also been reported that the failure load of the ACL decreases with the age of the cadaver[152] and in comparing male and female cadavers under the age of 50 years, the male ACL has a failure load that is almost 30% greater than the female ACL.[31]

In addition to the stresses that can be generated in the ACL due to external loads applied to the tibia, contraction of the quadriceps, hamstrings and gastrocnemii can also alter ACL strain. Hall effect transducers and other strain and load measuring devices have been used with the ACL in cadavers and in living humans to determine how contractions of the muscles surrounding the knee alters strains and forces in the ACL.[9,58,131,133,144,174]

Arms et al.[9] used a Hall effect transducer on the ACL to show that forces generated by the quadriceps did not strain the ACL when the knee was flexed beyond 60°, however, the ACL was significantly strained from 0-45° of knee flexion. Markolf et al.[131] measured forces in the ACL using a load-cell/bone-plug construct and a 200 N force on the quadriceps tendon increased the ACL strain at all angles of knee flexion. This strain was a result of the anteriorly directed component of the forces in the patellar tendon, pulling the tibia anterior relative to the femur. Renstrom et al.[174] also used Hall effect transducers on cadaver ACLs and simulated hamstring contraction alone, quadriceps contraction alone and simultaneous contraction of these 2 muscle groups together. The authors showed that a quadriceps force alone, between 0-45° of flexion, increased ACL strain and forces generated by the quadriceps and hamstrings simultaneously increased ACL strain from 0-30°of flexion. They also concluded that the hamstrings were not able to resist the potentially harmful effects of simultaneous quadriceps contractions unless knee flexion angles were greater than 30°. Markolf et al.[133] reported similar results for the quadriceps and hamstrings and one of their more important findings was the ability of the hamstrings to almost entirely eliminate the ACL force produced by an applied 100 N anterior tibial force beyond approximately 60° of flexion. In one of the only studies addressing the role of the gastrocnemii on ACL strain, Fleming et al.[58] applied a differential variable reluctance transducer to the ACL in-vivo and stimulated the gastrocnemii, hamstrings and quadriceps in 6 subjects using a transcutaneous electrical muscle stimulation device. Stimulating the gastrocnemii alone at flexion angles of 5° and 15° increased ACL strain and co-stimulating the gastrocnemii and hamstrings together at 15° and 30° of knee flexion produced ACL strains that were higher than the strains produced by stimulating the hamstrings alone. All these studies clearly indicate that strain in the ACL can be induced from both externally applied loads and from loads induced by the contraction or co-contraction of the major muscle groups surrounding the knee.

2.4 ACL Injuries: Injury Mechanisms, Gender Bias and Risk Factors

There has been a vast amount of information published in the literature on the ACL but many unanswered questions still remain with respect to the non-contact injury mechanisms, the etiology and the gender bias associated with this integral knee ligament. Since the inception of Title IX of the United States Educational Assistance Act in 1972, female sports participation at the college level has increased over 500%[23] and this increased participation over the past 30 years, coupled with a 2-8 times greater ACL injury rate in females compared to males,[1,8,128] has resulted in a substantial rise in female ACL injuries. In addition to the gender bias for ACL injury rate, females also demonstrate a greater incidence of patellofemoral pain syndrome and iliotibial band friction syndrome compared to males.[205]

ACL injuries have significant implications to both the healthcare system and to the individuals who sustain these injuries. Understanding the injury mechanisms, the risk factors involved and the gender disparity of the injury can all help with the prevention and reduction of this devastating injury. The trauma and instability that results from an ACL injury most often requires an invasive and expensive surgical procedure to replace the damaged ligament and whether the surgery is performed or not, accelerated osteoarthritic changes generally occur to the inflicted knee.[124,147,213] The ACL is the most commonly injured knee ligament during sporting activities[102,175] and of the individuals who experience an acute knee hemarthrosis (accumulation of blood in the joint), a complete or partial ACL tear will be present in 70-80% of the knees.[102]

Understanding the actual injury mechanisms of non-contact ACL injuries is essential if ACL injuries are to be reduced or prevented. McNair et al.[141] reported on 23 individuals who previously sustained an ACL injury and found that 70% of the injuries were non-contact in nature with most subjects injuring their ACL at foot strike when the knee was close to full extension and the tibia internally rotated. Studies by Ebstrup et al.,[52] Boden et al.,[21] Olsen et al.[160] and Ireland[99] all described and explored non-contact

ACL injury mechanisms based on information they accumulated by analyzing video footage of athletes actually tearing their ACL during different athletic activities. Similar to the results of McNair et al.,[141] Boden et al.[21] reported from video footage that approximately 70% of the ACL injuries were a result of a non-contact injury mechanism at foot strike with the knee close to full extension during a sharp deceleration prior to a change of direction or landing from a jump. Boden et al.[21] did note, however, that their patients had a slightly higher incidence of external rotation of the tibia at the time of the injury in comparison to the findings by McNair et al.[141] Olsen et al.[160] analyzed videotapes of female ACL injuries during European handball and concluded that there were 2 main mechanisms of injury. The most common mechanisms of injury were a plant and cutting maneuver and a 1 legged jump shot landing with the knee going forcefully into valgus with either internal or external tibial rotation near full extension. They also reported that while the injuries were classified as non-contact in nature, there was generally some form of perturbation (often with another player) that altered the player's coordination or movement. Ebstrup et al.[52] concluded from their video analysis that cutting maneuvers where the tibia was internally rotated and the knee was loaded in valgus predisposed individuals to ACL ruptures. Ireland[99] stated that a common injury mechanism in basketball players involved the athlete coming down in an uncontrolled landing while trying to catch a ball or attempting to not go out at the baseline. When the ACL actually tears during the non-contact maneuver, a whip-like snap of the lower extremity is seen and the athlete often reports hearing a "popping" sensation within the knee. A large amount of swelling immediately follows and the athlete is almost always unable to continue playing. While a great amount of valuable information has been gained from analyzing video footage of ACL injuries, there are still many questions that remain unanswered related to non-contact ACL injury mechanisms and the gender bias associated with this devastating injury.

The greater ACL injury rates observed in females over males has researchers trying to identify ACL injury risk factors to improve on the current understanding of the non-contact injury mechanism and to help with the prevention and reduction of this devastating injury, particularly in females.[72,80,210,225] Risk factors have been studied and identified primarily by comparing various features of asymptomatic and ACL injured subject groups and/or by also comparing features between male and female subject groups. ACL injury risk factors are generally classified as either intrinsic or extrinsic risk factors within the literature.[74,164] Intrinsic risk factors tend to be more sex-specific and are generally considered uncontrollable. These factors include measures such as lower limb alignment, intercondylar notch width, quadriceps femoris angle (Q angle), joint laxity, navicular drop or subtalar joint pronation and size of the ACL. Extrinsic risk factors have been described as being more controllable and these factors include muscle strength, conditioning, shoe-surface interaction, playing surface, motivation, neuromuscular control strategies, acquired skills and coordination. Despite there being some minor discrepancies between studies in the overall classification scheme of the various risk factors, overview articles by Dugan,[50] Harmon and Ireland,[74] Yu et al.,[225] Hewett et al.,[80] Hughes and Watkins,[94] Huston et al.[95] and Ireland.[99] have done a superb job of compiling and summarizing the numerous ACL injury risk factors. Some of these overview articles have classified ACL injury risk factors as anatomic, hormonal, environmental and biomechanical[72,225] in order to avoid the confusion that can arise in determining whether a risk factor is intrinsic or extrinsic. While it is beyond the scope of this literature review to describe in detail all the risk factors that have been identified in the literature, it is worth highlighting some of the main anatomic, hormonal and environmental risk factors that have been investigated with respect to ACL injuries. Because the focus of this thesis will be on the biomechanical and neuromuscular risk factors associated with running and cutting-related maneuvers, these risk factors will not be reviewed until later in the chapter when cutting maneuvers are reviewed (Section 2.5).

Anatomical differences between males and females have been identified for lower limb alignment, joint laxity, ACL size, intercondylar notch width and muscle strength; however, not all of these differences necessarily pose as ACL injury risk factors. Females have on average a larger Q angle (angle formed between a line drawn from the anterior superior iliac spine (ASIS) to the center of the patella and a line drawn through the center of the patella and tibial tuberosity) than males[85,207] but it does not appear that this measure is predictive of an ACL injury during dynamic movements.[70] Intercondylar notch width has also been described as having a possible influence on ACL injuries. The ACL is positioned within this notch and it has been proposed that a small notch width may indicate a smaller and weaker ACL and may also lead to impingement of the ACL during rotational stresses.[74] Females have a narrower notch width than males[187] and ACL injuries have also been shown to be associated with a narrower notch width.[67,115,126,187,208,210] Some studies have compared notch width index (intercondylar notch width normalized to femoral condyle width) instead of notch width and often in these studies the notch width index does not capture gender differences or describe ACL injury rates.[5,115,206] Differences in the results between notch width studies have been attributed to variability in the measurement techniques (i.e. radiographs, MRI, calipers in cadavers) and with these different results it still remains unclear as to the role that the intercondylar notch size has with increased ACL injury rates.

Hyper-pronation of the foot and ankle complex has also been proposed as an ACL risk factor[13,125] and the navicular drop test provides a measure of this pronation. Pronation of the foot has been shown to be coupled with internal rotation of the tibia,[135,150] which is a motion that the ACL has a primary role in controlling.[62,130] Studies have shown that ACL injured subjects have greater navicular drop test scores, suggesting that hyper-pronation of the foot and ankle complex may be an ACL injury risk factor.[3,13,222] Although Allen and Glasoe[3] identified greater hyper-pronation in ACL injured subjects, they did not capture differences between genders.

There have been a number of studies identifying ligamentous or joint laxity to be greater in females compared to males,[44,97,149,176] but whether this laxity contributes to knee joint injuries is less evident and varies throughout the literature. Analyzing football players, Nicholas[149] found that loose jointed individuals suffer more knee injuries and these results have been supported by additional studies stating that joint laxity can predispose athletes to knee injuries.[70,197,210] In contrast to these finding, other studies measuring laxity have been unable to find a correlation between joint laxity and knee injury rates,[69,75,105] thus making the relationship of joint laxity to ACL injury uncertain.

Hormones associated with the female's menstrual cycle, such as estrogen and progesterone, have also been investigated to determine if these hormones have an effect on the properties of the ACL, athletic performance and ACL injury rates. Estrogen and progesterone receptors are present on the ACL[123] and it was demonstrated using rabbits that the administration of estrogen can significantly decrease the tensile properties or failure load of the ACL.[194] Several studies have also tried to find an association between hormone fluctuations during the menstrual cycle to ACL injury and determine if there is a specific phase where females are more susceptible to injury.[143,146,219] Findings across these studies are not consistent and it has been suggested in the literature that a more global definition of the menstrual cycle phases is required and that many of the studies need increased sample sizes before definite conclusions can be made.[80,225] Moller-Nielsen and Hammer[143] studied 86 female soccer players and noted that females taking oral contraceptives had a significantly lower injury rate. Hormone dependent changes throughout the menstrual cycle can alter physical performance and it has been shown specifically that fluctuations in estrogen concentrations can affect muscle function, neuromuscular control of the joints and the central nervous system.[118,168,182] Sarwar et al.[182] also suggested that taking oral contraceptives may control the large fluctuations of hormones, thereby limiting the effect hormones can have on neuromuscular control and joint stability.

Muscle strength imbalances and neuromuscular control strategies can affect knee joint stability and capturing gender differences related to these measures can help with the identification of non-contact ACL injury risk factors. It has been reported that women have significantly less hamstring and quadriceps strength than males, even when normalized to body weight.[71,97,107,120,142] Females appear to be more ligament-dominant and men more muscle-dominant when it comes to knee joint stability.[27] Females also rely more on the function of their quadriceps and gastrocnemii and less on their hamstrings during athletic activities.[82,97] Huston and Wojtys[97] used an unanticipated anteriorly directed force applied to the posterior aspect of the lower leg to demonstrate that muscle recruitment differed between genders. Females generally activated their quadriceps first in response to the force whereas males tended to activate their hamstrings first. The quadriceps dominant pattern in females suggests that if the quadriceps contract without the hamstrings contracting, the tibia may translate anteriorly and place the ACL under greater strain.[122] A study by Ahmad et al.[2] compared muscle strength of adolescent boys and girls as they aged and found that boys had a greater increase in hamstring strength with maturity (179%) in comparison to girls as they matured (27%). It was also concluded that female athletes after menarche increased their quadriceps strength at a greater magnitude than their hamstrings strength, thereby possibly placing the ACL at greater risk of being injured. Co-contraction of the muscle groups surrounding the knee is important for joint stability during athletic maneuvers and weak or under recruited hamstrings can limit the ability for muscular co-contraction to protect the knee ligaments, particularly the ACL.[199] Females have a smaller hamstring to quadriceps strength ratio compared to males,[82] however, it has been recommended that further prospective studies are required before determining if increased hamstring to quadriceps ratios can decrease the risk of knee ligament injury.[55]

Environmental factors including playing surface, weather conditions and shoe-surface interaction also contribute to non-contact ACL injuries and while these factors are not necessarily related to gender, many of these factors are of particular interest because they can potentially be modified or altered in an attempt to reduce injury rates. Although the interaction between playing surface and shoe type is difficult to quantify, Lamson et al.[111] showed that shoes with a greater number of cleats and greater torsional resistance are associated with an increase in the number of ACL injuries in American football. Powell and Schootman[170] compared surfaces in the National Football League (NFL) and demonstrated that overall differences in ACL injury rates were not evident between playing on artificial turf or natural grass. Two prospective studies looking at soccer[54] and team handball[146] also did not find a relationship between floor type and ACL injury rate, however, a study by Olsen et al.[161] concluded that the risk of ACL injury in women was higher on artificial floors compared to wooden floors and it was speculated that greater friction was the reason for this difference. Weather conditions also play a role in injury rates and a study on the professional Australian Football League reported that ACL injuries are more common under conditions that make the grass playing surface drier, such as low rainfall, high temperatures and high water evaporation.[162-164] Cold weather has also been associated with lower ACL injury rates and it is believed that the colder weather affects the shoe-surface interface.[165]

Based on this brief overview of risk factors and mechanisms of non-contact ACL injuries, it is clear that while a great amount of knowledge has been accumulated in the area of ACL injuries, there are still many unknowns related to this injury and many conflicting views on which risk factors have the greatest influence on this injury.

Analyzing cutting maneuvers and other maneuvers in which the ACL is most likely to be injured from a non-contact mechanism is important and attempting to identify risk factors that might be modifiable through training programs is an exciting area of research that could potentially help reduce the incidence of this injury in the future.

2.5 Cutting Maneuver Literature

2.5.1 Overview of Cutting Maneuvers

Side-cutting and cross-cutting maneuvers are used to change direction in multidirectional sports such as basketball, soccer, handball and rugby. A cutting maneuver can entail a directional change from only a few degrees to more than 90° and the method in which the cut is performed can vary significantly between individuals and sport.[6] The quick directional change associated with cutting or pivoting has been recognized as a common injury mechanism related to non-contact ACL ruptures, particularly in females. Between 70-80% of all ACL injuries are non-contact in nature and occur while landing from a jump or while carrying out a side-cut or cross-cut maneuver.[21,153] With the emergence of these non-contact ACL injuries, numerous in-depth analyses have been performed in the past 10 years attempting to identify biomechanical and/or neuromuscular risk factors associated with non-contact ACL injuries and cutting-related maneuvers.[18,39,60,87,89,127,137,139,167,191]

The side-cut maneuver is an athletic task where the individual runs and plants one foot, pivots on that leg and then moves in a direction opposite to the planted foot. The cross-cut maneuver involves planting one foot and pivoting on that leg so that the opposite leg moves across the body, allowing the individual to move in the same direction as the planted foot. Andrews et al.[6] was the first to provide a detailed description of cutting and in doing so, divided the cutting maneuver into 3 phases: i) preliminary deceleration, ii) plant and cut and iii) takeoff. In the deceleration phase, the player running at top speed must decrease his/her momentum before making the cut. The quadriceps, hamstrings and gastrocnemii all have important roles in providing the muscular power required for deceleration. The plant and cut phase is where the change in momentum occurs and it is the hip rotators that turn the torso toward the intended direction of travel. As the planted leg is providing the last bit of deceleration, the free leg provides a degree of acceleration as it swings in the new direction. In the side-cut maneuver, the torso and pelvis are rotated internally on the femur to allow the player to change directions. For the cross-cut maneuver, however, the torso and pelvis are rotated externally on the femur to make the directional change. Push off for both maneuvers involves the planted foot accelerating in the new direction and this is accomplished by having the hip and knee extending and the ankle undergoing complete plantar flexion. The final takeoff phase requires that the player leans forward more than usual so that acceleration in the new direction can take place.[6]

The 1990s saw a shift in focus from the diagnosis and treatment of ACL injuries to identifying mechanisms and risk factors for non-contact injuries.[72] Analyzing cutting maneuvers in the laboratory offers the unique opportunity of identifying potentially modifiable biomechanical and neuromuscular features related to ACL injuries. Focusing specifically on side-cutting and cross-cutting, the following sections address: i) knee biomechanics of the side-cut, ii) knee biomechanics of the cross-cut, iii) ankle and hip biomechanics of cutting maneuvers, iv) EMG analysis of cutting maneuvers, v) female specific and gender related features of cutting maneuvers, vi) unanticipated versus preplanned cutting maneuvers and vii) ACL deficiency, ACL reconstruction and bracing related to cutting.

2.5.2 Knee Biomechanics of the Side-cut Maneuver

The deceleration required to change directions in the side-cut maneuver generates larger knee external flexion moments compared to a straight run.[18] Besier et al.[18] found that the greatest flexion moments occurred at peak push off and that the magnitudes for these moments averaged approximately 2.0 Nm/kg. Simonsen et al.[192] used a knee model to predict peak forces in the ACL during a side-cut and concluded that during the braking phase of the maneuver, the peak knee flexion moment was 3.0 Nm/kg and the predicted ACL load was 520 N. Related to these findings and a simulation study by McLean et al.,[137] it has been suggested that the side-cut maneuver is not capable of rupturing the ACL based on sagittal plane biomechanics alone.

The adduction-abduction and internal-external rotation moments at the knee are greater during a side-cut compared to a straight run,[18] however, it is the hip that experiences the majority of the non-sagittal moments during the side-cut.[41] Besier et al.[18] showed that a 60° side-cut maneuver can generate 2-6 times the knee adduction-abduction moment during early stance compared to the adduction moment generated while running. In this study, adduction-abduction moments had large standard deviations at peak push off and the authors attributed this to 6 subjects exhibiting an abduction moment and 5 subjects exhibiting an adduction moment at peak push off. Pollard et al.[167] had male and female soccer players undergo an unanticipated 45° side-cut and they measured peak knee abduction moments of approximately 0.34 Nm/kg and peak internal rotation moments of approximately 0.11 Nm/kg. Besier et al.[18] also measured internal rotation knee moments during the side-cut cut and determined that these moments were larger compared to the straight run. The internal rotation moments during early stance were up to 4 times the magnitude of the external rotation moment while running and the internal rotation moments during peak push off or mid-stance were up to 5 times the moments experienced during straight running.

Three dimensional joint rotational angles of the knee have also been measured during the side-cut cutting maneuver.[18,41,139,140,148] Knee flexion angle patterns during the stance phase of the side-cut are quite consistent between studies and at foot strike or initial contact, knee flexion angles have been reported to range from approximately 20-40°. As the body decelerates and prepares to push-off and change directions, the knee continues to flex and reaches a maximum flexion angle of approximately 35-65°. After peak flexion is reached during mid-stance, the knee starts to extend and as the foot comes off the ground, the knee flexion angles are approximately 15-35°.[18,41,139,140,148] The magnitudes of abduction-adduction and internal-external rotation angles during cutting maneuvers are much smaller than the flexion angles and are inconsistent between studies. The large variability associated with these small frontal and transverse plane angles are likely the result of kinematic crosstalk errors[166,171] or differences in the cutting styles between subjects and studies. In summary, the greatest external moments and angles experienced at the knee during the side-cut maneuver occur in the sagittal plane, with net external moments in all 3 planes being greater than the corresponding moments generated during a straight run.

2.5.3 Knee Biomechanics of the Cross-cut Maneuver

The cross-cut maneuver is a less extensively studied maneuver compared to the side-cut and non-contact ACL injuries have been reported to be less frequent during the cross-cut compared to the side-cut.[38] Besier et al.[18] found external knee flexion moments during a 30° cross-cut to be of comparable magnitudes to flexion moments experienced while running straight. Houck and Yack[88] had subjects undergo a modified 45° cross-cut after stepping off a platform and reported peak knee flexor moments of approximately 1.66 Nm/kg at 20% into stance. Nyland et al.[155] also measured comparable peak knee flexor moments (1.96 Nm/kg) in a group of un-fatigued recreational female athletes during a 90° cross-cut maneuver.

Frontal and transverse plane knee moments and knee flexion angles during the cross-cut have also been reported by Besier et al.,[18] Nyland et al.[155] and Houck and Yack.[88] Besier et al. showed that cross-cutting generated adduction moments that were more than twice the magnitude of straight running throughout stance, with peak adduction moments being approximately 1.2 Nm/kg at peak push off. Nyland et al.[155] and Houck and Yack[88] reported peak adduction moments of 1.22 Nm/kg in un-fatigued females and 1.01 Nm/kg in healthy controls during the cross-cut, respectively. Related to transverse knee moments, it has been reported that the cross-cut generates large external rotation moments compared to the straight run. Nyland et al.[155] measured peak transverse plane moments of 2.3 Nm/kg whereas Besier and his colleagues reported significantly smaller peak transverse plane moments of approximately 0.35 Nm/kg. The discrepancy between these studies may be a result of the different cutting protocols and the different cutting angles, with subjects stepping and cross-cutting at 45° in Houck and Yack's study and subjects having to run and cross-cut at approximately 90° in Nyland et al.'s study.

Knee flexion angles for the cross-cut are comparable to the angles experienced during the side-cut maneuver.[18] Knee flexion angles at foot strike or initial contact range between approximately 20-30° during the cross-cut[18,39,155] and it has been shown that the risk of ACL injury is highest when small flexion angles are combined with large externally applied loads.[130] Peak knee flexion angles of approximately 45-55° have been reported for the cross-cut cut and these peak angles occur during mid-stance.[18,155] Like the side-cut, the knee joint moments and angles for the cross-cut are greatest in the sagittal plane and the knee joint moments in all 3 planes tend to be greater for the cross-cut in comparison to the corresponding moments for the straight ahead tasks.

2.5.4 Ankle and Hip Biomechanics of Cutting Maneuvers

Unlike the knee joint, there are only a few articles in the literature with an emphasis on ACL injuries that focus on hip and ankle biomechanics during cutting-related maneuvers. Nyland and his colleagues addressed knee and ankle dynamics during a 90° cross-cut, with one study comparing neutrally aligned and coxa varus-genu valgus aligned females[154] and the other study looking at the effects of muscle fatigue on joint dynamics.[155] The peak ankle dorsiflexion angle during the stance phase of the cross-cut was approximately 20° in the alignment study. For the alignment and fatigue-related studies,[154,155] the peak external ankle plantar-flexion moment during the absorption phase was approximately 0.30 Nm/kg and the peak external ankle dorsiflexion moment during the pivoting phase was approximately 1.8-2.0 Nm/kg.[154]

Ford et al.[60] analyzed a jump-stop unanticipated side-cut maneuver and reported that maximum ankle eversion angles were approximately 14-20° and maximum ankle inversion angles were approximately 7.5-11° throughout stance. McLean et al.[139] had subjects perform a side-cut maneuver with and without a defender and represented the ankle joint as having 2 degrees of freedom. Peak ankle pronation angles were determined to be on average between 1.5-7°. It is evident from these few studies that more research needs to be performed to better understand how the ankle complex should be modeled biomechanically and to also determine if the ankle complex has a contributing role towards ACL injuries.

The study by McLean et al.[139] also compared peak hip angles between genders for the 45° side-cut. On average, peak hip flexion angles were approximately 43-54° during early stance. As stance progressed, flexion angles continued to decrease until foot off where the hip was at approximately 0° flexion or in slight extension. Similar patterns for hip flexion were also reported by Pollard et al.[167] for a 45° side-cut and by Branch and Hunter[22] for a 90° side-cut. Based on the graphs in the study by Pollard et al.,[167] hip flexion angle at initial contact was approximately 30° and at foot off the hip was extended approximately 10°. The small discrepancies in hip flexion angles across studies can most likely be attributed different subject groups and to slight variations in the cutting protocols (i.e. cutting angle, approach speed, etc).

Like the knee, hip adduction-abduction angle and hip internal-external rotation angle waveforms during cutting maneuvers tend to be more variable across studies.[22,139,167] Internal-external rotation angles are generally less than 15-20° in magnitude. Branch and Hunter[22] reported small hip external rotation angles (<10°) during early stance whereas McLean et al.[139] and Pollard et al.[167] reported small internal rotation angles during early stance (<15°). As stance progressed for all 3 studies, however, the hip tended to move into external rotation at a magnitude of less than 20°. With respect to the hip adduction-abduction angle for the same studies, the hip was generally abducted throughout the majority of stance at an angle less than approximately 30°.

The only ACL related study to focus on hip moments during a cutting maneuver was by Pollard et al.[167] and this is surprising since it has been suggested that the hip likely has a contributing role towards ACL injuries.[78,81,227] Pollard et al.[167] reported that external peak hip adduction moments for males and females were approximately 0.97 Nm/kg and that peak internal rotation moments were approximately 0.48 Nm/kg for an unanticipated side-cut maneuver. It was also apparent from the moment waveform plots that peak moments occurred within the first approximate 20% of stance. This study did not report on hip flexion moments.

It is apparent from this brief literature overview of hip and ankle biomechanics during cutting maneuvers that there is a general lack of information on how the biomechanics of these 2 joints might contribute or help prevent ACL injuries. Simultaneously comparing the hip, knee and ankle along with the neuromuscular response of the lower limb during these athletic maneuvers could provide insight into the mechanisms and risk factors associated with this devastating knee injury.

2.5.5 EMG Analysis of Cutting Maneuvers

Most studies addressing muscle activity during cutting maneuvers have focused on the hamstrings and quadriceps.[14,16,37,39,148,192] These two muscle groups help with knee joint stability and protection of the ACL, especially during athletic tasks that generate large non-sagittal plane loads. As previously mentioned, the hamstrings are important agonists to the ACL in resisting anterior tibial translation[133,144] and contracting the quadriceps can significantly increase ACL loads.[9,174] Proper coordination and co-

contraction of these two muscle groups is critical in protecting the ACL and other ligamentous structures during dynamic tasks. When the neuromuscular system is perturbed, the knee can be placed in an unstable state which can lead to excessive ACL loads and potential ligament rupture.

EMG activity levels of the quadriceps and hamstrings, normalized to maximum voluntary isometric contractions (MVIC), are greater when performing a cutting maneuver in comparison to a straight run and it has been proposed that these higher activity levels are necessary for stabilizing the knee and dealing with the increased external loads and moments.[16] The quadriceps and hamstrings are both activated prior to foot strike and these muscle groups remain active well into the stance phase of the cut.[14,16,39,148,192]

Peak activity levels of the quadriceps occur close to mid-stance when the quadriceps are eccentrically contracting to prevent excessive knee flexion.[37,39,148] Colby et al.[39] noted that activity levels of the quadriceps, normalized to MVIC, can be as high as 200-300%. Peak EMG amplitudes (normalized to MVIC) for the vastus medialis and vastus lateralis during the breaking phase of the side-cut have been reported to be 87% and 101%, respectively, with both these muscles remaining active until about 150 msec before the foot comes off the ground.[192] Neptune et al.[148] also reported that the vastus medialis peaks before the vastus lateralis during the side-cut and concluded that this was related to patellar tracking and stabilization. They also suggested that the rectus femoris muscle is likely acting more as a knee extensor and less as a hip flexor because during peak rectus femoris activity, the hip is just beginning to extend.

Hamstring activity levels for cutting maneuvers are significantly smaller than quadriceps activity levels. Colby et al.[39] reported hamstring activity levels between 50-150% of MVIC and Simonsen et al.[192] noted peak EMG amplitudes for the medial hamstring and lateral hamstring to be 34% and 39% of MVIC, respectively, during a side-cut cutting maneuver. The hamstrings can aid in preventing excessive tibial rotations and translations,[155] act as hip extensors to eccentrically decelerate the center of mass during impact and also provide power and acceleration during the propulsion phase of the cut.[148]

Neptune et al.[148] also reported on muscle activity for the medial gastrocnemius, gluteus maximus and gluteus medius during a side-cut in their study that focused on ankle sprains. The gluteus maximus and medius exhibited a single burst of activity that peaked before mid-stance whereas the single burst of activity for the medial gastrocnemius peaked just before the foot left contact with the ground. Gluteus medius activity and hip joint adduction-abduction were nearly constant during stance, suggesting that this muscle isometrically stabilized the hip rather than providing mechanical power. It was proposed that the gluteus maximus provided impact absorption, hip stabilization and initialization of a stretch-shortening cycle to enhance propulsion. For the medial gastrocnemius, it was also concluded that the late burst of activity provided propulsion before the foot left the ground, thereby transferring knee power to the ankle.

In addressing non-contact ACL injuries, it is important that activation patterns of the muscles surrounding the hip, knee and ankle all be considered when trying to identify ACL risk factors and mechanisms of injury. The quadriceps, hamstrings and gastrocnemii all have a direct influence at the knee, however, muscles controlling the hip also likely contribute to protecting the knee by properly controlling and stabilizing the hip and lower limb.

2.5.6 Female Specific and Gender Related Features of Cutting Maneuvers

The higher prevalence of ACL injuries in females compared to males has lead many investigators to focus specifically on females when analyzing different athletic tasks that place the ACL at risk of being injured. Olsen et al.[160] analyzed 20 videos of females tearing their ACL while playing Norwegian team handball and concluded that the two main scenarios for ACL injury was a plant and cut movement and a one legged landing from a jump shot. Sixty percent of these injuries were a result of the plant and cut and in all cases, the planting foot was positioned lateral to the knee.

A number of studies have compared males and females during running and cutting maneuvers with the purpose of identifying gender-related risk factors that may be predisposing females to higher ACL injury rates.[60,127,139,140,167] Most of these studies have focused on detecting gender differences in joint kinematics while only a select few have addressed gender differences related to joint kinetics or muscle activity patterns.

One of the first cutting studies to focus on gender differences was a study by McLean et al.[140] and they compared knee joint kinematics between 16 male (19.4 ± 2.2 yrs) and 14 female (19.1 ± 1.8 yrs) high performance athletes while performing a side-cut maneuver. Three dimensional knee joint kinematics were recorded for both the left and right legs during a straight run and a side-cut maneuver. The approach speed and cutting angle for each side-cut trial was required to fall between 5.5-7.0 m/s and 35-60°, respectively. No statistically significant differences were found between running and cutting speeds and between left and right legs. The straight run also did not identify gender-related differences in the maximum, minimum and range of motion for all 3 joint angles of the knee. Maximum knee abduction angle during the stance phase of the side-cut was larger for the females compared to the males; however, the authors noted that these differences were not of clinical significance. Females also had higher inter-trial variability for internal-external rotation angles while side-cutting and a strong linear relationship was observed between level of experience in years (including males and females) and inter-trial variability of internal-external rotation. This relationship indicated that variability in knee motion is more likely to be influenced by the degree of exposure to side-cutting rather than influenced by gender.[140]

McLean et al.[139] also introduced a simulated defender during a side-cut maneuver to determine the effects that gender and a defender had on lower limb joint kinematics and ground reaction forces. Hip, knee and ankle kinematics along with ground reaction forces were compared between 8 male (21.4 ± 3.2 yrs) and 8 female (23.2 ± 3.8 yrs) active but noncompetitive athletes during a side-cut maneuver. The cutting maneuvers were performed with and without a simulated defender and the approach speed and cutting angle for all trials were required to fall between 4.5-5.5 m/s and 30-40°, respectively. Comparing females to males, females demonstrated less hip and knee flexion, less hip and knee internal rotation and less hip abduction during the cutting maneuvers. Females also demonstrated larger knee abduction and foot pronation angles along with increased knee abduction and internal rotation variability. The simulated defender resulted in increases in peak medial ground reaction forces, increases in hip flexion and abduction angles and increases in knee flexion and abduction angles. This study demonstrated that the hip and ankle may also have a role in controlling knee abduction during side-cutting and that the introduction of a defender creates an environment in the laboratory that is closer to a real game-like situation.

Malinzak et al.[127] also identified gender differences in knee kinematics and EMG activation patterns for a preplanned straight run, side-cut and cross-cut by comparing 11 male (24.5 ± 2.5 yrs) and 9 female (24.6 ± 1.0 yrs) recreational athletes. Subjects were required to cut at 45° on their dominant leg and the approach speed for both males and females was approximately 5.0 m/s. EMG signals were collected for the lateral hamstring, medial hamstring, vastus lateralis and vastus medialis and all activations were MVIC normalized to exercises performed prior to the cutting maneuvers. A regression analysis model was used to compare knee motion patterns between gender and the variables considered in this model included knee flexion angle, knee adduction-abduction angle, MVIC normalized hamstring activations and MVIC normalized quadriceps activations. Compared to males, females exhibited smaller knee flexion angles, larger knee abduction angles, greater quadriceps activity levels and lower hamstring activity levels during the stance phase of all 3 athletic maneuvers. These gender differences along with other risk factors have been used to help develop neuromuscular and plyometric training programs aimed at reducing the incidence of ACL injuries in athletes.[79,145]

Unanticipated or randomly-cued cutting maneuvers have also been used to identify gender differences in ankle and knee kinematics[60] and hip and knee mechanics.[167] Pollard et al.[167] compared joint angles and moments at the hip and knee between 12 male (19.7 ± 1.5 yrs) and 12 female (19.3 ± 1.1 yrs) collegiate soccer players during an unanticipated 45° side-cut, a straight ahead run and a jump stop. To be consistent with the studies by Malinzak et al.[127] and McLean et al.,[140] the approach speed for these unanticipated maneuvers were required to fall between 5.5-6.5 m/s and the exit speed for the maneuvers were required to fall between 4.5-5.5 m/s. A target board with 3 different colored lights, located 1.5 m in front of the force platform, cued the participants to perform the appropriate maneuvers in a random fashion.

ACL injuries occur predominantly in the early stance phase of a landing or cutting maneuver.[21,160] It has also been shown that the ACL experiences its greatest strain at small flexion angles.[9,130,174] Based on this, Pollard and her colleagues[167] only compared the kinematics and kinetics during the first 40° of knee flexion for the stance phase of the unanticipated maneuvers. The only angle or moment difference captured at the knee or hip was in hip adduction, with females having less peak hip adduction than males. Not identifying gender differences in knee abduction angles was in contrast to the results reported by McLean et al.[140] and Malinzak et al.,[127] who both reported gender differences in knee abduction angles. While McLean et al.[140] noted that their abduction angle differences were not of clinical importance, they did note that females tended to land and stay in a more knee abducted position during the stance portion of the cutting maneuver. The differences in abduction angle findings between these studies might possibly be attributed to differences in the experience level of the participants or to the fact that Pollard et al.[167] analyzed unanticipated maneuvers and the other authors analyzed preplanned maneuvers.

An article published by Ford et al.[60] in 2005, knee and ankle kinematics during an unanticipated jump-stop cutting maneuver were compared between 54 male (14.5 ± 2.2 yrs) and 72 female (14.3 ± 1.9 yrs) adolescent middle/high school basketball players. The participants were cued using a lighting system to initiate the maneuver by first jumping forward 0.4m, side-cutting at a 45° angle to the left or right side and then running past a marker 2.5 m away. At initial contact, females had larger knee abduction angles compared to males for both the dominant (3.7 ± 0.9° versus 1.2 ± 1.1°) and nondominant legs (4.0 ± 0.8° versus 1.6 ± 0.8°). Females also exhibited greater maximum ankle eversion angles and smaller maximum ankle inversion angles during the stance phase of the cutting maneuver. Although the participants in this study were much younger than the participants in the studies by Malinzak et al.[127] and McLean et al.,[140] all 3 studies detected larger knee abduction angles in females compared to males during the stance phase of side-cut. Increased abduction angles at the knee and increased ankle eversion angles are both believed to be potential risk factors related to the higher prevalence of ACL injuries in females. Shea et al.[186] reported that the gender difference in ACL injury rates appears at 12 years of age and so it would be of interest to see if gender differences in the abduction angle are not present in a group of athletes under 12 years of age.

Knee joint kinematics and kinetics have been the most commonly compared measures between genders for cutting-related studies addressing ACL injuries, with a number of these studies identifying greater knee abduction angles in females compared to males during the stance phase of the cutting maneuvers.[60,127,140] Results for other measures at the hip, knee or ankle tend to vary across studies and this is most likely the result of differences in how the cutting maneuvers were performed or differences in the age or experience level of the subjects being analyzed. There is also a lack of gender comparative studies addressing muscle activation patterns, particularly for unanticipated cutting maneuvers.

2.5.7 Unanticipated versus Preplanned Cutting Maneuvers

Unanticipated cutting has been incorporated into more recent studies in an attempt to better replicate sporting maneuvers that place the ACL at high risk of being injured.[16,17,60,167] As part of one of the most comprehensive cutting studies to date, Besier and his research group published two papers comparing muscle activation strategies[16] and knee joint loadings[17] during unanticipated and preplanned running and cutting. Unanticipated cutting maneuvers were analyzed because it was thought that preplanned cutting maneuvers do not provide a true reflection of the knee loads and muscular response experienced during a true sporting scenario where the ACL is most likely to be injured.

Eleven male soccer players (21.3 ± 3.4 yrs) with no history of lower limb injury underwent a complete EMG analysis of 11 muscles surrounding the knee and a 3 dimensional biomechanical analysis of the knee during unanticipated and preplanned cutting maneuvers. A target board with light emitting diodes was used to randomly cue the participants to perform one of four maneuvers: i) straight run, ii) 30° side-cut, iii) 60° side-cut and iv) 30° cross-cut cut. Participants were barefoot during the testing and all tasks were required to have an approach speed of 3.0 m/s and the delay of the light on the target board was adjusted for each participant so that individual reaction times were considered.[17]

No differences were detected in external knee flexion-extension moments between the unanticipated and preplanned maneuvers; however, knee adduction-abduction and internal-external rotation moments were as much as 2 times greater during the unanticipated compared to the preplanned maneuvers. It was proposed that the reduction in reaction time to make the appropriate postural adjustment strategies in the unanticipated tasks was responsible for the increased external moments.[17] Related to the muscle activation strategies for stabilizing the knee, the preplanned maneuvers showed selective activations of the medial-lateral and internal-external rotation muscles, whereas the unanticipated maneuvers demonstrated generalized co-contraction strategies. Also of interest is that while the adduction-abduction and internal-external rotation knee moments increased by approximately 100% for the unanticipated side-cut maneuvers, net muscle activations only showed a 10-20% increase when going from the preplanned to unanticipated maneuver. This mismatch between the increase in activation patterns and external joint loads for the unanticipated maneuvers is thought to have a possible role in the etiology of non-contact ACL injuries.[16]

Houck et al.[89] also found differences between preplanned and unanticipated maneuvers, comparing frontal plane trunk kinematics and hip and knee moments during both a straight walk and a walking side-cut maneuver. The unanticipated side-cut maneuver had reduced hip abduction angles when compared to an unanticipated straight walk, preplanned straight walk and preplanned side-cut and these angles were related to foot placement and lateral trunk orientation. Near initial contact, the unanticipated cut produced an immediate knee abduction moment whereas the other 3 maneuvers had a brief knee adduction moment prior to generating a knee abduction moment. The authors described this difference by suggesting that during the preplanned cut, the subjects completed weight acceptance and then executed the turn whereas for the unanticipated cut, the subjects attempted to initiate the cut immediately at initial contact.

2.6 Summary of the Literature Related to the ACL

The primary role of the ACL is to resist anterior translation and internal rotation of the tibia with respect to the femur, particularly during sports that involve frequent maneuvers such as cutting, pivoting, decelerating and landing from a jump. Externally applied forces to the foot and forces generated from the contraction of the musculature surrounding the knee can significantly alter the load on the ACL when individuals perform these athletic maneuvers. The ACL, the most frequently injured ligament at the knee, is often torn during a cutting or landing maneuver where no major contact has been made with an opposing player. Generally an invasive surgical procedure is required to replace the injured ligament and an intensive rehabilitation program follows in order for the athlete to return to playing sports. Females have a 2-8 times greater non-contact ACL injury rate than males and this gender bias has served as the motivation for many studies attempting to identify ACL injury risk factors.

Anatomical, hormonal, environmental and biomechanical risk factors have been investigated and identified in the literature. Specifically for cutting-related laboratory studies, most previous studies have focused primarily on preplanned maneuvers in attempting to identify non-contact ACL injury risk factors related to gender. As well, no cutting study has simultaneously compared the biomechanics of the hip, knee and ankle along with the neuromuscular response of the muscles surrounding the knee joint.

It has been shown throughout different studies that during the stance phase of cutting, females compared to males demonstrate greater knee valgus angles, increased quadriceps activity and reduced hamstring activity. Females have also been found to cut with smaller hip and knee flexion angles and gender differences have also been reported for hip abduction and ankle eversion angles.

The current study aims to measure complete lower limb biomechanical (hip, knee and ankle) and neuromuscular activation patterns (quadriceps, hamstrings and gastrocnemii) during unanticipated running and cutting maneuvers and compare these measures between elite male and female adolescent soccer players.

2.7 Analysis of Biomechanical and EMG Waveforms

One of the major difficulties of analyzing biomechanical and electromyography waveforms is with the reduction and clinical interpretation of the vast amounts of data that make up the waveforms. Providing both magnitude and temporal information, these waveforms are also quite complex, highly variable, multidimensional and contain both linear and nonlinear correlations.[33]

2.7.1 Parameter-based Analysis

More traditional analysis techniques of biomechanical waveform data has involved subjectively defining and extracting parameters that describe discrete instants or events associated with the waveforms (i.e. mean values for specific events of the waveform, ranges, peak values and time to peak values). A problem with parameter-based analysis techniques can occur when pre-defined parameters are extracted from the waveform of one population in order to be compared to another population. The parameters that may be present in a female or asymptomatic population, for example, may be unidentifiable in a male or symptomatic population. Events might also be occurring at different phases throughout the waveforms for the different groups and so a comparison of similar parameters would actually be comparing different events.[47] Disadvantages of parameter-based analysis techniques include the subjective nature in which the parameters to be analyzed are chosen, temporal characteristics of the waveforms are ignored, there is limited information on the variability of the entire waveform and the chosen parameters can be highly correlated.[46,159]

2.7.2 Waveform Analysis Techniques

Waveform analysis techniques permit the entire waveform shape to be incorporated into the analysis, thereby eliminating many of the limitations of parameter based analysis techniques. The application of waveform analysis techniques to biomechanical and EMG data is relatively new and quite effective; however, it is more difficult to use than parameter-based analysis techniques.

Modern biomechanical and EMG analyses result in a large volume of data that is highly complex and this generally requires that the data be reduced or simplified in order for clinically relevant information to be obtained and properly understood by both biomechanists and clinicians. The main challenges in analyzing quantitative waveform data, from a technical point of view, include dealing with the high dimensionality, temporal dependence, high variability, correlations between curves and nonlinear relationships.[33] Biomechanical and EMG data also has intrasubject, intersubject, within-trial and between-trial variability, as well as variability that is introduced as part of the data collection process. This variability is difficult to control and because the variability can be high, statistical conclusions from the data can be weakened.[33]

In more recent years, many different waveform analysis techniques have been applied to biomechanical and EMG waveform data in an attempt to reduce the data and extract useful information from the highly correlated time-dependent variables. Some of these techniques include fuzzy analysis, neural networks, wavelet analysis, fractal dynamics and multivariate statistical techniques including factor analysis, multiple correspondence analysis and principal component analysis (PCA), with each technique offering benefits and limitations when applied to biomechanical waveform data analysis.[33,34] The ideal data analysis technique is one that is able to simultaneously address the constant challenges of high dimensionality, temporal dependence and curve correlations.

2.7.3 Principal Component Analysis (PCA)

PCA is a multivariate analysis technique that has recently been shown to be very effective in analyzing biomechanical and EMG waveform data. This technique has superb capabilities in i) reducing the dimensionality of the data, ii) extracting important features of variation from the waveform data and iii) detecting group differences across entire waveforms.[33] One of the advantages of using PCA is that the technique can capture subtle changes in the waveforms that may be overlooked or not clearly evident if only curve parameters are examined.[224] Applied to various types of biomechanical and neuromuscular waveforms, PCA has been effective in capturing and describing gait differences between asymptomatic and knee osteoarthritis patients,[46,47,91,112,136] core muscle differences between asymptomatic and chronic low back pain patients,[93] asymmetrical differences in gait[159,177-179] and lifting differences prior to low back pain.[224]

PCA can be summarized as an orthogonal transformation or eigenvector decomposition of an original dataset into new uncorrelated variables or principal components (PCs).[86] The individual PCs not only capture different features of variation within the original dataset but are also linear combinations of the original dataset. The PCs are arranged in decreasing order based on the amount of variation each PC captures. The projection of an individual waveform onto the PC itself is called a principal component (PC) score and it is these PC scores that can be tested statistically. PCA is also very effective in reducing the dimensionality of a dataset, particularly when the majority of the variation is explained by the first few PCs. When this is the case, each individual waveform can accurately be reconstructed using only the larger variance PCs and discarding the lower variance PCs.

Based on the outlined advantages that PCA has over more traditional parameter-based analysis techniques, PCA was chosen as the analysis technique for the present study. PCA was used to analyze all biomechanical and EMG waveforms for the male and female adolescent athletes during the unanticipated running and cutting maneuvers.

Chapter 3 - Methodology

3.1 Subjects and Subject Recruitment

Participating in this study were 21 female and 21 male elite adolescent soccer players between the ages of 14 and 18 years. These participants were recruited from the 2005 Nova Scotia Canada Games soccer teams and the 2004 Nova Scotia Provincial youth soccer teams, with testing taking place in the Dynamics of Human Motion (DOHM) laboratory at Dalhousie University between January and July of 2004. Prior to testing, an information session was conducted at the Nova Scotia Indoor Soccer Facility to explain the details of the study to all players and coaches. A consent form (Appendix A) was provided to all soccer players at the information session and taken home to be discussed with their parent(s) or guardian(s). The consent form informed the subjects about the testing procedure and the risks and benefits of the research. At a later date, subjects were phoned on an individual basis and the subjects interested in participating in the study were booked for testing. During the telephone conversation, subjects were screened to make sure they had no prior history of major trauma or injury to either lower limb, such as meniscal damage or significant ligament damage to the knee. Subjects who had experienced an ankle sprain in the past were permitted to take part in the study only if the sprain had occurred at least 1 year prior to the testing date and that the ankle was pain free at the time of testing. Upon arriving at the lab and prior to testing, all participants were required to have their consent form signed by themselves and by their legal guardian or parent.

3.2 Testing Procedure Overview

Ethics approval for this study was obtained from the Research Ethics Board for Health and Medical Sciences at Dalhousie University. Before testing commenced, the subject completed a questionnaire (Appendix B) related to soccer position, hand and foot dominance, frequency and duration of an average week of training (winter and summer), a list of other sports played and a history of injuries sustained in the past. Females also were asked to answer 2 optional questions regarding their menstrual cycle.

A brief training session followed that entailed a demonstration of the side-cut and cross-cut maneuvers for each subject. A light guiding system located at the front of the laboratory randomly cued the subject as to which direction to run and cut for each trial. The maneuvers were practiced first without the light guiding system and then once the subjects became comfortable with the maneuvers, the light guiding system was used to allow the subjects to practice a few unanticipated maneuvers. After the practice session was completed, subject setup was carried out for the motion and EMG analysis.

All subjects wore spandex shorts, a short sleeve T-shirt and their own indoor/turf soccer shoes during the testing procedure. Subject setup began by placing 7 EMG electrodes (Bortec, Inc. Calgary, AB, Canada) on the musculature surrounding the right knee. A series of manual muscle tests were administered to validate electrode positions and ensure adequate EMG signal quality. Infrared light emitting marker diodes (Northern Digital, Inc. Waterloo, ON, Canada) were also placed on the subject's shoulder, pelvis and lower right limb for the kinematic analysis. All wires from the light emitting markers and the EMG electrodes were taped to the skin and an ultra thin stretchable stocking was then placed over the right leg to prevent damage and entanglement of the wires. After subject setup was complete and prior to performing the running and cutting maneuvers, virtual anatomical landmarks were identified on each subject using a digitizing probe. These virtual landmarks in combination with the light emitting markers were later used to create bone embedded coordinate systems for the kinematic and kinetic analysis.

The running and cutting maneuvers had the subject starting at one end of the laboratory with the light guiding system located at the opposite end of the laboratory. The subject began each trial by running towards an AMTI force platform (Advanced Medical Technology, Inc, Watertown, MA, USA) located in the center of the runway. Two timing gates located just prior to the force platform measured the approach speed and also triggered the light guiding system to randomly select which of the 3 maneuvers the subject was to execute for that trial. The 3 unanticipated tasks included a straight run, a side-cut and a cross-cut with the right foot planted on the force platform for all 3 maneuvers. The motion analysis portion of the study ended after 5 successful trials were collected for each of the 3 maneuvers.

Immediately after the running and cutting maneuvers were completed, the light emitting markers were removed and an EMG subject bias trial was collected with the subject lying supine and relaxed. Maximum voluntary isometric contractions (MVIC) exercises were then performed so that the EMG data from the running and cutting maneuvers could be amplitude normalized. A Cybex dynamometer (Lymex, Inc.

Ronkonkoma, NY, USA) was used for 5 of the 6 MVIC trials and torque readings from the dynamometer also provided an isometric strength measure for knee flexion, knee extension and ankle plantar-flexion. After the exercises were performed and electrodes removed from the subject, EMG system bias and gain trials were collected to end the data collection portion of the study.

All EMG, kinematic, force platform and Cybex data were processed in custom written Matlab (The MathWorks, Inc. Natick, MA, USA) software. EMG waveform profiles for the pre-contact, early stance and entire stance phases of the 3 maneuvers, in addition to the entire stance phase biomechanical waveform profiles (joint angles and moments) for the hip, knee and ankle were analyzed using the waveform analysis technique of PCA. Statistical testing for gender and/or medial-lateral muscle site differences were performed using either a Student T-test or 2-factor mixed ANOVA model.

3.3 Subject Setup, Instrumentation and Data Acquisition

Meticulous attention was taken in preparing the subject for testing, particularly with the placement of the EMG electrodes and infrared light emitting marker diodes to the lower limb of the subject. Subject setup took between 30-45 minutes at the beginning of the testing procedure and the following subsections will describe this setup, the instrumentation used and the acquisition of the EMG and biomechanical signals.

3.3.1 EMG Setup and Instrumentation

Muscle activation patterns were recorded for the following 7 muscle sites on the right limb: lateral gastrocnemius, medial gastrocnemius, vastus lateralis, vastus medialis, rectus femoris, lateral hamstring and medial hamstring. Summarized in Table 3.1 and displayed in Figure 3.1, electrode placements were based on those described by LeVeau and Andersson[121] and Hubley-Kozey and her colleagues.[91,92]

Table 3.1.
Electrode placements for the seven muscle sites surrounding the knee

Muscle Site	Location
Lateral Gastrocnemius	30% of the distance from the knee's lateral joint line to the calcaneus
Medial Gastrocnemius	35% of the distance from the knee's medial joint line to the calcaneus
Vastus Lateralis	25% of the distance from the knee's lateral joint line to the anterior superior iliac spine (ASIS)
Vastus Medialis	20% of the distance from the knee's medial joint line to the anterior superior iliac spine (ASIS)
Rectus Femoris	50% of the distance from the superior border of the patella to the anterior superior iliac spine (ASIS)
Lateral Hamstring	50% of the distance from the knee's lateral joint line to the ischial tuberosity
Medial Hamstring	50% of the distance from the knee's medial joint line to the ischial tuberosity

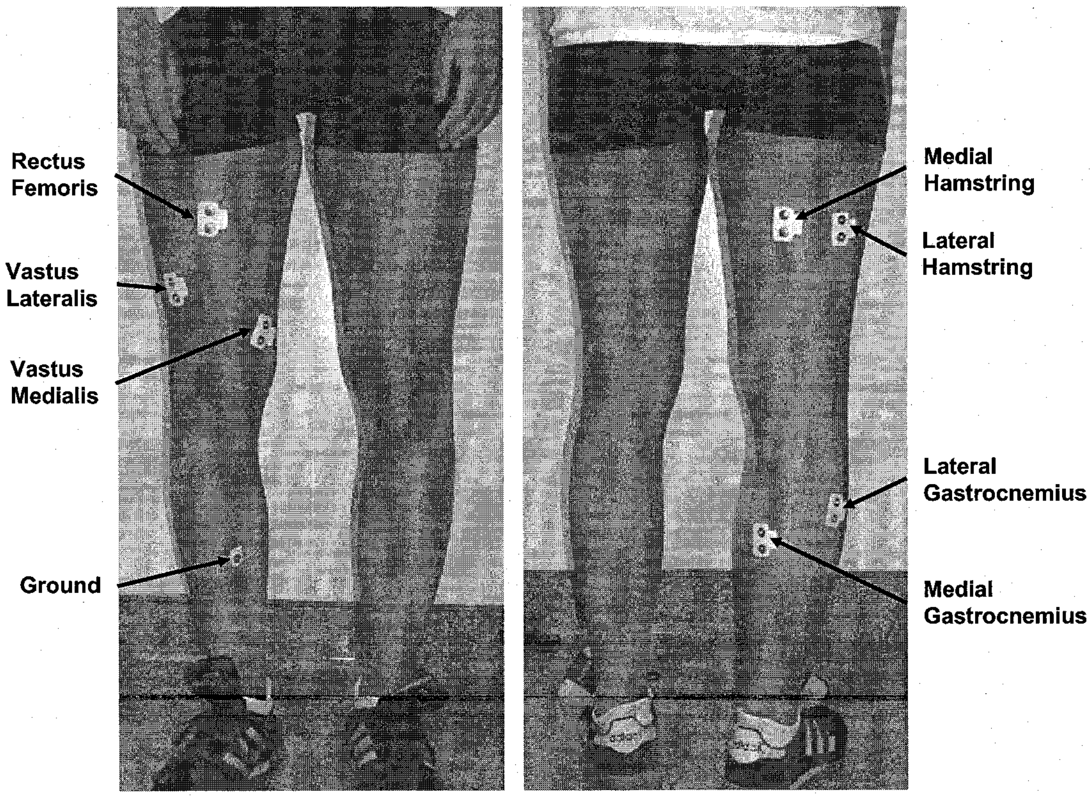

Figure 3.1. Electrode placements for EMG analysis
Location of electrodes for the 3 quadriceps, 2 hamstrings and 2 gastrocnemii muscles along with the reference ground electrode.

Variability in anatomy required minor changes to some of the electrode placements across the subjects. After locating the appropriate muscle sites for electrode placement, the skin was shaven to remove hair and dead skin and then cleaned with rubbing alcohol. Silver/silver chloride pellet surface electrodes (0.79 mm^2 contact area, Bortec, Inc. Calgary, AB, Canada) were positioned over the prepared sites along the direction of the muscle fibers in a bipolar configuration (20 mm center-to-center). A reference electrode (ground) was positioned over the tibial shaft and a series of manual muscle tests were also performed separately for the gastrocnemii, hamstrings and quadriceps to validate the placement and signal quality for each muscle site.[108,217] During the manual muscle testing, the gains for the 7 channels were manually adjusted between 500-5000 times to ensure that the signal to noise ratio was adequate and that the signal did not saturate at the ± 2.0 volt limit of the AMT-8 EMG system (Bortec, Inc. Calgary, AB, Canada). The EMG system had i) preamplifers with gains of 500 times, a frequency bandwidth of 10-1000 Hz, a common mode rejection ratio (CMRR) of 115 dB and an input impedance of approximately 10 GΩ. The 7 electrode pairs plugged directly into a battery operated patient isolation unit that was strapped around the subject's waist with a belt. The measured skin impedance was also required to be less than 200 KΩ approximately 10 minutes after electrode placement to ensure that the ratio of skin-electrode impedance to input impedance of the amplifier was less than the 1% recommended ratio.[172,216]

3.3.2 Motion Analysis Setup and Instrumentation

For three dimensional kinematics and kinetics (inverse dynamics) to be quantified during the running and cutting maneuvers, a series of infrared light emitting markers were placed on each subject. After the EMG electrodes were positioned and validated, a total of 16 light emitting markers were fixed to the shoulder, pelvis and right lower limb of the subject (Figure 3.2). Individual markers were placed on bony landmarks including the shoulder, greater trochanter, lateral epicondyle and lateral malleolus. Marker triads consisting of 3 rigidly fixed markers were attached to the pelvis, thigh, shank and foot.

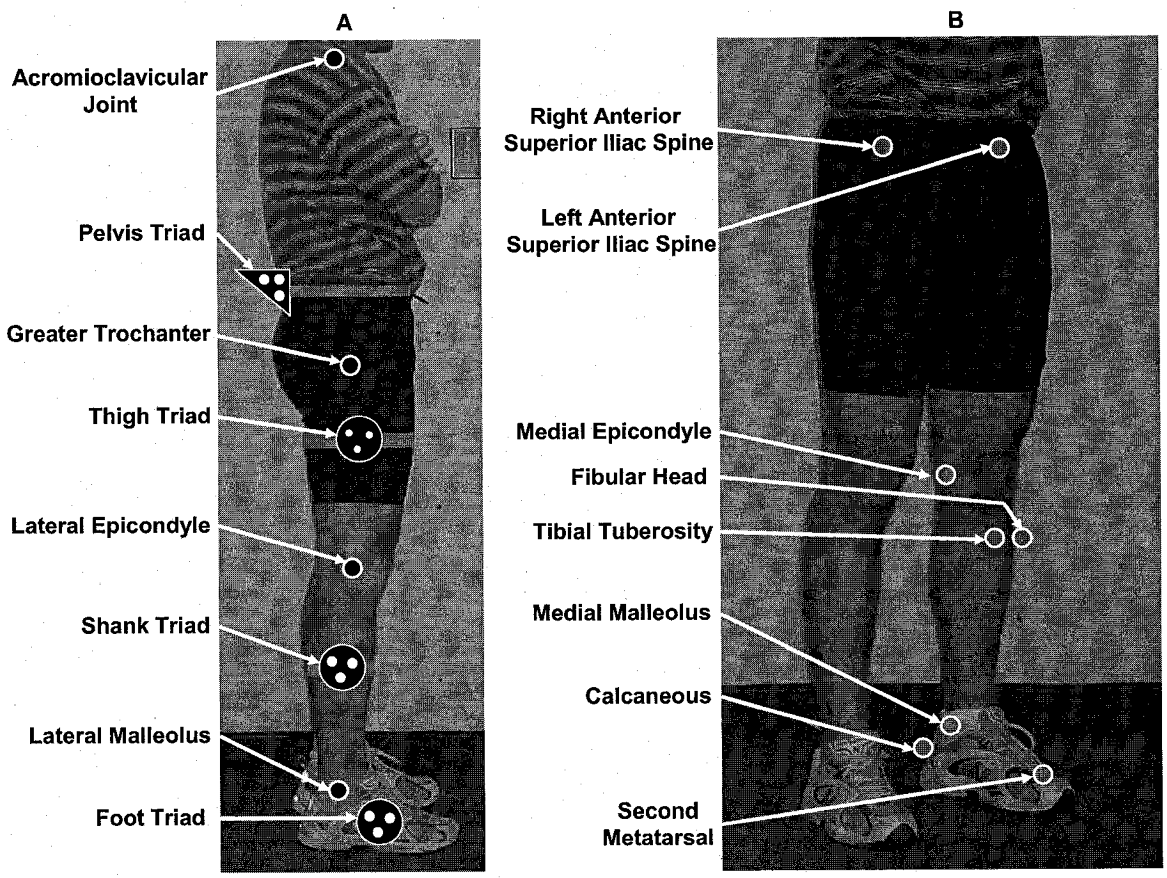

Figure 3.2. Location of infrared markers and virtual landmarks for motion analysis **A)** Infrared light emitting marker diodes tracked during motion trials and **B)** Virtual landmarks identified prior to motion trials.

Once all markers were in place, wires taped down and the ultra-thin stocking placed over the right leg, a 1 second calibration trial with the subject standing in a neutral position was captured by the 2 Optotrak 3020 position sensors (Northern Digital, Inc. Waterloo, ON, Canada). Eight virtual landmarks including the right anterior superior iliac spine, left anterior superior iliac spine, medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head and calcaneous[28] were identified with a digitizing probe prior to the motion trials (Figure 3.2). The combination of the trackable markers and the virtual landmarks enabled bone embedded coordinate systems to be established throughout the motion trials so that joint kinematics and kinetics could be determined for the hip, knee and ankle.

3.3.3 Data Acquisition

The ODAU data acquisition unit of the Optotrak motion analysis system simultaneously captured all EMG data, force platform data and Cybex dynamometer data at 1000 Hz and synchronized this data with the motion data captured at 100 Hz. The ODAU unit also collected a signal from the light guiding system at 1000 Hz and this signal indicated when during the trial the light came on and which direction the subject was to run towards. A custom written LabVIEW program (National Instruments Corporation, Austin, TX, USA) received signals from the 2 timing gates and provided immediate feedback on the approach speed for the running and cutting trials. The LabVIEW program also had a random number generator implemented so that when the barrier of the first timing gate was broken by the subject, the program randomly turned 1 of the 3 lights on, in order to guide the subject as to which direction to move towards after planting the right foot on the force platform.

3.4 Running and Cutting Maneuvers

Testing began with the subject standing at one end of the laboratory and the light guiding system at the opposite end of the laboratory, with the force platform located in the middle of the runway. On the command "Go" the subject began running towards the force platform with their eyes focused on the light guiding system in front of them. Two meters before arriving at the force platform, the running subject passed through the barrier of the first timing gate and this caused an electrical signal to be sent to the data acquisition computer in the control room. This signal triggered the custom written LabVIEW program to randomly light up 1 of the 3 arrows on the guiding system in order to direct the subject as to which direction to move towards once the right foot landed on the force platform. A lighted arrow pointing to the right required the subject to plant the entire right foot on the force platform and perform a cross-cut maneuver to their right side at an angle between 35-60° from the direction of travel. A lighted arrow pointing left required the subject to plant the right leg on the force platform and perform a side-cut maneuver to the left side at the same angle as the cross-cut (Figure 3.3). A lighted arrow pointing straight indicated that a straight run was to be performed by the subject. For all 3 maneuvers, approximately 2-5 steps were taken after landing on the force platform and making the appropriate response to the lighting system.

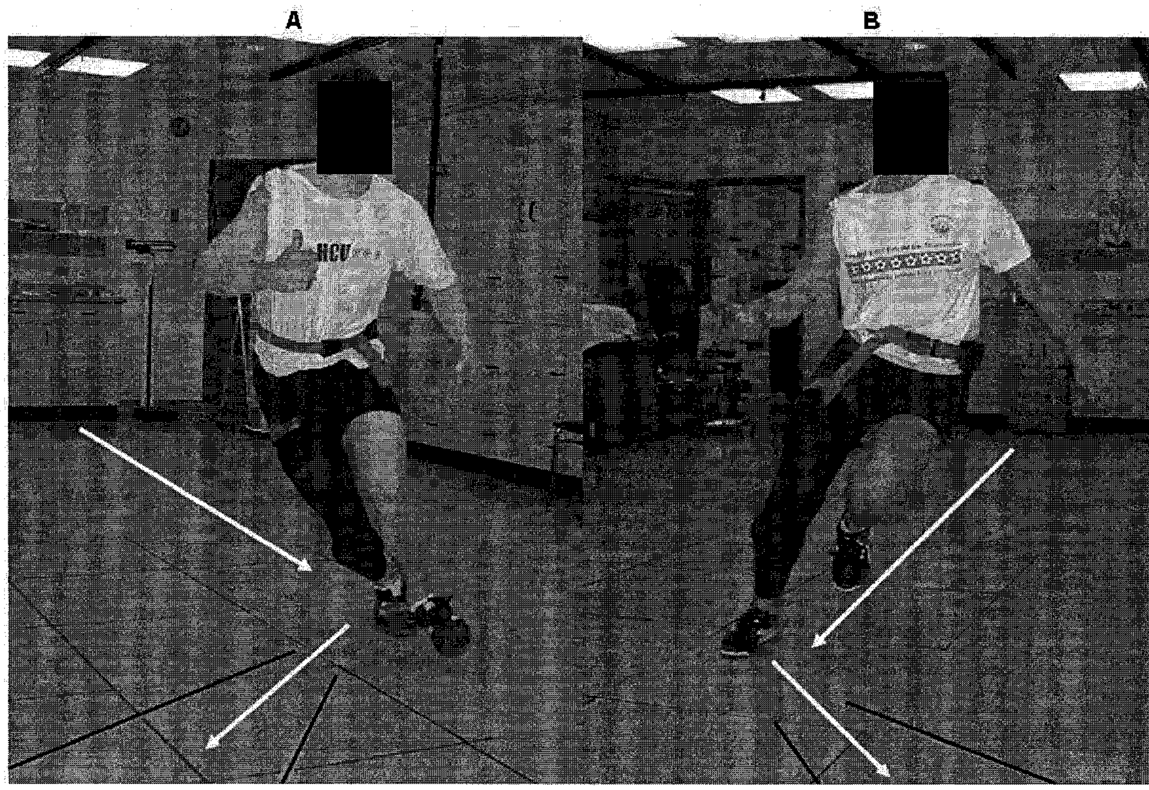

Figure 3.3. Frontal view of unanticipated cross-cut and side-cut maneuvers
A) Cross-cut and **B)** Side-cut at an angle between 35-60° from the direction of travel.

A second timing gate located immediately in front of the force platform was used in combination with the first timing gate so that the approach speed could be calculated immediately after each trial. Strips of tape aligned at a 35° and 60° angle were placed to the left and right of the force platform to help guide the subjects during the side-cut and cross-cut maneuvers. A trial was deemed successful if all the following condition were met: i) the approach speed was 3.5 ± 0.2 m/s, ii) the right foot had to land entirely on the force platform and iii) for the 2 cutting maneuvers, the left foot had to land between the 35° and 60° angled strips of tape after coming off the force platform.

3.5 Normalization Procedures and Strength Measures

After completing the running and cutting maneuvers, a series of maximum voluntary isometric contractions (MVIC) were elicited by each subject for the purpose of amplitude normalizing the EMG data. Five of the 6 normalizing exercises were performed on a Cybex dynamometer, which also provided a simultaneous measurement of the torque generated throughout the duration of the muscle contractions. Two trials were captured for each of the 6 exercises and a gravity correction trial with all the leg muscles relaxed was also collected for the different exercises. For all the exercises, the subject was instructed to sustain a maximum effort against the resistance for 3 seconds and between all trials, at least 1 minute of rest was provided.

The first exercise performed by the subject was knee extension while sitting supine on the Cybex (Figure 3.4). The knee joint center was aligned with the rotation axis of the Cybex and the lever arm pad was placed on the anterior side of the tibia. The back support of the Cybex was raised for the subject to lean back against and pillows helped with the supporting of the back. Straps stabilized the thigh and pelvis and the arm of the Cybex was positioned so that the knee was flexed at 45° for the contractions. The subject was then asked to extend the knee by pushing against the arm of the Cybex, sustaining the contraction for 3 seconds. The second exercise required the subject remain in the same position as the first exercise but instead of just extending the knee, the subject also had to simultaneously flex the hip against the resistance of the strap. The third exercise was knee flexion while sitting supine with the knee flexed at 45° (Figure 3.4). This exercise had the subject remaining in the same position as the first 2 exercises but with the lever arm pad moved to the posterior side of the tibia so that knee flexion could be resisted. The forth and fifth exercises had the subject plantar-flexing in 2 different positions. For the first plantar-flexion exercise the subject sat supine on the Cybex with the ankle in a neutral position and the malleoli aligned with the center of rotation of the Cybex. The subject then attempted to plantar-flex the ankle by pushing the foot against a fixed foot-plate (Figure 3.5). The second plantar-flexion exercise had the subject performing a heel rise while standing upright with a resistance placed on their shoulders (Figure 3.6). The sixth and final exercise required that the subject flex the knee at a knee flexion angle of 55° while lying prone on the Cybex (Figure 3.7). Pillows were also placed under the head and torso to improve comfort and straps were used to stabilize the pelvis and thigh.

A B

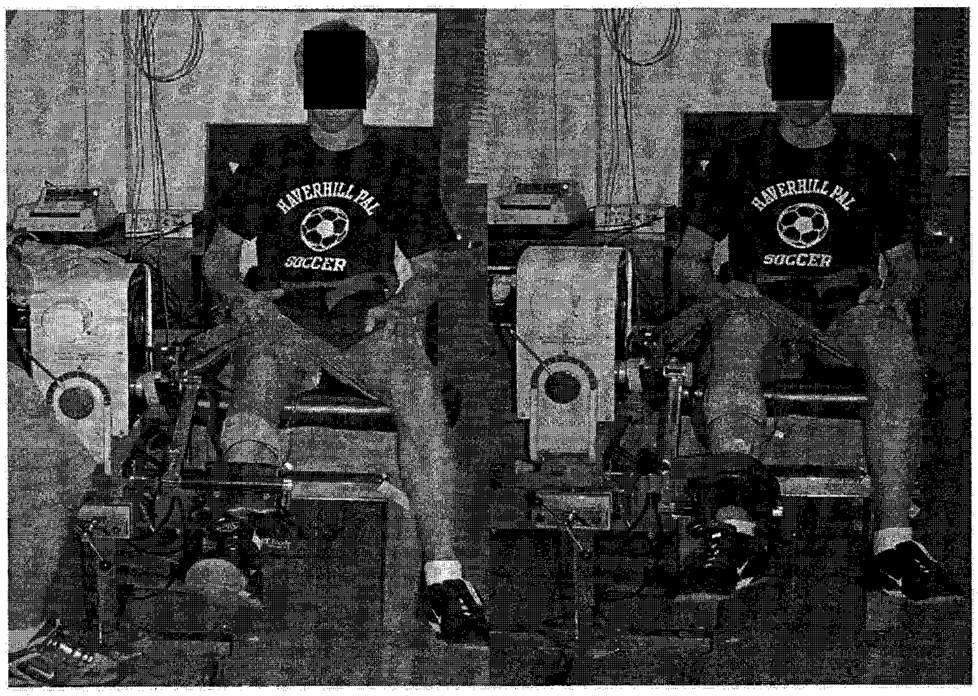

Figure 3.4. Normalization exercises for quadriceps and hamstrings sitting supine
A) The 2 exercises performed in this position included i) knee extension at 45° and ii) simultaneous knee extension and hip flexion to isolate the rectus femoris, **B)** In this position, knee flexion was performed with the knee flexed at 45°. The resistance for these 3 exercises was provided by the Cybex arm.

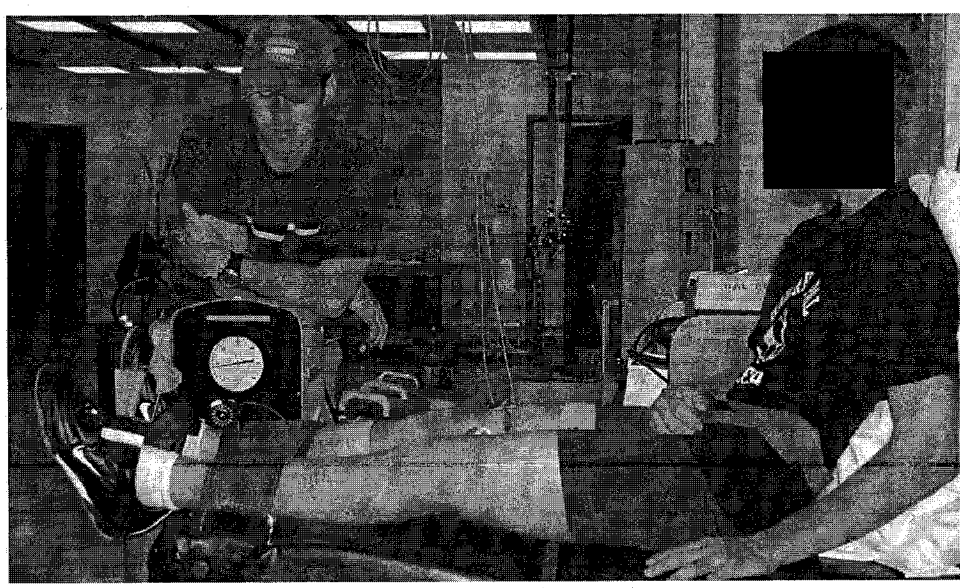

Figure 3.5. Normalization exercise for gastrocnemii while sitting supine
In this position the subject plantar-flexed the ankle by trying to rotate the fixed foot-plate about the Cybex's center of rotation while sitting supine with the knee straight and ankle in a neutral position.

Figure 3.6. Normalization exercise for gastrocnemii while standing upright
This exercise involved the subject contracting the gastrocnemii to perform a heel rise while a resistance was placed on the shoulders of the subject for the duration of the trial.

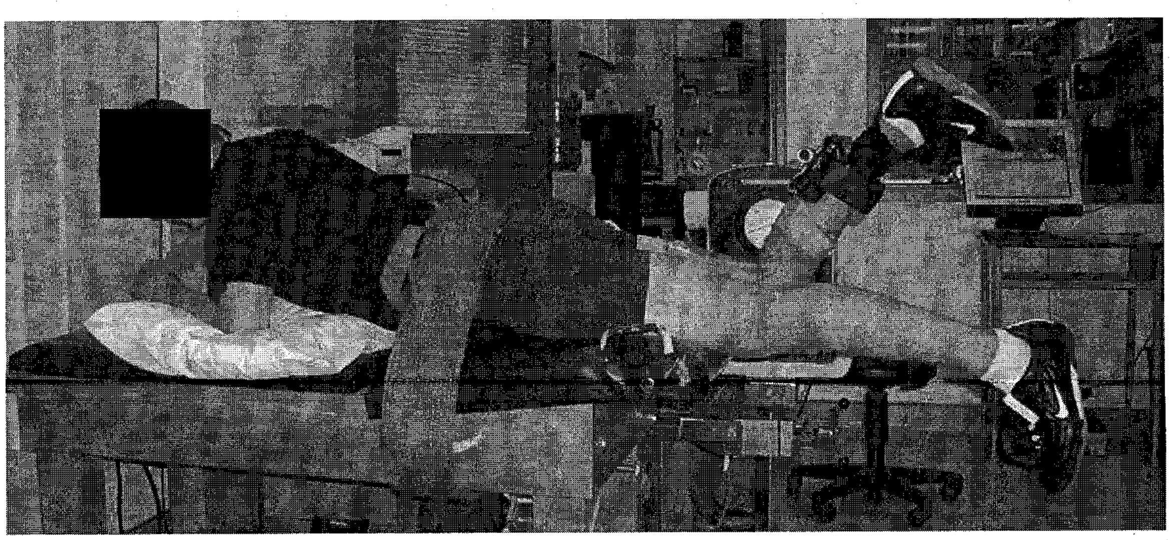

Figure 3.7. Normalization exercise for hamstrings while lying prone
This exercise had the subject undergoing knee flexion against the resistance of the Cybex arm while lying prone, with the knee flexed at 55°.

The Cybex was also used to obtain torque measures for the knee flexors (Exercises 3 and 6), knee extensors (Exercise 1) and plantar-flexors (Exercise 4). The maximum torque value for each 3 second normalization trial was obtained by dividing the trial into 0.5 second intervals and the interval with the greatest mean torque value was then chosen as the maximum torque for that particular trial. The chosen 0.5 second interval could not include a burst of muscle activity or torque production and had to be of a steady state. The Cybex dynamometer also had to be calibrated at the end of the data collection and this was done by generating a calibration curve that related the generated moment to the voltage from the Cybex. Two trials were collected to generate this curve and they included i) a trial with a known weight attached to the end of the Cybex lever arm positioned horizontally and ii) no weight attached to the end of the lever arm positioned vertically. The calculated torque readings (Nm) from the 4 exercises were then used to make strength measure comparisons between genders.

3.6 Data Processing

3.6.1 Joint Kinematics

Three dimensional joint angles for the stance phase of the 3 athletic maneuvers were calculated from the filtered kinematic data for the hip, knee and ankle. The virtual landmarks and infrared light emitting marker data during the motion trials were used to create bone embedded anatomical coordinate systems for the pelvis, thigh, shank and foot. These 4 segments were all modeled as rigid bodies and to quantify the orientation of the adjacent segments with respect to each other, the floating axis joint coordinate system proposed by Grood and Suntay[73] was used for each of the 3 joints.

Three rotation axes were identified at the hip, knee and ankle and the calculated joint angles were then described about these axes. The flexion-extension axis at the knee was a bone embedded axis passing through the lateral and medial femoral epicondyles, with flexion being a positive angle. The knee's internal-external rotation axis was a bone embedded axis through the long axis of the tibia and internal rotation was a positive angle. The adduction-abduction axis, or floating axis as it is commonly referred to, was an intermediate axis that was orthogonal to both the flexion-extension and internal-external rotation axes of the knee. Adduction was considered a positive angle and as the knee joint deviated from the neutral position, the flexion-extension and internal-external rotation axes would change orientation with respect to one another, resulting in non-orthogonal axes. The hip joint followed the same joint angle convention as the knee but with the hip the flexion-extension axis running parallel to a line passing through the right and left anterior superior iliac spines and the internal-external rotation axis running through the long axis of the femur. The ankle joint in this study was modeled as having 3 degrees of freedom with the flexion-extension axis passing through the lateral and medial malleoli and plantar-flexion being a positive angle. Inversion-eversion was described as a rotation occurring about the long axis of the foot and this axis ran from the second metatarsal to the midpoint of the calcaneus, with eversion being a positive angle. The floating axis of the ankle joint complex described the toe-in and toe-out angle and toe-in was positive. All joint angle waveforms were time normalized according to the stance phase of the each maneuver, with each waveform represented by 101 data points ranging from 0% (foot contact) to 100% (foot off) in 1% increments.

3.6.2 Joint Kinetics

An inverse dynamics approach was used to calculate the net external forces and moments acting at the hip, knee and ankle during the stance phase of the running and cutting maneuvers. Using Matlab custom written software, the kinematic and ground reaction force data, along with the segment inertial properties for the foot, shank, thigh and pelvis, were used to arrive at these forces and moments. The 4 segments were each modeled as a rigid body with a local bone embedded coordinate system located at the segment's center of mass and also aligned with the principal axes of inertia for the specific segment. Inertial properties for the 4 segments were calculated by inputting various anthropometric measures into regression equations that were based on known inertial properties from cadavers.[212] Also required for calculating the joint forces and moments were segment velocities and accelerations and this information was obtained by differentiating each segment's kinematic displacement.

Joint forces and moments were calculated by starting with the most distal segment, the foot, and determining the resultant force at the ankle required for balancing both the ground reaction forces and the effects of gravity and accelerations on the foot. The resultant ankle moment was then calculated based on the moments created from the forces applied to the foot and also from the moment generated through contact with the ground. After the net external forces and moments were calculated at the ankle, these forces and moments were then used with the kinematics and inertial properties of the shank to calculate the resultant forces and moments for the knee joint. The final step involved using the net external forces and moments at the knee joint along with the kinematics and inertial properties of the thigh to calculate the net external resultant forces and moments for the hip joint. The net external resultant moments for the hip, knee and ankle were all expressed about the same joint coordinate system used to describe the joint angles in this study.[112,136,138] The moment waveforms were time normalized similar to the joint angle waveforms and were amplitude normalized to body weight so that to be expressed in Nm/kg.[18,112,167]

3.6.3 EMG

All processing of the raw EMG data was performed in Matlab using custom written software. The raw EMG data was bias corrected, full-wave rectified and low pass filtered at 6 Hz using a zero lag 4th order Butterworth filter.[215] To correct for biases and noise in the EMG signals, a subject bias trial with the subject lying completely relaxed and an EMG system bias trial were captured and subtracted from all EMG trials. A 100 msec moving window algorithm was used to identify maximum EMG amplitudes for the 7 muscle sites during the normalization exercises and these values were then used to amplitude normalize the EMG data during the running and cutting maneuvers.[91]

For the running and cutting maneuvers, 3 different phases of the EMG waveform data were analyzed and these phases included i) the entire stance phase, ii) a pre-contact phase and iii) an early stance phase. Similar to the joint angle and moment waveforms, the entire stance phase waveforms were represented with 101 data points ranging from 0% (foot strike) to 100% (foot off) in 1% increments. The pre-contact phase entailed the 100 msec prior to initial contact or foot strike and the waveforms during this phase were also represented with 101 data points. The early stance phase corresponded to the first 20% of stance for each maneuver and like the pre-contact and entire stance phase, the waveforms were made up of 101 data points.

3.7 Data Analysis

All EMG, joint angle and joint moment waveforms were analyzed using PCA and statistical hypothesis testing was performed using either a Student T-test or a 2-factor mixed model ANOVA in Minitab (Minitab, Inc. State College, PA, USA). For each separate joint angle, joint moment and rectus femoris waveform measure, gender differences were tested for by entering the male and female waveforms into separate PC analyses and then comparing the generated PC scores using Student T-tests. For each of the 3 separate muscles groups including the gastrocnemii, hamstrings and quadriceps, gender and medial-lateral muscle site differences were tested for by simultaneously entering male and female medial and lateral muscle site waveforms into a separate PC analysis and then comparing the generated PC scores using a 2-factor (group, muscle) mixed model ANOVA, with muscle site treated as the repeated measure.

For each waveform measure, an n x p matrix was created that contained the waveform data to be analyzed from each subject. All waveforms were made up of p=101 data points and for the joint angle, joint moment and rectus femoris waveforms, there were 21 male and 21 female subjects and hence n=42 waveforms were entered into the data matrix, **X**. For each analysis of the 3 different muscle groups (quadriceps, hamstrings and gastrocnemii) there were n=84 waveforms entered into the data matrix, due to the fact that every male and every female had both medial and lateral muscle sites analyzed simultaneously. Prior to the application of PCA, the column means of the data matrix, that was either 42x101 or 84x101, were removed and then the covariance matrix, $\mathbf{C} = \overline{\mathbf{X}\mathbf{X}}^{\mathrm{T}}$, was calculated for the mean removed dataset ($\overline{\mathbf{X}}$).

PCA involved performing an eigenvector decomposition of the **C** matrix and this decomposition was represented as $\mathbf{C}=\mathbf{T}\mathbf{\Lambda}\mathbf{T}^{\mathrm{T}}$ with the transform matrix **T** being a matrix of patterns (orthogonal eigenvectors or principal components (PCs)) and $\mathbf{\Lambda}$ being a diagonal matrix of the associated variances (eigenvalues). The PCs are extracted hierarchically based on the amount of variation that the PCs explain and this is calculated by dividing the specific eigenvalue for each corresponding PC by the trace of the covariance matrix. Although a PC is extracted for each of the original variables in the covariance matrix, generally the majority of the variation can be described by the first few extracted PCs and the later PCs can then be ignored.

Every waveform in the model gets scored based on its similarity to the set of PCs that are retained in the analysis. The PC scores for each subject are calculated as $\mathbf{Z}=\overline{\mathbf{X}}\mathbf{T}$, with the PC score being a measure of the distance a subject's waveform is from the mean of that particular PC. A subject with an original waveform that is similar to a given PC receives a high PC score and the maximum and minimum waveforms based on the PC scores are then used in combination with the PC itself to help interpret the feature of variation that the specific PC is actually describing.[103] The features of variation captured by the PCs are then interpreted for biomechanical and neuromuscular meaning and the PC scores are used in the statistical hypothesis testing as described above. Normality tests and plots of the residuals were performed in Minitab for all the PC scores to ensure that the scores were normally distributed for the statistical hypothesis testing. The PC scores from the different groups were also assessed for equal variances using the Bartlett and Levene's test in Minitab. The PC scores for the joint moment, joint angle and rectus femoris waveforms were tested for gender differences using Student T-tests. PC scores for the waveforms of the quadriceps, hamstrings and gastrocnemii muscle groups were tested for both gender and medial-lateral muscle site differences using a 2-factor mixed model ANOVA with Tukey adjusted pairwise comparisons.

Chapter 4 - Neuromuscular and Lower Limb Biomechanical Differences Exist Between Male and Female Elite Adolescent Soccer Players During an Unanticipated Side-cut Maneuver

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4.1 Introduction

The anterior cruciate ligament (ACL) of the knee has an important role in joint stability, particularly in resisting internal rotation and anterior translation of the tibia with respect to the femur.[130] Injury to the ACL can be detrimental to an individual's athletic career, often requires invasive surgery to repair, is 2-8 times more prevalent in females than males[1,8] and also leads to accelerated osteoarthritic changes to the knee joint.[213] While the ACL can be injured from a contact blow to the knee, 70-80% of the time this ligament is injured while performing a non-contact maneuver such as landing from a jump or cutting to quickly change directions,[21,153] in sports like soccer, basketball, volleyball and European handball.

Comprehensive overview articles exist throughout the literature that summarize the numerous studies addressing non-contact ACL injury risk factors and the gender disparity associated with this injury.[72,80] Physiological and biomechanical risk factors can potentially be controlled and altered to reduce this risk, but it is difficult to accurately measure these factors during sport-specific scenarios where ACL injuries occur. Measuring body positioning, joint loading and neuromuscular coordination during athletic maneuvers in a laboratory setting offers great potential for capturing and understanding risk factors related to non-contact ACL injuries, particularly in females.

Several studies focusing on cutting-related maneuvers[60,127,138-140,167,191] have analyzed combinations of lower limb kinematics, kinetics and/or electromyography (EMG) in an attempt to identify ACL injury risk factors associated with females. Although findings between studies vary, they have been able to identify gender related differences in recreational, high school or collegiate level athletes during various phases of the cutting maneuvers.

It has been demonstrated that contraction of the quadriceps at knee flexion angles less than approximately 45° strains the ACL[9,174] and hamstring contraction for a flexed knee can help protect the ACL by reducing ligament strain in an agonist manner.[133,144,174] Activation patterns of the quadriceps and hamstrings have been compared between genders for preplanned athletic maneuvers and differences have been detected. Malinzak et al.[127] demonstrated greater quadriceps activation levels (vastus medialis (VM) and vastus lateralis (VL) averaged together), normalized to maximum voluntary contractions (MVC), in females compared to males during preplanned straight running and cutting maneuvers. Sigward and

Power[191] analyzed only the VL and not the VM and found that within the first 20% of the stance phase of a preplanned side-cut, the VL in teenage female soccer players was more activated than their male counterparts (191% MVC vs. 151% MVC).

Gender differences in hamstring activity can vary between different athletic tasks. Malinzak et al.[127] demonstrated that while female recreational athletes have significantly reduced hamstring activity (lateral hamstring (LH) and medial hamstring (MH) averaged together) during the stance portion of a preplanned straight run and cross-cut, for a side-cut manuever these activation differences between genders are less evident. Sigward and Power[191] analyzed a preplanned side-cut maneuver only and gender differences in hamstring activity were not captured between the male and female subject groups.

The gastrocnemii, the third main muscle group crossing the knee, has received little attention with respect to cutting studies and the potential influence of this muscle group on the ACL. Studies using a computer based model[157] and a differential variable transducer implanted on the ACL[58] have shown that contraction of the gastrocnemii alone or in combination with the quadriceps is able to increase the load experienced by the ACL. No study has specifically evaluated gender differences for the gastrocnemii during cutting maneuvers and identifying activation differences between males and females for this muscle group may provide valuable information related to the higher prevalence of ACL injuries in females.

Kinematic comparisons of athletic maneuvers between genders are more plentiful than neuromuscular comparisons. Some of these studies have reported that females side-cut with greater knee valgus[60,127,139,140] and smaller knee flexion angles[127,139] compared to males, whereas other studies have found no knee kinematic differences between genders during a preplanned or unanticipated side-cut.[167,191] Gender differences in hip abduction, hip flexion and/or ankle inversion have also been identified for the side-cut maneuver.[60,139]

Many studies have analyzed joint moments of the lower limb during side-cutting[17,18,89,192] but only a select few have made gender comparisons of the moments.[167,191] Pollard et al.[167] reported no gender differences in hip and knee moments whereas Sigward and Powers[191] were able to demonstrate that females had smaller peak net internal knee flexion moments and greater net internal knee adductor moments during the first 20% of the side-cut stance phase.

Collectively these studies have identified potential risk factors associated with the higher prevalence of ACL injuries in females during cutting-related maneuvers. One of the main criticisms for most of these laboratory studies, however, is that the analyzed maneuvers are not optimally replicating a true game-like scenario where the ACL is most likely to be damaged from an unanticipated or perturbed non-contact maneuver. More recent laboratory studies have used light guiding systems to more closely approximate a true game-like situation by forcing the athlete to execute the cutting maneuver at the last possible moment.[16,17,60,89,167] Although it is difficult to access exactly how well these unanticipated laboratory maneuvers replicate the true-game like situation, Besier et al.[16] was able to show in male athletes that unanticipated running and cutting maneuvers generate greater knee joint moments and muscle activation levels compared to similar but preplanned maneuvers. Adduction/abduction and internal/external rotation knee joint moments increased approximately 100% for the unanticipated cutting maneuvers, whereas muscle activations only showed a 10-20% increase. The authors also concluded that muscle activation patterns were more selective for the preplanned maneuvers whereas for the unanticipated maneuvers, a more generalized co-contraction pattern was adopted for the musculature surrounding the knee.

Only a couple of studies have analyzed the biomechanics of the unanticipated side-cut with a focus on differences between genders.[60,167] None of these studies have simultaneously compared the kinematics and kinetics of the knee, hip and ankle along with the neuromuscular response of the muscles surrounding the knee during the unanticipated side-cut maneuver. As well, previous cutting studies have compared discrete waveform measures and have not made group comparisons based on features identified using the entire waveform during stance.

Traditionally, biomechanical and neuromuscular waveforms have been analyzed by subjectively defining and extracting parameters describing discrete instants or events associated with the waveforms. Limitations related to these analysis techniques include the subjective nature in which the parameters to be tested are chosen, waveform temporal information is often ignored, there is limited information on the variability of the entire waveform and the chosen parameters can be highly correlated.[46] Recently, the multivariate analysis technique of principal component analysis (PCA) has been effectively used to analyze gait[47,112,136] and EMG[91,93] waveform data. This technique has distinctive advantages over the more traditional analysis techniques, with PCA having increased sensitivity in detecting differences in kinematic and kinetic data over traditional parameter based analysis techniques.[224] PCA is also very capable of i) reducing the dataset's dimensionality, ii) objectively extracting important features from the waveform data based on the variability in the data and iii) detecting group differences across entire waveforms.[33] PCA is an orthogonal or eigenvalue decomposition of an original dataset into new uncorrelated variables or principal components (PCs). These individual PCs describe salient features of variation within the original dataset that can then be related to biomechanical or neuromuscular waveform characteristics. Individual waveforms in the analysis get scored based on their similarity to the extracted features (PCs) and then statistical hypothesis testing can be performed on these scores to test for differences (i.e. group, condition).

The purpose of this study was to measure and compare muscle strength, hip, knee and ankle kinematic and kinetic waveforms, as well as muscle activation waveforms of the quadriceps, hamstrings and gastrocnemii, during the stance phase of an unanticipated side-cut maneuver in an elite adolescent soccer population using PCA. It was hypothesized that gender and medial-lateral muscle site differences would exist in both the magnitude and temporal characteristics of these waveforms and that these differences would help explain risk factors related to the higher prevalence of non-contact ACL injuries in females compared to males. The long term goal of this study is to use the identified gender and medial-lateral muscle site differences collectively in an effort to help develop or improve preventative training programs aimed at reducing the incidence of ACL injuries, particularly in female athletes.

4.2 Methods

4.2.1 Subjects

Forty two healthy elite adolescent soccer players (males=21, females=21) between the ages of 14-18 years (Table 4.1) were recruited from the Nova Scotia provincial youth and Canada Games soccer teams. Each subject had no significant injury at the time of testing and had no prior history of major injury to either lower limb (i.e. meniscus damage or substantial ligament damage to the knee or ankle). Individuals with previous ankle sprains were permitted to take part in the study if the sprain occurred at least 1 year prior to testing and they were no longer experiencing any pain while playing soccer. The Research Ethics Board for Health and Medical Sciences at Dalhousie University approved this study and all subjects, along with their respective guardian, were required to sign a written consent form prior to testing.

4.2.2 Experimental Design

Upon arrival in the laboratory, the athletic maneuvers were demonstrated to the subjects and then practiced by each individual prior to testing. The 3 maneuvers included a straight run, a running side-cut between 35°-60° from the direction of travel (cutting to the left with the right foot planted on the force platform) and a running cross-cut between 35°-60° from the direction of travel (cutting across the body to the right with the right foot planted on the force platform). Two infrared timing gaits were used to ensure the approach speed was 3.5 ± 0.2 m/s and just prior to landing on the force platform, a 3-light guiding system was used to randomly cue the subjects to either run straight, cut to the left (side-cut) or cut to the right (cross-cut). Subjects had approximately half a second to react and make the cut and the maneuvers were repeated until 5 acceptable trials were obtained for the 3 maneuvers. Only the results for the side-cut maneuver will be discussed in this paper, with the results for the straight run and cross-cut maneuvers being presented in another paper.[114]

4.2.3 EMG and Motion Analysis

A complete three dimensional analysis including motion and force data as well as muscle activation patterns of the right leg were collected for the stance phase of the side-cut. Patient setup began with standard skin preparation (shaving and cleaning with alcohol) followed by placement of silver/silver chloride pellet surface electrodes (0.79 mm^2 contact area, Bortec, Inc. Calgary, AB, Canada) over the appropriate muscles locations. The electrodes were attached in a bipolar configuration (20 mm center-to-center) along the direction of the muscle fibers on the right leg for the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), lateral hamstring (LH), medial hamstring (MH), lateral gastrocnemius (LG) and medial gastrocnemius (MG).[91,92,121] A reference electrode was positioned over the tibial shaft and proper electrode placement was validated by assessing the EMG recordings[217] while the subjects performed a series of isolated movements.[108] Raw EMG signals were preamplified (500 times) and further amplified (bandpass 10-1000 Hz, CMRR = 115 dB (at 60 Hz), input impedance ~ 10 Gohm) with an 8 channel surface EMG system (AMT-8 EMG, Bortec, Inc. Calgary, AB, Canada).

Motion data was captured at 100 Hz using an Optotrak motion analysis system (Northern Digital, Inc. Waterloo, ON, Canada) and ground reaction force data was captured at 1000 Hz using an AMTI force platform (Advanced Medical Technology, Inc. Watertown, MA, USA). Infrared light emitting marker diodes were placed on the shoulder, greater trochanter, lateral epicondyle and lateral malleolus of the right leg. Marker triads consisting of 3 rigidly fixed infrared markers were placed on the pelvis, thigh, shank and foot. Virtual points including the right and left anterior superior iliac spines, medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head and calcaneous[28] were collected to create anatomical coordinate systems and a standing calibration trial was captured as the reference position to base all joint angle calculations on. To prevent damage and entanglement of the EMG electrode and infrared marker wires during testing, an ultra-thin stretchable stocking was placed over the right leg.

Upon completion of the motion trials, an EMG subject bias trial was recorded with the subject relaxed and supine. Six maximum voluntary isometric contraction (MVIC) exercises were performed to elicit maximal activation amplitudes for EMG amplitude normalization purposes.[91] Five of the 6 exercises were carried out on a Cybex dynamometer (Lumex, Inc. Ronkonkoma, NY, USA) and four of these exercises provided a measure of muscle strength (Nm) for the muscle groups. The 6 MVIC exercises included i) sitting supine and extending the knee at 45°, ii) simultaneous extending the knee at 45° and flexing the hip while sitting supine, iii) flexing the knee at 45° while sitting supine, iv) flexing the knee at 55° while lying prone, v) plantar-flexing the ankle with the knee fully extended and the ankle in a neutral position and vi) plantar-flexing the ankle against a resistance while standing on toes. All torques were gravity corrected and the EMG data was captured at 1000 Hz.

4.2.4 Data Analysis

Three dimensional joint angles and net external moments for the hip, knee and ankle were calculated using Matlab (The MathWorks, Inc. Natick, MA, USA) custom written inverse dynamics analysis software. The foot, shank, thigh and pelvis were modeled as rigid bodies and the position and orientation of these segments were determined using a least squares optimization routine.[30] Joint angles were reported according to the floating axis joint coordinate system[73] with flexion (or plantar-flexion at the ankle), internal rotation (or eversion at the ankle) and adduction (or toe-in at the ankle) all being positive for the 3 joints. The net external moments were described about the same rotation axes used for the joint angle data.[112,136,138]

The EMG data was bias corrected, converted to μV, full-wave rectified and low pass filtered at 6 Hz using a zero lag 4th order Butterworth filter in Matlab. All kinematic, kinetic and EMG waveform data were time normalized with the maneuver's stance phase represented by a 101 data points ranging from 0% (foot strike) to 100% (foot off). The moment data was amplitude normalized to body mass and the EMG data was amplitude normalized to maximal EMG amplitudes attained during the MVIC normalization exercises using a 100 msec moving window algorithm for each muscle.[91] Three to 5 side-cut trials were averaged together to create an ensemble average profile for each waveform measure.

The analysis technique of PCA was applied to the ensemble average angle, moment and EMG waveforms to identify features of variation in the waveforms that were then tested statistically for gender and/or medial-lateral muscle site differences. PCA is a multidimensional analysis tool that has become increasingly popular for analyzing biomechanical and neuromuscular waveform data in recent years.[33] A dataset that includes all the waveforms of a particular variable or measure are first arranged in a matrix and the mean value at each instant of time is then subtracted from all waveforms in the dataset. The covariance matrix of this mean removed dataset is calculated and entered into a PC analysis. PCA involves performing an orthogonal or eigenvector decomposition of the covariance matrix for a group of waveforms in order to identify or capture biomechanical waveform features (i.e. overall magnitudes, local magnitudes, phase shifts and amplitudes) based on the patterns of variability in the waveform dataset. The biomechanical features are represented by the eigenvectors or principal components (PCs) of the analysis and then each subject's waveform receives a score (PC score) based on how similar their waveform is with that specific PC. Statistical comparisons are performed on the PC scores and the PCs are ordered in a manner so that the first PC describes the greatest amount of waveform variation, the second PC describes the second greatest amount of variation and so fourth. The salient features that the PCs capture can be discriminatory or non-discriminatory in nature and the PC scores that each waveform obtains provides some indication of how much that particular feature is contributing to the overall waveform pattern.

The waveforms for hip, knee and ankle angles and moments and RF activation patterns for the male and female athletes were analyzed using separate PC analyses for each individual variable or biomechanical/neuromuscular component. Each separate PC analyses involved inputting the male and female waveforms for the particular variable being analyzed into the analysis and then statistically testing the PC scores for gender differences using Student t-tests. For each of the quadriceps (VL and VM), hamstrings (LH and MH) and gastrocnemii (LG and MG) muscle groups, gender and medial-lateral site differences were analyzed by simultaneously including medial and lateral muscle site waveforms for both males and females into a separate PC analyses for each of the 3 different muscle groups. A 2-factor mixed-model ANOVA, with the repeated measure being lateral and medial muscle sites, was used along with Tukey adjusted post-hoc pairwise comparisons ($p<0.05$) to identify differences between medial-lateral muscle sites and between genders for the 3 muscle groups. Gender differences in anthropometric measures, strength and years of playing experience were tested using Student t-tests ($p<0.05$). All analyses and statistical testing were performed in Matlab and Minitab (Minitab, Inc. State College, PA, USA).

4.3 Results

4.3.1 Subject Demographics and Maneuver Approach Speeds

All subjects were free of injury at the time of testing, although many subjects reported minor lower limb injuries (i.e. ankle sprains, muscle strains and broken bone) previously in their soccer careers (male=62%, female=86%). Males were 8.81 kg heavier ($p<0.01$) and 0.12 m taller ($p<0.01$) than their female counterparts; however, no differences were detected for age, BMI and years of playing experience (Table 4.1). The side-cut was performed in an indoor/turf soccer shoe by all athletes and the approach speed for the maneuver did not differ statistically between the males (3.50 ± 0.09 m/s) and females (3.44 ± 0.10 m/s) (Table 4.1).

4.3.2 Strength Measures

Males produced greater maximal moments than females for knee flexion (prone and supine), knee extension and ankle plantar-flexion strength exercises on the Cybex dynamometer (Table 4.1). The largest muscle moment mean difference between genders was for plantar flexion while sitting supine with males generating a 31.4 Nm ($p<0.005$) larger moment than females. No statistically significant differences between genders were identified for the ratios of knee flexion (prone and supine) versus knee extension (Table 4.1). When maximal moments were normalized to the body weight and height of the subjects, no differences between genders for the 4 strength measures were found.

4.3.3 EMG

Four separate PC analyses were performed on the gastrocnemii (LG and MG), hamstrings (LH and MH), quadriceps (VL and VM) and RF muscle activation waveforms to compare the male and female ensemble average muscle activation waveforms for the side-cut maneuver. The first 3 PCs for the 4 analyses explained the majority of the total variance in the magnitude and overall shape pattern of the temporal waveforms. The total variance explained by these 3 PCs was 96.5%, 93.3%, 97.2% and 97.1% for the gastrocnemii, hamstrings, quadriceps and RF activation waveforms, respectively. The general overall magnitude of the activation waveforms during stance was captured by PC1 for the hamstrings, quadriceps and RF. For the gastrocnemii, PC1 captured early to mid-stance activation magnitudes (≈0-70% of stance) and PC2 captured late stance (≈70-100% of stance) activation magnitudes. The remaining PCs captured more subtle features of the temporal waveforms and these features were not as effective in detecting gender or muscle site differences. Two female VM activation waveforms and 3 male MG activation waveforms were not included in the analyses due to insufficient signal quality during the MVIC normalization trials.

4.3.3.1 Gastrocnemii Activation Waveforms

Figure 1 provides an example of the gastrocnemii ensemble average waveforms (Figure 4.1A) along with the PC1 loading vector that captured an overall magnitude during early to mid-stance (Figure 4.1B). The waveforms from an individual with a high and low PC1 score (Figure 4.1C) for each analysis were used to help with interpretation of the waveform features. Means of the PC scores corresponding to the waveform magnitudes and standard errors of these means for each group were also plotted (Figure 4.1D).

Gender and medial-lateral muscle site differences in activation magnitudes during the side-cut were captured for the gastrocnemii (Table 4.2). Pairwise comparisons of the PC1 scores illustrated that both the female LG and MG had larger overall magnitudes than the LG and MG of males ($p<0.003$) during early to mid-stance. For the same phase of stance and comparing the medial and lateral muscle sites within gender, females had higher LG activation magnitudes compared to their MG ($p=0.05$) whereas statistically significant differences were not identified between the male MG and LG muscle sites. During late stance, a medial-lateral muscle activation imbalance was detected in females only, with the LG being more activated than the MG ($p=0.02$, Figure 4.2A and 4.2B).

4.3.3.2 Hamstrings Activation Waveforms

No overall activation magnitude differences between genders were detected by PC1 throughout the entirety of stance for both the LH and MH (Table 4.2). In males, however, LH activity was greater than MH activity throughout stance ($p=0.02$) but this medial-lateral imbalance was not present in females (Figure 4.2C and 4.2D). The relationship between muscle activation levels during early stance and mid-stance was captured by PC2 (see Figure

A1 in Appendix A for PC waveform) with the difference being statistically significant in males only (male p=0.001; female p=0.09). For this feature, the LH and MH mean activation levels were comparable during early stance; however, the main difference was during mid-stance where the LH activity was significantly higher with a more distinctive peak than the MH in males only. The MH demonstrated on average greater activity during early stance compared to mid-stance. A female difference may not have been detected for the PC2 feature due to a lack of adequate power (0.645).

4.3.3.3 Quadriceps Activation Waveforms

The PC analysis of the quadriceps that simultaneously tested the VL and VM for both genders found no gender or medial-lateral muscle site differences (Figure 4.2E and 4.2F). Analyzing the RF muscle site, however, demonstrated larger activation magnitudes in females compared to males throughout stance (p=0.05, Table 4.2 and Figure 4.2G and 4.2H).

4.3.4 Kinematics

PCA was used to test for differences in joint angle waveforms for the hip, knee and ankle between males and females. Knee adduction and internal rotation angles were not examined because their relative values are of a comparable magnitude to measurement errors from marker skin motion and kinematic crosstalk.[15,104,166] Joint angle differences between genders were most prominent at the hip, with more subtle differences evident at the ankle and no significant differences present at the knee. The first 3 PCs for each joint angle component at all joints captured between 94.6-99.0% of the total variance in the waveform data. To aid with interpreting the results from the PC analysis, all kinematic and kinetic PC waveforms that were statistically significant or approached significance (Table 4.3) are plotted in Figure 4.5, along with the percent variation explained by each specific PC.

PC1 for hip flexion and hip internal rotation described the overall magnitude throughout stance (Table 4.3). Females demonstrated significantly less hip flexion than males (Figure 4.3A). Mean hip flexion at foot strike was 38.9 ± 8.8° and 44.1 ± 7.6° for females and males, respectively, and this approximate magnitude difference was evident throughout stance. Internal rotation angles throughout stance were also different, with males having a more internally rotated femur in comparison to females having a more externally rotated femur (p=0.03) (Figure 4.3B). Males had a mean internal rotation angle during stance of 3.00 ± 1.78° whereas females had a mean external rotation angle of 2.48 ± 2.3°. PC2 captured a difference in the pattern of the internal rotation angle with males maintaining a more steady-state internal rotation angle throughout stance compared to females who tended to go from internal to external rotation as stance phase progressed (p=0.05). Gender differences in hip adduction were not detected.

Knee flexion angle differences between genders were not found (Figure 4.3C) and the only gender difference captured in ankle kinematics was a subtle shift in the timing of the plantar-flexion waveforms (Figure 4.3D). Females tended to dorsiflex their ankle sooner during early to mid-stance and plantar-flexed the ankle sooner during late stance in comparison to the male athletes (PC3 p=0.02) (Table 4.3).

4.3.5 Kinetics

Differences in joint moments between genders were identified for all 3 joints throughout both the entire stance phase and at specific phases of stance (Table 4.3 and Figure 4.4). Four PCs were examined for each joint moment and generally the third and fourth PCs captured waveform differences during early stance. The first 4 PCs for the 3 ankle moments captured at least 96.6% of the total waveform variance. For the knee and hip, at least 81.2% and 86.1% of the moment waveform variance was captured by the first 4 PCs, respectively.

The most notable moment differences captured between genders occurred at the hip followed by less subtle differences at the ankle and knee. PC2 for hip flexion moment captured the overall magnitude throughout stance with males exhibiting a greater flexion moment magnitude compared to females for the duration of stance (p=0.002) (Figure 4.4A). PC3 also captured a feature of variation in hip flexion moment magnitude during early stance (≈ first 10%), however, this feature was not quite statistically significant for a gender difference (p=0.06).

Differences between males and females in hip internal rotation (Figure 4.4B) and hip adduction moment magnitudes (Figure 4.4C) were captured during the first approximate 12% of stance by PC3. Females generated a larger hip external rotation moment than males (p=0.03) and tended to have a hip adduction moment in comparison to a hip abduction moment in males during the early stance phase (p=0.04) (Table 3).

No differences between genders for knee flexion moment were found (Figure 4.4D) and the only moment difference that approached significance at the knee was adduction moment during the first 12% of stance (p=0.06) (Figure 4.4E). PC3 captured this magnitude difference with males having a larger abduction moment than females during early stance. With respect to the ankle, PC4 captured a gender difference in eversion moment during the first 20% of stance (p=0.05, Figure 4.4F). Males were more apt to experience a small eversion moment during the first 20% of stance followed by the generation of a larger inversion moment for the remainder of stance. Females, however, had an inversion moment immediately after foot strike and maintained this inversion moment throughout stance.

4.3.6 Results Summary

Differences were found in kinematic, kinetic and muscle activation waveforms between genders as well as between medial and lateral sites for the side-cut maneuver. Features of variation related to the overall magnitude and pattern of the waveforms were captured with the most notable gender differences being detected for the gastrocnemii and RF activation patterns and hip flexion angle and moment waveforms. Females had higher activated LG, MG and RF and also demonstrated a reduced hip flexion angle and moment compared to males throughout the stance phase. PC3 and PC4 for several joint moment measures (hip adduction, hip internal rotation, knee adduction and ankle eversion) also captured gender related differences, particularly within the first 20% of stance.

4.4 Discussion

This study identified neuromuscular and biomechanical differences between genders in an elite adolescent soccer population during an unanticipated side-cut maneuver. The application of PCA to the muscle activation waveforms demonstrated that females have greater LG, MG and RF muscle activation magnitudes during the stance phase of the side-cut than males. Females also exhibited smaller hip flexion angle and moment magnitudes throughout stance compared to males. Hip adduction, hip internal rotation, knee adduction and ankle eversion moment differences were also captured by PCA during the first approximate 10-20% of stance when non-contact ACL injuries most often occur.[21] Related to strength measures for knee flexion, knee extension and ankle plantar-flexion, no differences were identified between genders for the generated moments normalized to body weight and height. The ratio of knee flexion strength to knee extension strength was also compared between males and females and no differences were detected.

Muscle activation magnitude differences between the gastrocnemii of males and females during the side-cut were the most notable differences identified in our study and the contribution of these differences as potential risk factors for ACL injury has not been previously addressed in the literature. No previous study on cutting maneuvers has compared gastrocnemii activity between genders and landing studies analyzing the gastrocnemii have not identified gender related differences.[40,56,176] In our study, females demonstrated greater LG and MG activity compared to males during early to mid-stance. In females only, a medial-lateral muscle site imbalance for the entire stance duration of the side-cut was also evident, with the LG being more active than the MG. Males exhibited similar activation magnitudes for the medial and lateral sites throughout stance.

The higher gastrocnemii activity may be necessary to help the quadriceps and hamstrings stabilize and stiffen the female knee joint, which tends to be more lax and less stiff in comparison to the male knee joint.[90,220] Although the higher gastrocnemii activity in females could be helping to protect the knee, it may also be acting to increase ACL strain. Studies using a computer based model[157] and a differential variable transducer implanted on the ACL[58] have shown that contraction of the gastrocnemii alone or in combination with the quadriceps is able to increase the load on the ACL. As well, the medial-lateral site imbalance present in only females may also be a risk factor and further investigation is warranted to determine if this imbalance places the knee and/or the posterolateral aspect of the knee in a more vulnerable state for injury.

In addition to greater LG and MG activity, females compared to males also demonstrated greater RF activity throughout stance. Contraction of the quadriceps at knee flexion angles less than approximately 45° can increase ACL strain,[9,174] therefore the higher RF activity in females may be increasing ACL strain during the side-cut and potentially be placing females at greater risk of ACL injury.

Differences in VL and VM activity between males and females were not found and this in contrast to the findings of Malinzak et al.[127] and Sigward and Power.[191] Both studies had subjects perform the side-cut in a preplanned manner and at an approach speed greater than 5.0 m/s. Malinzak et al. demonstrated greater female VL and VM activity (averaged together) throughout stance whereas Sigward and Power demonstrated greater female VL activity compared to males during early stance. The unanticipated nature of the side-cut, slower approach speeds (3.5 ± 0.2 m/s) and the differences in skill levels among these studies, with ours having more skilled athletes, may have contributed to the different findings. Although future investigations are recommended to help understand the influence the RF has on ACL injuries and at the hip, capturing gender differences in RF activity and not in VM and VL activity suggests that females might possibly be activating the biarticulate RF muscle at a greater magnitude than males to help more with controlling of the hip rather than the knee.

Differences between males and females in hamstring activation magnitudes were not captured and these findings agree with Sigward and Power[191] who also found no differences between genders in hamstring activity levels during early stance. Malinzak et al.,[127] however, reported that females compared to males have smaller hamstring activation magnitudes (LH and MH averaged together) during stance of a preplanned straight run, side-cut and cross-cut, with the differences being most pronounced for the straight run and cross-cut. Differences in hamstring findings between the studies might possibly be attributed to the subjects being tested. Sigward and Power and our study used more skilled and experienced teenage soccer players whereas Malinzak et al.[127] used older recreational athletes to make gender comparisons.

Contracting the hamstrings at knee flexion angles greater than approximately 30° can reduce ACL strain by increasing knee joint stability and resisting anterior tibial translation with respect to the femur.[144,174] A reduction in hamstring function during cutting or landing is a potential ACL injury risk factor and while we were not able to identify hamstring differences between genders, we did identify a statistically significant medial-lateral hamstring muscle imbalance present in males that was not significant in females. The LH was activated at a greater magnitude than the MH in males and this difference was particularly evident during mid-stance when the knee was experiencing large flexion, adduction and external rotation moments. It is difficult to conclude if this medial-lateral site imbalance exists to help males perform the side-cut more efficiently or if it serves as a protective mechanism against the higher rotational moments present during the side-cut. The higher LH activity in males could also be providing increased stability to the posterior lateral corner where structural damage and bone bruising often occurs in tandem with non-contact ACL injuries.[24,200]

Sagittal plane kinematic differences between males and females were captured at the hip but not at the knee for the unanticipated side-cut maneuver. Similar to the findings of McLean et al.,[139] hip flexion angles throughout stance of the side-cut were smaller in females compare to males. At the knee, no differences between gender were identified and this agrees with previous side-cut studies.[60,167,191] It must be noted that flexion angle differences between genders do vary throughout the literature, with other studies reporting different results. In contrast to our findings, Pollard et al.[167] found no hip flexion differences between genders and Malinzak et al.[127] and McLean et al.[139] determined that females performed the side-cut with less knee flexion than males. While flexion angle results vary across cutting studies, cutting with less hip and/or less knee flexion can place an individual in a more erect posture. Small flexion angles have been shown to generate higher impact forces[63,204] and therefore the reduced hip flexion angles in females might possibly be increasing knee joint loadings and thereby be placing the ACL at greater risk of being injured. The gender differences in hip internal rotation and ankle plantar-flexion were relatively small and both deemed to be clinically irrelevant as risk factors for ACL injury. In contrast to our findings where gender differences were not detected for ankle eversion-inversion, Ford et al.[60] found that females side-cut with a greater maximum eversion angle and a decreased maximum inversion angle compared to males. The discrepancies between these 2 studies can most likely be attributed to the method in which the unanticipated side-cuts were performed. Our subjects ran straight prior to making the side-cut whereas Ford et al.'s subjects performed a forward jump and then a light randomly cued the subjects to side-cut either to the left or right side.

Gender differences were captured for hip flexion moment, with males having a larger overall flexion moment magnitude than females throughout stance. While requiring further investigation, this greater hip flexion moment combined with a greater hip flexion angle in males could be helping to increase hip joint stability and thereby be placing the ACL in a less vulnerable state of being injured compared to their female counterparts. Other kinetic differences between genders were also detected during the first 10-20% of stance, where ACL injuries are most likely to occur. These differences were captured for hip internal rotation, hip adduction and ankle eversion moment, however, the moment magnitudes were much smaller than the maximal moments reached later in mid-stance. It remains unclear if these moment differences at the smaller magnitudes during early stance serve as potential risk factors for ACL injury.

Limitations related to the analysis technique and the testing protocol were acknowledged in this study. The waveform analysis technique of PCA was effective in identifying features in the biomechanical and neuromuscular waveform data that were statistically different between the male and female athletes. The limitation of this analysis technique, however, was that once differences were detected, the magnitude of these differences were not quantifiable with respect to the units the waveforms were reported in. The second limitation, related to the testing protocol, was that the athletes were told to side-cut in a manner that felt natural to them and this most likely introduced variability in the data based on individual differences in cutting technique, making it more difficult to detect differences. Side-cutting in a natural manner, however, did increase the validity of the movement being measured.

4.5 Conclusion

In summary, this comprehensive study represents the first time PCA has been used successfully to detect biomechanical and neuromuscular differences between genders during an unanticipated running side-cut maneuver in an elite adolescent soccer population. Using the variation in the waveform data, PCA objectively identified a number of biomechanical and neuromuscular features that potentially serve as risk factors in the predisposition of higher ACL injury rates in females compared to males. This was the first study to demonstrate that females have greater gastrocnemii activity and a medial-lateral gastrocnemii muscle site magnitude imbalance that is not present in males during side-cutting. Other differences identified that may have a contributing role towards higher ACL injury rates in females include greater RF activity in females and reduced hip flexion angles and moments throughout the stance portion of the unanticipated side-cut.

4.6 Acknowledgements

The authors would like to thank Nike, Inc. Sports Research Laboratory (Beaverton, Oregon) and NSERC for financial support and Soccer Nova Scotia for their help in subject recruitment.

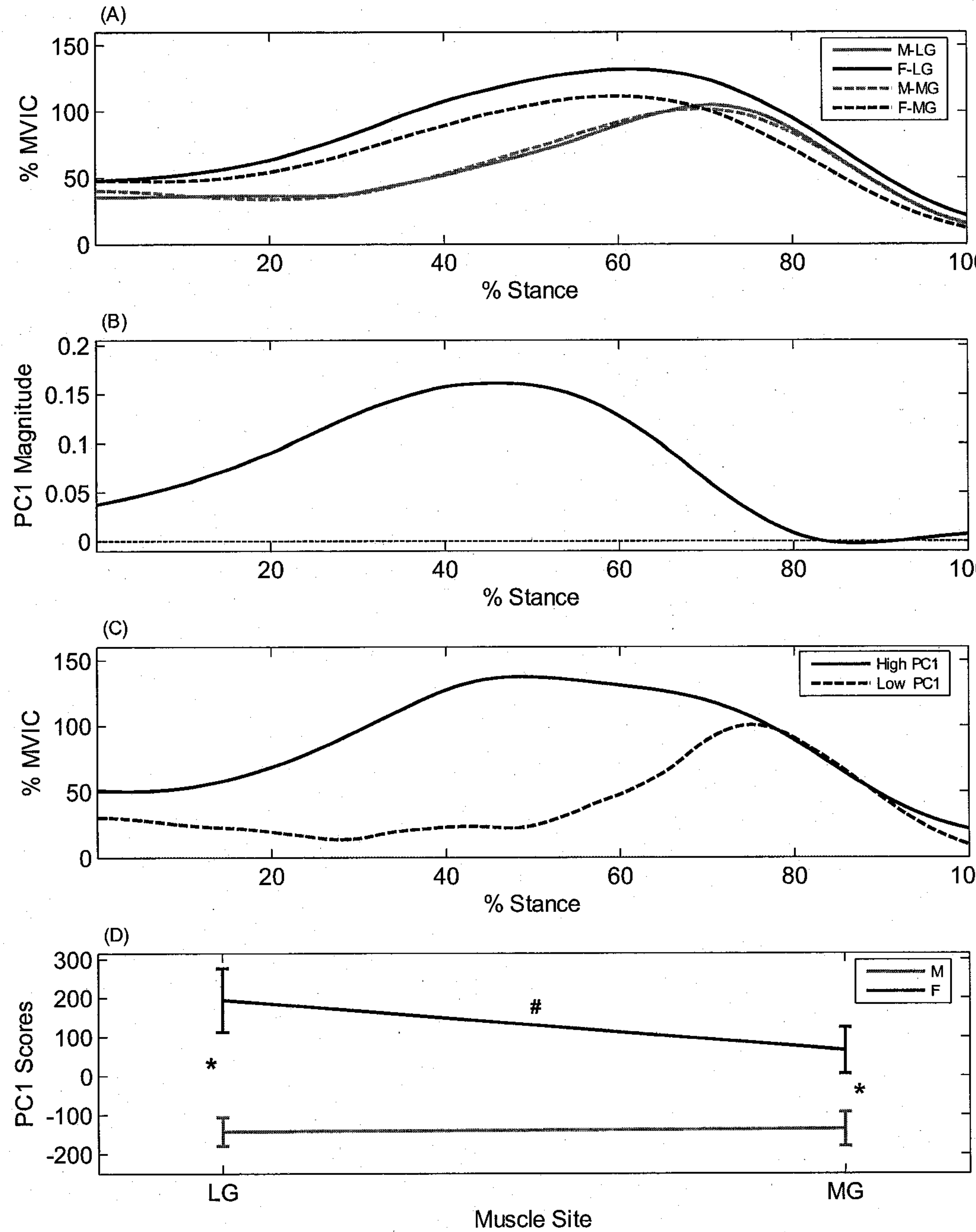

Figure 4.1. Male and female mean gastrocnemii activation waveforms for the stance phase of the side-cut, PC waveform, high and low PC score waveforms and PC score means

A) Group means for the MVIC normalized ensemble average activation waveforms of the LG and MG for males and females during the stance phase of the side-cut. **B)** PC1 capturing the overall muscle activation magnitude during early to mid-stance. **C)** Muscle activation waveforms for two subjects with a high and low PC1 score. **D)** PC1 score means with standard error of the means for the LG and MG of males and females. * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).

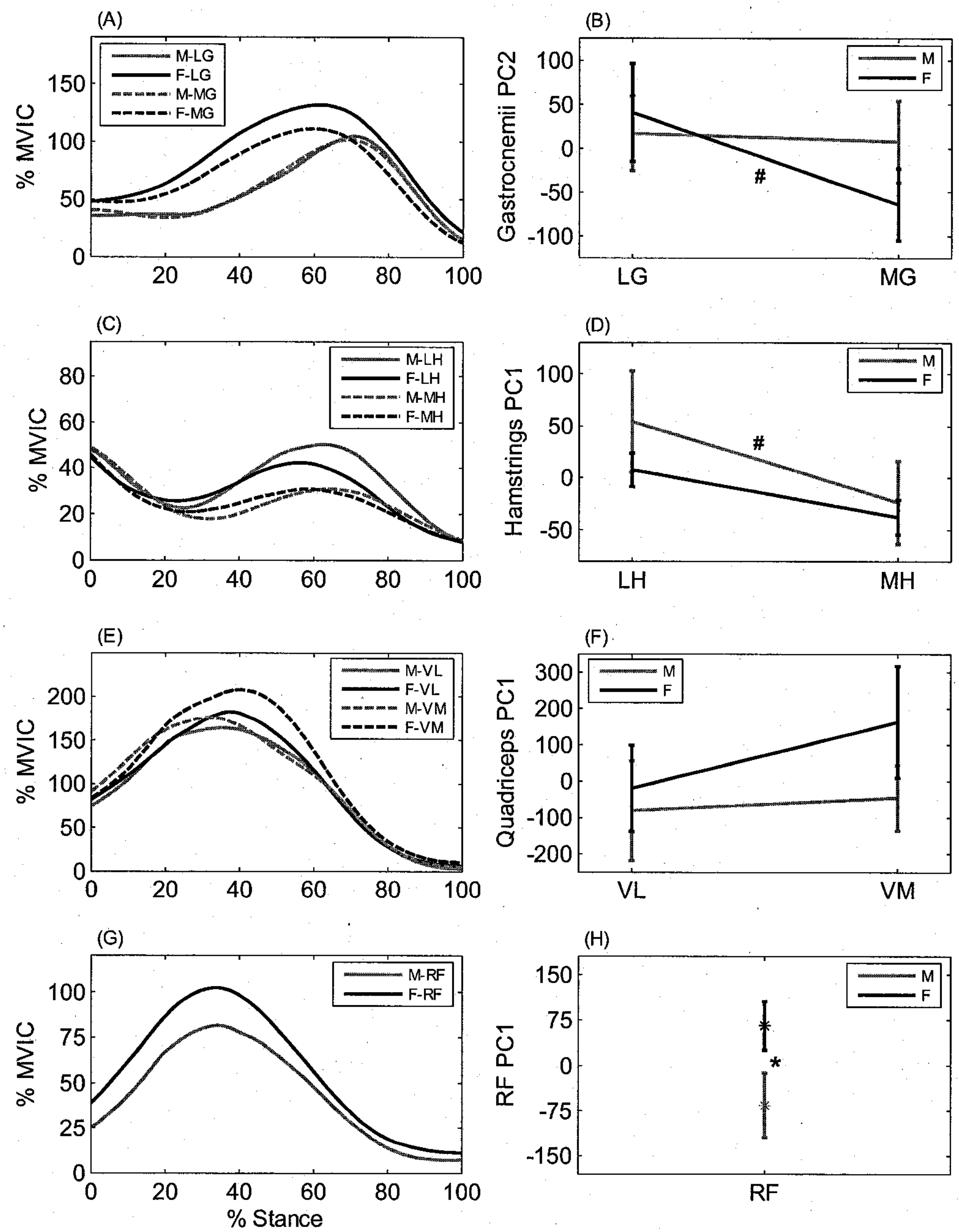

Figure 4.2. Male and female mean muscle activation waveforms for the stance phase of the side-cut and corresponding PC score means

Left column includes group means of the **A)** LG and MG, **C)** LH and MH, **E)** VL and VM and **G)** RF for the male and female MVIC normalized ensemble average activation waveforms during stance. Right column includes male and female PC score group means with standard error of the means for **B)** PC2 (magnitude during late stance) of the LG and MG, **D)** PC1 (magnitude throughout stance) for the LH and MH, **F)** PC1 (magnitude throughout stance) for the VL and VM and **H)** PC1 (magnitude throughout stance) for the RF. * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).

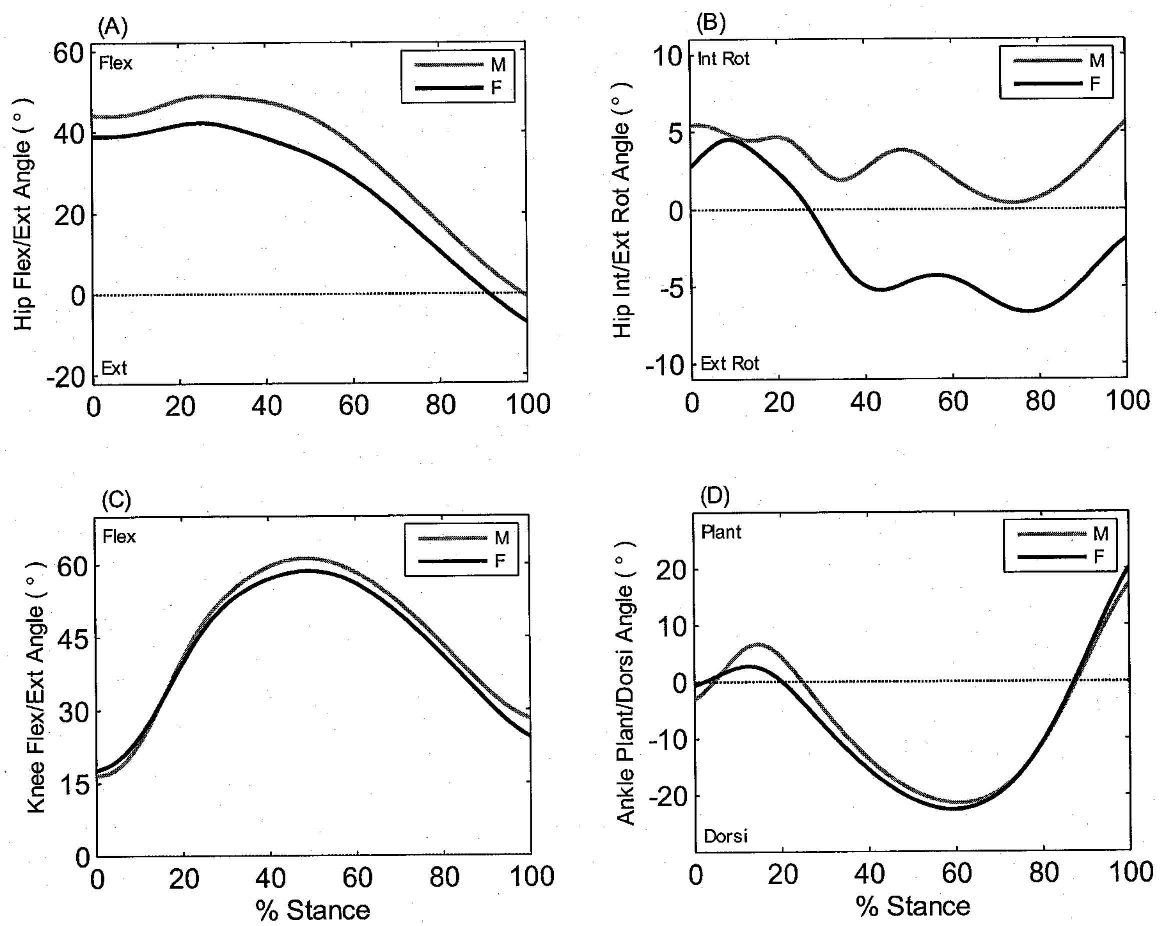

Figure 4.3. Male and female mean joint angle waveforms for the stance phase of the side-cut

A) hip flexion/extension, **B)** hip internal/external rotation, **C)** knee flexion/extension and **D)** ankle plantar/dorsiflexion.

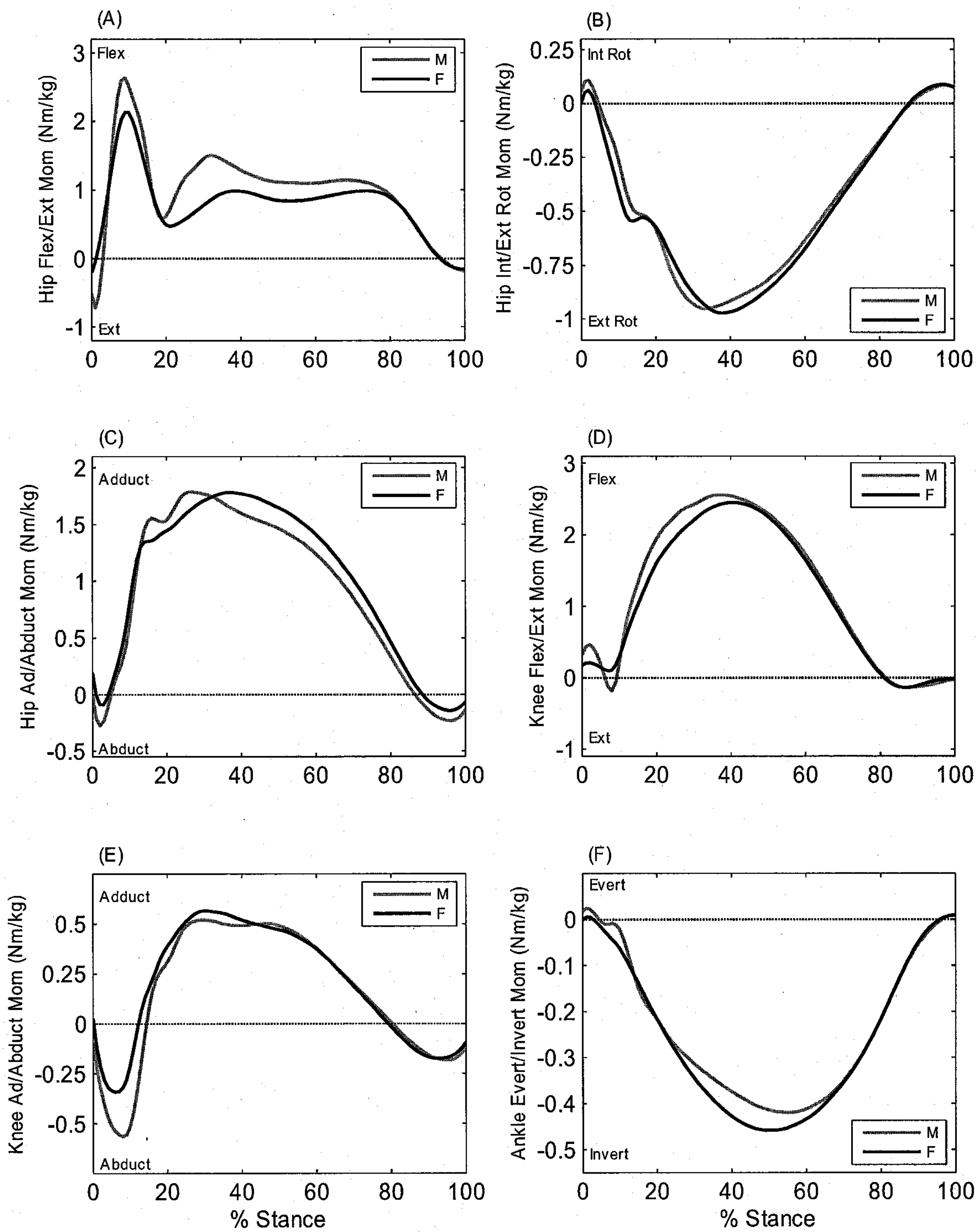

Figure 4.4. Male and female mean joint moment waveforms for the stance phase of the side-cut

A) hip flexion/extension, **B)** hip internal/external rotation, **C)** hip adduction/abduction, **D)** knee flexion/extension, **E)** knee adduction/abduction and **F)** ankle eversion/inversion.

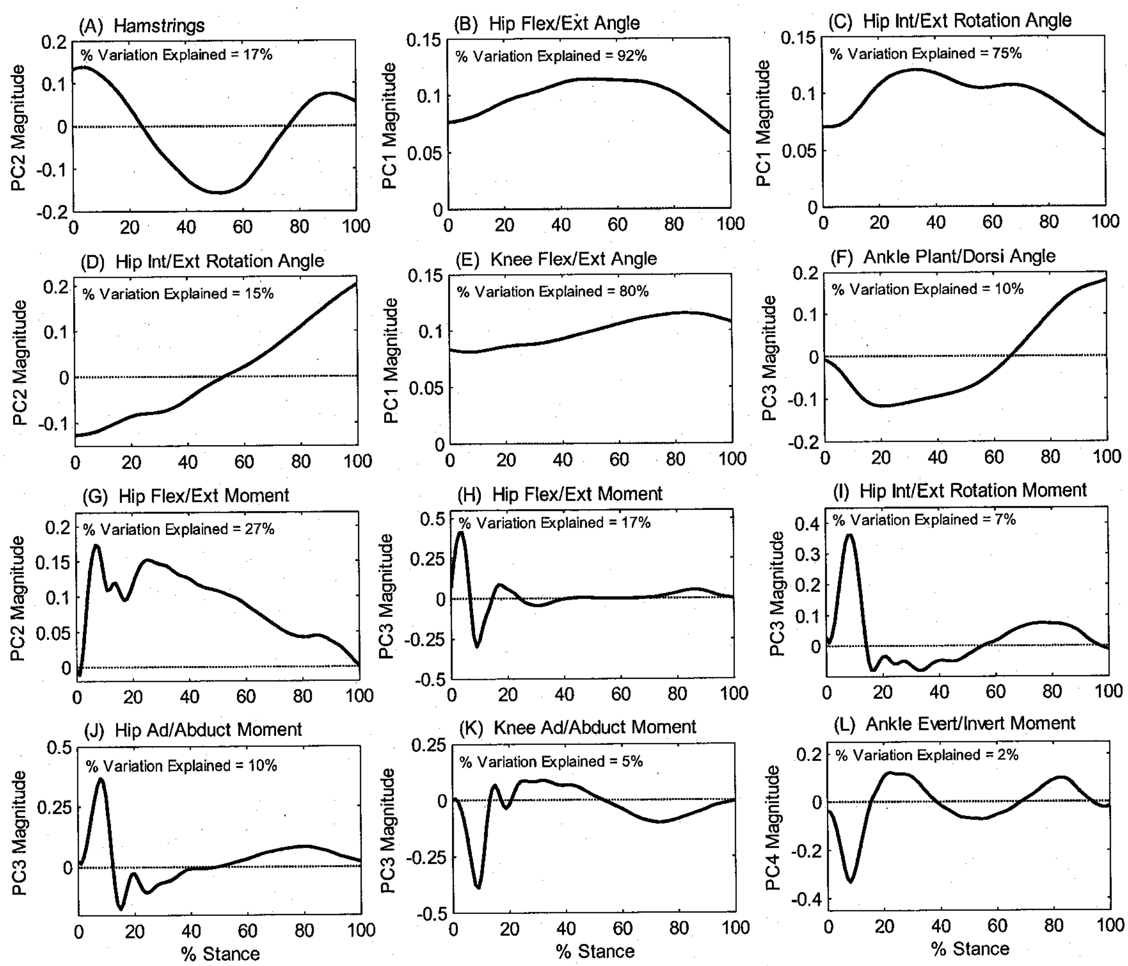

Figure 4.5. Side-cut PC waveforms for PC2 of the hamstrings and all kinematic and kinetic measures reported in Tables 4.2 and 4.3

Each of the 12 plots include an individual PC waveform and the total variation explained by that specific PC.

Table 4.1.
Descriptive and strength mean (SD) data for male and female subjects

	Male	**Female**	**p-value**
Anthropometrics			
Age (yrs)	17.0 (0.6)	16.7 (1.0)	0.19
Height (m)	1.77 (0.05)	1.65 (0.07)	**<0.0001**
Weight (kg)	69.6 (6.6)	60.8 (5.5)	**<0.0001**
BMI (kg/m^2)	22.1 (1.7)	22.4 (1.8)	0.63
Cutting Characteristics			
Approach Speed (m/s)	3.50 (0.09)	3.44 (0.10)	0.08
Soccer Experience			
Years Played (yrs)	10.7 (1.7)	9.8 (2.1)	0.15
Strength			
KE45° supine (Nm)	139.5 (24.8)	115.5 (20.7)	**0.001**
KF55° prone (Nm)	86.8 (22.5)	66.3 (13.8)	**0.001**
KF55° supine (Nm)	74.4 (27.5)	52.9 (14.1)	**0.003**
PF seated (Nm)	122.4 (39.4)	91.0 (21.7)	**0.003**
KF55° supine / KE45°	0.53 (0.16)	0.46 (0.08)	0.10
KF55° prone / KE45°	0.62 (0.12)	0.58 (0.11)	0.24

Student t-tests used to test for differences between genders. Statistically significant differences in bold (p<0.05). KE=knee extension, KF=knee flexion, PF=plantar-flexion

Table 4.2.
Interpretation and p-values for the muscle activation PC waveforms during the side-cut maneuver

Muscle Group	**PC**	**Interpretation**	**Gender Comparison p-value**		**Med-Lat site Comparison p-value**	
Gastrocnemii (LG & MG)	PC1	Magnitude during early to mid-stance (≈0-70%)	Med site	**<0.003**	Male	1.0
			Lat site	**<0.003**	Female	**0.05**
	PC2	Magnitude during late stance (≈70-100%)	Med site	0.14	Male	1.0
			Lat site	0.89	Female	**0.02**
Hamstrings (LH & MH)	PC1	Magnitude throughout stance	Med site	0.95	Male	**0.02**
			Lat site	0.29	Female	0.32
	PC2	Magnitude /shape during early and mid-stance	Med site	0.62	Male	**0.001**
			Lat site	0.97	Female	0.09
Quadriceps (RF site only)	PC1	Magnitude throughout stance	-	**0.05**	-	-

Repeated measures ANOVA used on PC scores for hamstrings and gastrocnemii activation waveforms, using Tukey adjusted post-hoc pairwise comparisons. Student t-tests used to test for differences in PC scores for RF. Significant differences in bold (p<0.05). Med=medial, Lat=lateral

Table 4.3.

Interpretation, gender means, standard error of the means and p-values for the kinematic and kinetic PC waveforms during the side-cut maneuver

Gait Measure	PC	Interpretation	PC Score Means (SEM) Male	PC Score Means (SEM) Female	p-value
Joint Angles					
Hip Flex/Ext	PC1	Magnitude throughout stance	36.2 (21.3)	-36.2 (17.0)	**0.01**
Hip Int/Ext Rotation	PC1	Magnitude throughout stance	27.6 (18.4)	-27.6 (15.3)	**0.03**
	PC2	Amplitude/shape throughout stance	11.1 (7.3)	-11.1 (8.0)	**0.05**
Knee Flex/Ext	PC1	Magnitude throughout stance	9.0 (18.9)	-9.0 (13.9)	0.45
Ankle Plant/Dorsiflex	PC3	Phase shift throughout stance	-8.6 (4.8)	8.6 (4.8)	**0.002**
Joint Moments					
Hip Flex/Ext	PC2	Magnitude throughout stance	1.38 (0.64)	-1.38 (0.52)	**0.02**
	PC3	Amplitude during early stance (≈0-20%)	-0.67 (0.54)	0.67 (0.45)	0.06
Hip Int/Ext Rotation	PC3	Magnitude during early stance (≈0-12%)	-0.16 (0.09)	0.16 (0.10)	**0.03**
Hip Ad/Abduct	PC3	Magnitude during early stance (≈0-12%)	0.42 (0.21)	-0.42 (0.33)	**0.04**
Knee Ad/Abduct	PC3	Magnitude during early stance (≈0-12%)	0.23 (0.16)	-0.23 (0.18)	0.06
Ankle Evert/Invert	PC4	Magnitude during early stance (≈0-20%)	-0.045 (0.04)	0.045 (0.02)	**0.05**

Student t-tests used to test for differences between genders in the PC scores for kinematic and kinetic waveforms. Statistically significant differences in bold ($p<0.05$).

Chapter 5 - Unanticipated Running and Cross-cutting Maneuvers Demonstrate Neuromuscular and Lower Limb Biomechanical Differences Between Elite Adolescent Male and Female Soccer Players

In large part, the contents of this chapter were submitted for review on January 25, 2007 in the American Journal of Sports Medicine.

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5.1 Introduction

The anterior cruciate ligament (ACL) is a knee ligament that is commonly injured in sports such as soccer, basketball and volleyball where maneuvers like decelerating, landing from a jump and/or cutting to change directions are often performed. Depending on the sport, the ACL injury rate is 2-8 times higher in females compared to males[8,128] and 70-80% of the time, the injury is non-contact in nature with no direct blow occurring at the knee.[21,153] ACL injuries can immediately affect the activity level and quality of life of individuals inflicted with this injury and secondary knee disorders such as subsequent meniscal tears and post-traumatic knee osteoarthritis can often follow.[213]

The 1990s saw a shift in focus from the diagnosis and treatment of ACL injuries to defining ACL injury risk factors and identifying non-contact injury mechanisms.[72] While ACL injury risk factors have most commonly been categorized as either intrinsic (i.e. joint laxity, Q-angle, femoral notch width) or extrinsic (i.e. playing surface, shoe-surface interaction, neuromuscular control strategies),[8,95,164] they have also been categorized as environmental, anatomical, hormonal and biomechanical in the literature.[42,72,225]

Biomechanical or neuromuscular risk factors are difficult to quantify during actual games or practices where an ACL injury is most likely to happen. It is believed that potentially modifiable biomechanical risk factors such as body positioning, joint loading and neuromuscular coordination can be identified in the motion laboratory by comparing males and females and then later used to help develop and improve upon preventative training regiments aimed at reducing ACL injuries, particularly in females.

Running and then cutting has been identified as a maneuver that often results in non-contact ACL injuries and there have been many laboratory based studies that have attempted to identify injury risk factors by comparing joint kinematics, kinetics and/or lower limb electromyography between genders. Most of the gender comparative studies looking at running and cutting have focused on the side-cut,[60,127,137-140,167,191] with only a select few focusing on running and/or cross-cutting.[57,127,140]

Ferber et al.[57] compared hip and knee joint kinematics and kinetics during the first 60% of stance for running and found that females generated greater peak hip adduction, peak hip internal rotation and peak knee abduction angles compared to their male counterparts.

Although joint moments were measured in this study, statistical comparisons between genders were not carried out. The kinematic gender differences were not discussed in terms of ACL risk factors; however, the authors did comment that the larger hip internal rotation angle coupled with the greater knee abduction angle in females could be resulting in a greater dynamic Q-angle. The link between a larger Q-angle and an increased knee injury rate continues to be debated within the literature. Shambaugh et al.[185] looked at 45 recreational basketball players and found that the average Q-angle for athletes with knee injuries was significantly greater than the average Q-angle for the uninjured athletes. Others, however, have concluded that knee injury rates are not related to Q-angle and that the static Q-angle is not predictive of ACL injury risk during dynamic tasks.[70,77]

In one of the most comprehensive biomechanical and neuromuscular gender comparative studies related to ACL injury risk factors, Malinzak et al.[127] analyzed 3 separate athletic maneuvers including a preplanned straight run, cross-cut and side-cut. While joint kinetics were not reported, they were able to identify kinematic differences at the knee as well as neuromuscular differences between genders for the quadriceps and hamstrings during the stance phase of all 3 maneuvers. Females demonstrated larger knee abduction angles than males throughout stance for the maneuvers and this is in agreement with the same gender difference reported by Ferber et al.[57] during straight running. Also related to knee kinematics, Malinzak et al.[127] reported that females performed the maneuvers with less knee flexion than males throughout stance. Non-contact ACL injuries frequently occur with the knee close to full extension and with the knee in an abducted position during jumping and cutting tasks performed in sports such as soccer and basketball.[21,160] Therefore these kinematic gender differences may have a contributing role towards females having a greater risk of sustaining a non-contact ACL injury compared to males during dynamic tasks.

In contrast to the kinematic gender differences captured in the previously mentioned running studies, McLean et al.[140] also compared knee kinematics between genders while running and did not report any differences for mean maximum, minimum and range of motion for the 3 knee joint rotations during stance. Discrepancies between the studies could be attributed to McLean et al.[140] analyzing high performance athletes and Malinzak et al.[127] and Ferber et al.[57] both focusing on recreational athletes. McLean et al.[140] stated that males and females, particularly at the competitive level, are more likely to be equally capable of performing common locomotive movements such as running because the movements are learned and practiced extensively, which may not be the case for the recreational athlete.

Related to neuromuscular control, Malinzak et al.[127] were also able to show that females in general had greater quadriceps activity and less hamstring activity compared to males during the preplanned running and cross-cutting maneuvers. Contraction of the quadriceps at knee flexion angles less than approximately 45° has been shown to increase ACL strain through anterior pull of the patellar tendon on the tibia[9,19,174] and contraction of the hamstrings at knee flexion greater than approximately 30° can decrease ACL strain and resist anterior tibial translation.[144,174] The increased quadriceps activity and decreased hamstring activity in females, combined with the kinematic gender differences reported by Malinzak et al.,[127] all appear to have potential influences related to risk factors for female ACL injuries.

Gender comparative studies of running and cross-cutting maneuvers have only focused on preplanned maneuvers[57,127] and have ignored the potentially more dangerous unanticipated cutting maneuver, where the loads at the knee can be greater in comparison to preplanned maneuvers.[17] Light guiding systems in the laboratory have been used to more closely approximate a game-like situation and force the subjects to execute the athletic maneuvers at the last possible moment in an unanticipated manner.[16,17,60,89,167] In a study that did not address gender differences, Besier et al.[16,17] compared preplanned and unanticipated running and cutting maneuvers and concluded that muscle activations only increased approximately 10-20%, whereas joint moments increased approximately 100% when going from a preplanned to unanticipated maneuver. It was also determined that muscle activations took on a generalized co-contraction pattern for the unanticipated maneuvers and a more selective pattern for the preplanned maneuvers.

Principal component analysis (PCA), a multivariate analysis technique described in detail in previous papers,[47,91,112] has been used effectively to analyze biomechanical and neuromuscular waveform data and has become more commonly used in recent years within the biomechanical literature. PCA is an alternative analysis technique to the traditional parameter based analysis technique which subjectively chooses parameters such as means, maximums and minimums for statistical comparisons. PCA can be summarized as an orthogonal decomposition of an original dataset (group of waveforms) that objectively captures features of variation based on the variation within the original dataset. These features, which are extracted from entire waveforms, get related to specific biomechanical or neuromuscular waveform characteristics and then statistical hypothesis testing can be used to compare groups based on these features.

A comprehensive gender comparative study that simultaneously contrasts the lower limb neuromuscular response and the biomechanics of the hip, knee and ankle during unanticipated cross-cutting and straight running does not exist in the literature. Comparing activation patterns between the medial and lateral muscles sites for each of the 3 main muscle groups surrounding the knee (quadriceps, hamstrings and gastrocnemii) has also not been done for unanticipated running and cross-cutting maneuvers. Therefore, the purpose of this paper was to measure and compare the neuromuscular patterns of the lower limb as well as the kinetics and kinematics of the knee, hip and ankle during the stance phase of an unanticipated cross-cut and straight run maneuver in an elite adolescent soccer population using PCA. The hypothesis for this study was that biomechanical and neuromuscular differences would exist both between genders and between medial-lateral muscle sites and that these differences would help explain and/or identify non-contact ACL injury risk factors. While 3 different athletic maneuvers were performed in the same testing session for the study, this paper focuses only on the findings from the cross-cut and straight running maneuvers, with a previous paper focusing on the side-cut maneuver.[113]

5.2 Methods

5.2.1 Subjects

Participants for this study (males=21, females=21) were between the ages of 14 and 18 years (male=17.0 ± 0.6 yrs, female=16.7 ± 1.0 yrs) and were recruited from the Nova Scotia Provincial and Canada Games soccer teams. Participating subjects were required to have no prior history of major injury to the lower limbs (i.e. meniscus damage or substantial ligament damage to the knee or ankle) at the time of testing. Those subjects who reported previous ankle sprains were permitted to participate in the study if they no longer had pain or symptoms from the injury and sustained the injury at least 1 year prior to testing. All subjects and their respective guardian were required to sign a written consent form prior to testing and ethics approval for this study was obtained from the Research Ethics Board for Health and Medical Sciences at Dalhousie University.

5.2.2 Experimental Design

Prior to placing the infrared light emitting diode markers and EMG electrodes on the subject, trials of 3 different athletic maneuvers were demonstrated and then practiced by the subjects. The 3 maneuvers included a straight run, a running cross-cut between 35°-60° from the direction of travel (cutting to the right with the right foot planted on the force platform) and a running side-cut between 35°-60° from the direction of travel (cutting to the left with the right foot planted on the force platform). As previously noted, this paper will focus on the findings from the unanticipated cross-cut and straight running maneuvers only.

LabVIEW (National Instruments Corporation, Austin, TX, USA) controlled timing gaits and a 3-light guiding system were used to attain an approach speed of 3.5 ± 0.2 m/s for each trial and to simulate the unanticipated nature of the maneuvers by randomly cueing the subjects to either run straight, cross-cut or side-cut. Subjects had approximately 0.5 seconds of reaction time to perform the maneuvers and 5 acceptable trials for each maneuver were required for testing to be completed.

5.2.3 EMG and Motion Analysis

Three dimensional (3D) kinetics, kinematics and muscle activation patterns of 7 muscles for the right leg were collected for the stance phase of the 3 maneuvers. Using standardized placements on shaven and alcohol cleaned skin, silver/silver chloride surface electrodes (Bortec, Inc. Calgary, AB, Canada) were attached in a bipolar configuration (20 mm center-to-center) along the direction of the muscle fibers for the following muscles: rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), lateral hamstring (LH), medial hamstring (MH), lateral gastrocnemius (LG) and medial gastrocnemius (MG).[91,92,121] All EMG signals were preamplified (500x) and further amplified (bandpass 10-1000 Hz, CMRR=115 dB, input impedance ~ 10 Gohm) with an 8 channel surface EMG system (AMT-8 EMG, Bortec, Inc. Calgary, AB, Canada). Isolated movements[108] were performed to validate electrode placement and assess the EMG recordings.[217]

EMG data and ground reaction force data from an AMTI force platform (Advanced Medical Techonology, Inc. Watertown, MA, USA) were captured at a 1000 Hz with the 3D motion data being captured at a 100 Hz using an Optotrak motion analysis system (Northern Digital, Inc. Waterloo, ON, Canada). Marker triads were placed on the pelvis, thigh, shank and foot and individual markers were placed on the shoulder, greater trochanter, lateral epicondyle and lateral malleolus. Anatomical coordinate systems were created for the four segments using the anatomical markers, marker triads and the following virtual points: right and left anterior superior iliac spines, medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head and calcaneous.[28,112]

After all markers were positioned on the subject, a standing calibration trial was captured as the reference position on which all joint angle calculations were based upon. An ultra-thin stretchable stocking was also placed over the right leg during testing to prevent damage and entanglement of the EMG electrode and infrared marker wires. An EMG subject bias trial with the subject relaxed and 6 maximum voluntary isometric contraction (MVIC) exercises were performed to elicit maximal activation amplitudes for EMG amplitude normalization purposes.[91] Five of the 6 exercises were performed on a Cybex dynamometer (Lumex, Inc. Ronkonkoma, NY, USA) and the 6 isometric exercises included i) flexing the knee at 45° while sitting supine, ii) flexing the knee at 55° while lying prone, iii) simultaneously extending the knee at 45° and flexing the hip while sitting supine, iv) extending the knee at 45° while sitting supine, v) plantar-flexing the ankle with the ankle in a neutral position and vi) plantar-flexing the ankle while standing upright on toes against a resistance.[91]

5.2.4 Data Analysis

Matlab (The MathWorks Inc, Inc. Natick, MA, USA) was used to calculate three dimensional joint angles and moments for the ankle, knee and hip. Net external joint moments were calculated using inverse dynamics and both angles and moments were described about the 3 rotation axes of the floating axis joint coordinate system.[112,136,138] Sign conventions for the 3 joints had flexion (or plantar-flexion at the ankle), internal rotation (or eversion at the ankle) and adduction (or toe-in at the ankle) all being positive. At the knee, only knee flexion-extension angles were reported because the error associated skin movement and kinematic crosstalk has been reported to be of a similar order of magnitude to knee adduction-abduction and internal-external rotation angles.[15,104] The EMG data was bias corrected, full-wave rectified and low pass filtered at 6 Hz using a zero lag 4th order Butterworth filter. The raw kinematic data was also filtered in Matlab using custom written software. All EMG, kinetic and kinematic data were time normalized based on the stance phase of the maneuver with 101 data points ranging from 0% (foot strike) to 100% (foot off) in 1% increments. Moment data was amplitude normalized to body mass and EMG data was amplitude normalized to the maximal MVIC EMG amplitudes obtained using a 100 msec moving window algorithm for each muscle during the 6 normalization exercises.[91] Three to 5 trials for both maneuvers were averaged together to generate ensemble average waveform profiles for each of the kinetic, kinematic and EMG measures.

Each group of waveforms were analyzed with PCA by first creating a dataset that included placing the waveforms in a matrix that had the mean value at each instant of time removed from all the individual waveforms. An eigenvalue decomposition of the covariance matrix of the mean removed waveform dataset generated eigenvectors or principal components (PCs) that represented waveform features such as overall waveform magnitudes, local magnitudes, phase shifts and amplitudes based on the variability in the data. Each individual waveform received a score (PC score) based on how similar the individual waveform was to the specific PC feature being considered and then statistical hypothesis testing for group differences were performed on the corresponding PC scores. The order in which the features were extracted was also based on the percentage of total waveform variation that each PC captured with the PCs describing the greatest amount of variation being extracted first.

The straight run and cross-cut maneuvers were analyzed independently using separate PC analyses. For each of the quadriceps (VL and VM), hamstrings (LH and MH) and gastrocnemii (LG and MG) muscle groups, medial and lateral muscle site waveforms for the male and female athletes were included together in a separate PC analysis so that gender and medial-lateral muscle site differences could be analyzed for each of the 3 muscle groups. Gender differences for the RF muscle activations and for each joint angle and moment component were tested by including the male and female waveforms of each measure into separate PC analyses.

To test for statistically significant differences between genders ($p<0.05$), Student t-tests were used on the anthropometric measures and on the PC scores from the joint angle, joint moment and RF activation waveforms. A 2-factor mixed-model ANOVA, with the repeated measure being muscle site (lateral and medial), was used for comparing the quadriceps, hamstrings and gastrocnemii muscle groups. Post-hoc pairwise comparisons tested for medial-lateral and gender differences using a Tukey adjustment ($p<0.05$) with all analyses and statistical testing being performed in Matlab and Minitab (Minitab, Inc. State College, PA, USA).

5.3 Results

5.3.1 Subject Demographics and Maneuver Approach Speeds

As previously reported in the side-cut companion paper,[113] gender differences for subject demographics and approach speeds were identified for height and weight only (Table 5.1). Males were 12.0 cm taller ($p<0.0001$) and 8.81 kg heavier ($p<0.0001$) than females, with no differences being detected for age, BMI, years of playing experience and approach speeds for both maneuvers.

5.3.2 EMG

Male and female ensemble average muscle activation waveforms for both the unanticipated cross-cut and straight run maneuvers were each analyzed using four separate PC analyses (gastrocnemii, hamstrings, quadriceps and RF). The majority of the total waveform variance for the two maneuvers was captured by the first 3 PCs, with these PCs accounting for no less than 96.0%, 91.2%, 98.1% and 97.5% of the total variance in the gastrocnemii, hamstrings, quadriceps and RF waveforms, respectively. The overall magnitude of the muscle activation waveforms were generally captured by PC1, with large activation magnitudes corresponding to large PC scores. More subtle and less discriminatory features were captured by PC2 and PC3.

5.3.2.1 Gastrocnemii Activation Waveforms

For both the cross-cut and straight run, the overall gastrocnemii activation magnitude during early to mid-stance ($\approx$ 0-70%) was captured by PC1 (Table 5.2 and Figure 5.1A and 5.1D). The LG of females was activated to a higher percent of MVIC than the MG of females (cross-cut $p=0.009$; straight run $p=0.02$) and also more activated than the LG of their male counterparts (cross-cut $p<0.001$; straight run $p=0.002$) during the early to mid-stance portion of both maneuvers (Figure 5.1B and 5.1E). The medial-lateral imbalance evident in females was not present in the gastrocnemii of the male subjects for both maneuvers (cross-cut p=0.97; straight run p=0.62).

Gastrocnemii activation magnitude during the later half of stance (≈ 50-100%) was captured by PC2 and the gender and medial-lateral muscle site differences detected were different for the 2 maneuvers (Figure 5.1C and 5.1F). The only difference in late stance for the cross-cut maneuver was a medial-lateral imbalance in males, with the MG being activated to a higher percent of MVIC than the LG (p=0.04). For the straight run, the only late stance difference identified was greater LG activity in females compared to males (p=0.03). No difference between genders was present at the medial site (p=0.99) and there was no significant medial-lateral muscle site imbalance for either gender (male p=0.86; female p=0.30) during the straight run.

5.3.2.2 Hamstrings Activation Waveforms

Females demonstrated lower LH (p=0.006) and MH (p=0.05) activity compared to males throughout the duration of stance (PC1) for the cross-cut (Table 5.2 and Figure 5.1G and 5.1H). For the straight run, females had lower LH activity (p=0.01) compared to males but a difference between genders was not significant at the MH site (p=0.16, Figure 5.1J and 5.1K). The medial site difference was comparable to the lateral site difference for the straight run and a lack of statistical power (0.178) may be the reason why a statistically significant difference was not captured for the medial site.

Hamstring activation differences between early and mid-stance were captured by PC3 for both the cross-cut and straight run (Table 5.2). Medial-lateral differences were found for the female athletes during the cross-cut maneuver only (p=0.003, Figure 5.1G and 5.1I). The female LH was less active than the MH during early stance and more active that the MH during mid-stance. For the straight run, a medial-lateral difference captured by PC3 was evident in the male subjects only (p=0.01, Figure 5.1J and 5.1L). The MH of the males was activated at relatively the same magnitude during early and mid-stance whereas the LH was activated at a greater magnitude during mid-stance compared to early stance.

5.3.2.3 Quadriceps Activation Waveforms

The VM and VL were analyzed simultaneously and the RF analyzed separately for both maneuvers (Table 5.2 and Figure 5.2). For the simultaneous analysis of the VM and VL, a medial-lateral site activation imbalance was not detected for either maneuver (Figure 5.2A-5.2D). Differences between genders for the VM and VL were detected for the straight run only (Figure 5.2C and 5.2D), with females having greater activation magnitudes than males throughout the duration of stance for both the medial ($p=0.01$) and lateral muscle sites ($p=0.02$). RF activity in females was greater than males for both the cross-cut ($p<0.001$, Figure 5.2E and 5.2F) and straight run ($p=0.006$, Figure 5.2G and 5.2H) maneuvers.

5.3.3 Kinematics

The most prominent kinematic differences between males and females were found at the hip followed by the ankle, with no differences detected at the knee for both maneuvers (Table 5.3 and Figure 5.3). PCA effectively described the cross-cut and straight run kinematic waveform data, with the first 3 PCs capturing between 96.0-99.6% of the total variance for each waveform measure. Mean PC scores for the male and female subject groups along with all the p-values for the kinematic and the kinetic gender comparisons are listed in Table 5.3. Figure 5.5 also includes all the kinematic and kinetic PC waveforms for the measures reported in Table 5.3 to aid with the interpretation of the PCA results.

Males demonstrated larger hip flexion angles compared to females (PC1) during the stance phase of the cross-cut ($p=0.01$, Figure 5.3A), however, the difference in hip flexion angle for the straight run was not statistically significant ($p=0.13$, Figure 5.3B). Hip adduction angle range of motion was captured by PC2 and between the 2 maneuvers, a difference between genders was statistically significant for the straight run only ($p=0.01$, Figure 5.3D). A difference of a similar magnitude was also present for the cross-cut, however, a lack of statistical power could be a possible explanation for this difference not being statistical significant ($p=0.08$, power=0.421, Figure 5.3C). Based on this feature, males landed with a smaller hip adduction angle and went into a more adducted position as stance progressed. Females, however, landed with a more adducted hip joint than males at initial contact and maintained a more constant hip adduction angle as stance progressed.

At the ankle, kinematic differences were detected for both maneuvers (Table 5.3 and Figure 5.3). Females demonstrated greater ankle eversion angles compared to males throughout the duration of stance (PC1) for the cross-cut maneuver (p=0.002, Figure 5.3E). For the straight run, an eversion angle difference based on gender was not detected (p=0.20, Figure 5.3F). Males did, however, perform the straight run with a larger toe-out angle for the entire stance phase (PC1) compared to females (p=0.04, Figure 5.3H). At the knee and for both maneuvers, no gender differences were captured for knee flexion angle (cross-cut p=0.34; straight run p=0.57). Because knee flexion angles are commonly reported in cutting and landing related studies, the PC waveforms for this measure were included in Figure 5.5 and the PC scores included in Table 5.3.

5.3.4 Kinetics

Differences between genders in net external joint moments were identified at the hip and knee with no differences identified at the ankle (Table 5.3 and Figure 5.4). Four PCs were analyzed for each joint moment component with PC1 capturing an overall moment magnitude throughout stance and PC2-PC4 capturing more subtle waveform features during different portions of the stance phase. For both maneuvers, the first 4 PCs for each waveform measure explained at least 91.4% and 97.2% of the variation in the knee and ankle moment waveforms, respectively. For the hip moments, the first 4 PCs described at least 86.6% of the variation in moment waveforms for both the cross-cut and straight run. Mean PC scores for the male and female subject groups along with all the p-values for the kinetic gender comparisons are listed below the kinematic gender comparisons in Table 5.3.

The first PC for hip flexion moment captured a biomechanical waveform feature that was related to both an early stance (≈ 0-10%) flexion-extension moment magnitude and also an overall flexion moment magnitude during the remaining stance phase (Figure 4A and 4B). For both maneuvers, males tended to land with a greater hip extension moment and as early stance progressed and the moment increased to a greater flexion moment, males tended to be experiencing a smaller hip flexion moment compared to the females. After early stance and for the remainder of stance, however, males experienced a greater overall hip flexion moment in comparison to the female athletes (cross-cut p=0.003; straight run p=0.004, Figure 5.4A and 5.4B). With respect to the frontal plane hip moment, females generated a greater hip adduction moment throughout stance for the cross-cut (p=0.03, Figure 5.4C) with no hip adduction moment differences detected for the straight run (p=0.23, Figure 5.4D). Hip external rotation moment differences were evident for the straight run (p=0.04, Figure 5.4F) but not the cross-cut (p=0.12, Figure 5.4E), with females experiencing a greater overall hip external rotation moment than males during the stance phase of the straight run.

Differences between males and females in knee flexion moment (PC3) for the cross-cut and straight run (Figure 5.4G and 5.4H) and in knee adduction moment (PC1) for only the cross-cut were also identified (Figure 5.4I). During early stance (≈0-12%), females tended to experience a knee extension moment in comparison to more of a knee flexion moment in males for both maneuvers (cross-cut p= 0.04; straight run p=0.01). For the knee adduction moment of the cross-cut only, females experienced a larger knee adduction moment throughout stance (p=0.03, Figure 5.4I).

5.3.5 Results Summary

Gender differences related to lower limb kinematics, kinetics and neuromuscular function as well as medial-lateral muscle site differences in neuromuscular function for the unanticipated straight run and cross-cut were identified using PCA in an elite adolescent soccer population. Females demonstrated greater LG activity compared to males as well as a medial-lateral gastrocnemii activation imbalance (LG activity > MG activity) that was not present in males for both the unanticipated maneuvers. Females also exhibited greater VL and VM activity for the straight run only and greater RF activity for both the cross-cut and straight run. For the hamstring muscle sites, females demonstrated less LH activity for both maneuvers and less MH activity for just the cross-cut maneuver.

Females performed the cross-cut with less hip flexion than males and for both maneuvers, females had a smaller hip flexion moment throughout stance. For the cross-cut only, females exhibited a greater hip and knee adduction moment and increased ankle eversion motion throughout stance. During early stance for both maneuvers, females also tended to have a knee extension moment whereas males were more likely to have a knee flexion moment.

5.4 Discussion

For an elite adolescent soccer population performing an unanticipated cross-cut and straight running maneuver, neuromuscular and biomechanical gender differences were identified and used to help explain and understand why females are at greater risk of injuring their ACL compared to males. The main differences proposed to be related to the ACL injury gender bias include differences in the muscle activation waveforms of the gastrocnemii, hamstrings and quadriceps, as well as differences in hip joint kinetics and kinematics. The gender and medial-lateral muscle site differences were throughout the duration of stance and at specific instants of the stance phase for the cross-cut and straight run. In addition to being the first study to simultaneously make medial-lateral and gender comparisons for the neuromuscular waveforms during the running and cutting maneuvers, this study is also one of the first to suggest that the gastrocnemii may have a contributing role towards the higher prevalence of non-contact ACL injuries seen in females compared to males.

Females demonstrated greater LG activity during early to mid-stance compared to males for both maneuvers. It is thought that while the increased female LG activity could be attempting to stabilize the posterolateral aspect of the knee by stiffening the female knee, which tends to be more lax compared to males;[176] the increased activity may also be increasing the load on the ACL. Studies using a computer based model[157] and a differential variable transducer implanted on the ACL in vivo[58] have shown that contracting the gastrocnemii alone or in combination with the quadriceps can increase ACL strain. The greater LG activity could also be leading to earlier fatigue onset in females and be placing the knee at further risk of injury due to an inability to properly stabilize the knee joint later in a game or practice. Also possibly contributing to knee joint instability is the fact that females showed a medial-lateral site activation imbalance with the LG being more activated than the MG for both maneuvers. This imbalance was not evident in the male subjects and to fully understand how the observed imbalance in females might be affecting the knee joint, further investigations are recommended.

Contracting the quadriceps at knee flexion angles less than approximately 45° can increase the load on the ACL through anterior pull of the patellar tendon on the tibia.[9,174] A larger quadriceps activation magnitude in females compared to males during various athletic maneuvers has also been identified as a potential risk factor for ACL injury.[127,191,227] In the current study, RF activity throughout stance was greater in females for both the unanticipated cross-cut and straight run. VL and VM activity was also greater in females compared to males for the straight run only, supporting the results of Malinzak et al.[127] who observed the greater quadriceps activity (VL and VM averaged together) in females, particularly for a preplanned straight run. Our quadriceps results for the unanticipated maneuvers along with the previously reported results for the preplanned maneuvers[127] suggest that gender differences between the two types of maneuvers are similar and that females could be experiencing greater ACL strains through the anterior pull of the tibia by the more highly activated quadriceps during the athletic maneuvers.

The hamstrings have an important protective role for the ACL and this muscle group is thought to be an ACL agonist during various dynamic tasks. A reduction in both anterior tibial translation and ACL strain has been demonstrated when the hamstrings contract or generate forces at knee flexion angles greater than approximately 30°.[144,174] Muscle contraction is also important for knee joint stability[65,199] and a reduction in hamstring activity during athletic maneuvers has been proposed as potential risk factor for ACL injuries, particularly in females.[127] For the stance phase of the unanticipated cross-cut, females demonstrated smaller LH and MH activation magnitudes compared to the male subjects. The same difference between genders was also present for the straight run, however, the MH site difference was not statistically significant (p=0.16) and lacked statistical power (0.178). These hamstring differences are also similar to the study by Malinzak et al.[127] who reported that normalized hamstring activation magnitudes for females were generally lower than males, especially for a preplanned cross-cut and straight run. Both studies show that female subjects tend to perform the two athletic maneuvers, whether preplanned or unanticipated, with less hamstring activity and more quadriceps activity compared to their male counterparts. Malinzak et al.[127] stated that while the increased activation of the quadriceps in females does not necessarily correspond to increased quadriceps force, the combination of the increased quadriceps activity and decreased hamstring activity in the female athletes certainly increases the likelihood of greater knee anterior shear forces and hence increased ACL strain in the female subjects during the athletic maneuvers.

Medial-lateral imbalances were also captured for the gastrocnemii and hamstrings and not for the quadriceps. A plausible explanation for this could be related to the attachment site of these muscles onto the tibia and femur as they cross the knee. These muscles are better positioned for selective activation in order to control loadings and movements at the knee. The quadriceps attach centrally through the patellar tendon and selective activation of either the VM or VL would tend to have little effect in controlling non-sagittal plane loads or movements at the knee. The hamstrings and gastrocnemii, on the other hand, have medial and lateral attachment sites on the tibia and femur, respectively, and selective activation of either the medial or lateral sites would tend to have a more substantial influence in controlling internal-external rotation or adduction-abduction movements and loads, based on the greater moment arms at the knee for these 2 muscle groups.

Related to lower limb biomechanics, previous gender comparative studies of cross-cutting and running maneuvers have focused on the mechanics of the knee,[127,140] with only one study including the hip.[57] In our study, the most prominent gender differences in kinematics and kinetics were at the hip. Sagittal plane hip differences had females generating a smaller hip flexion angle than males for the unanticipated cross-cut only. Salci et al.[181] also reported reduced hip flexion angles in females for a block landing maneuver; a task that like cross-cutting has been associated with a high incidence of non-contact ACL injuries.[21,160] It has also been addressed in a number of landing papers that knee and hip angles can influence forces at the knee, with small flexion angles generating higher forces at impact or landing.[63,204] The reduced hip flexion angles observed in females for the current study could be resulting in greater impact forces at the knee, possibly putting the ACL at greater risk of being injured when performing the unanticipated cross-cutting maneuver. For the unanticipated straight run where non-contact ACL injuries are less likely to occur, however, we did not detect a gender difference in hip flexion angle and this agrees with the findings by Ferber et al.[57] for a preplanned run.

For the unanticipated cross-cut maneuver where non-contact ACL injuries are more likely to occur compared to straight running, moment differences between genders were captured at the knee and hip both throughout stance and also during early stance when the injury has been noted to usually take place.[21] Males demonstrated a greater overall hip flexion moment throughout stance compared to females and this may have a series of implications towards the ACL injury gender bias. Males could be experiencing the larger hip flexion moment to deal with the increased hip flexion angle present throughout stance. The greater hip flexion moment would thereby require an increased demand from the musculature extending the hip to balance the external moment. As previously mentioned, males generated higher activation magnitudes for both the LH and MH throughout the stance phase of the cross-cut and this might be providing the required force needed to keep the hip balanced. The increased hamstring activity, which may be required at the hip, could thereby be serving a secondary function as an agonist for the ACL, providing a posterior pull on the tibia and thereby decreasing the strain on the ACL[144,174] during the athletic maneuvers.

It has been reported that when performing athletic maneuvers such as landing, females absorb more energy in the sagittal plane at the knee and ankle in contrast to males who use their hip musculature to a greater extent to absorb the energy.[43] In the current study, the greater hip flexion moment seen in males compared to females, for both maneuvers, would tend to support this finding and may be an indicator that males are controlling their hip in a more optimum manner by absorbing more energy at the hip, thereby possibly decreasing the load and impact on the knee and ACL. The hip and the gluteal muscles also have an important role in not only controlling hip internal rotation but also hip adduction.[227] In contrast to the hip flexion moment and compared to males, we found that females had greater hip and knee adduction moments throughout the stance phase of the cross-cut. Again, females may not have adequate hip musculature strength or neuromuscular control to balance the larger hip adduction moments, putting their knee and ACL at further risk of being injured. The larger knee adduction moment in females may also be dangerous for the ACL and while an abduction knee moment or angle has more commonly been described as an ACL injury risk factor,[81,191] studies using cadavers have found that an adduction moment at the knee combined with an anterior tibial force can actually increase the loading on the ACL in an additive manner.[130]

In the sagittal plane, the early stance gender differences in hip and knee moments may also have implications towards the higher non-contact ACL injury rates seen in females. Females tended to experience a hip flexion moment sooner, thereby having a greater hip flexion moment magnitude than males in early stance for both maneuvers. At the knee, males also tended to have a small flexion moment during early stance compared to females, who had a small extension moment for both maneuvers. Based on the muscle activation findings already discussed, the increased LG activity in females could possibly be trying to counteract the knee extension moment which was more prevalent in females compared to males. The more highly activated RF observed in females could also be contributing to the greater knee extension moment during early stance. It appears that it could be of a possible benefit to the female athletes if they were able to generate greater hamstring forces to balance the knee extension moment and greater hip flexion moment in early stance. Females in this study, however, demonstrated reduced hamstring activity throughout stance for the cross-cut, indicating that they may not be adequately controlling their musculature to properly handle the hip and knee moments generated during the athletic maneuvers. It has been shown in the literature that sagittal plane loadings alone can not injure the ACL,[137] however, it is possible that the ACL could be damaged from a non-contact maneuver through the combination of the sagittal plane moment differences between genders along with the greater frontal plane moments seen in females compared to males.

While no kinetic differences were detected at the ankle, kinematic differences were identified at the ankle. Females demonstrated greater ankle eversion angles than males throughout the stance phase of the cross-cut and this agrees with findings from a stop jump unanticipated side-cut study by Ford et al.[60] Excessive subtalar joint pronation has been described as a possible ACL injury risk factor[13] because ankle eversion is coupled with tibial internal rotation,[135,150] a motion that the ACL has a significant role in resisting and controlling.[62,130]

In attempting to detect, interpret and understand biomechanical related issues during human movement, one of the greatest difficulties is trying to deal with the high degree of variability that can be introduced throughout various stages of the study. Similar to other biomechanical and neuromuscular studies that have analyzed athletic maneuvers such as running and cutting, variability in how the different athletes actually perform the maneuvers can make it difficult to detect differences. While approach speed and angle of cut were both diligently controlled in the study, subjects were instructed to perform the maneuvers in a manner that felt natural to them. It was evident by observing the athletes during testing that there were slight variations in how the athletes carried out the maneuvers, especially in an unanticipated manner. Several differences were successfully captured between the male and female subjects but there were some comparisons that lacked statistical power. This lack of power could be related to the inter-subject variability while performing the maneuvers or to the sample size, although the sample size was relatively large in comparison to similar studies that have analyzed the neuromuscular response, joint kinematics and joint kinetics for athletic maneuvers. Despite the high degree of variability in the waveforms, it was encouraging to see that the application of PCA successfully described the majority of the waveform variability with only a few PCs or eigenvectors for each waveform measure.

5.5 Conclusion

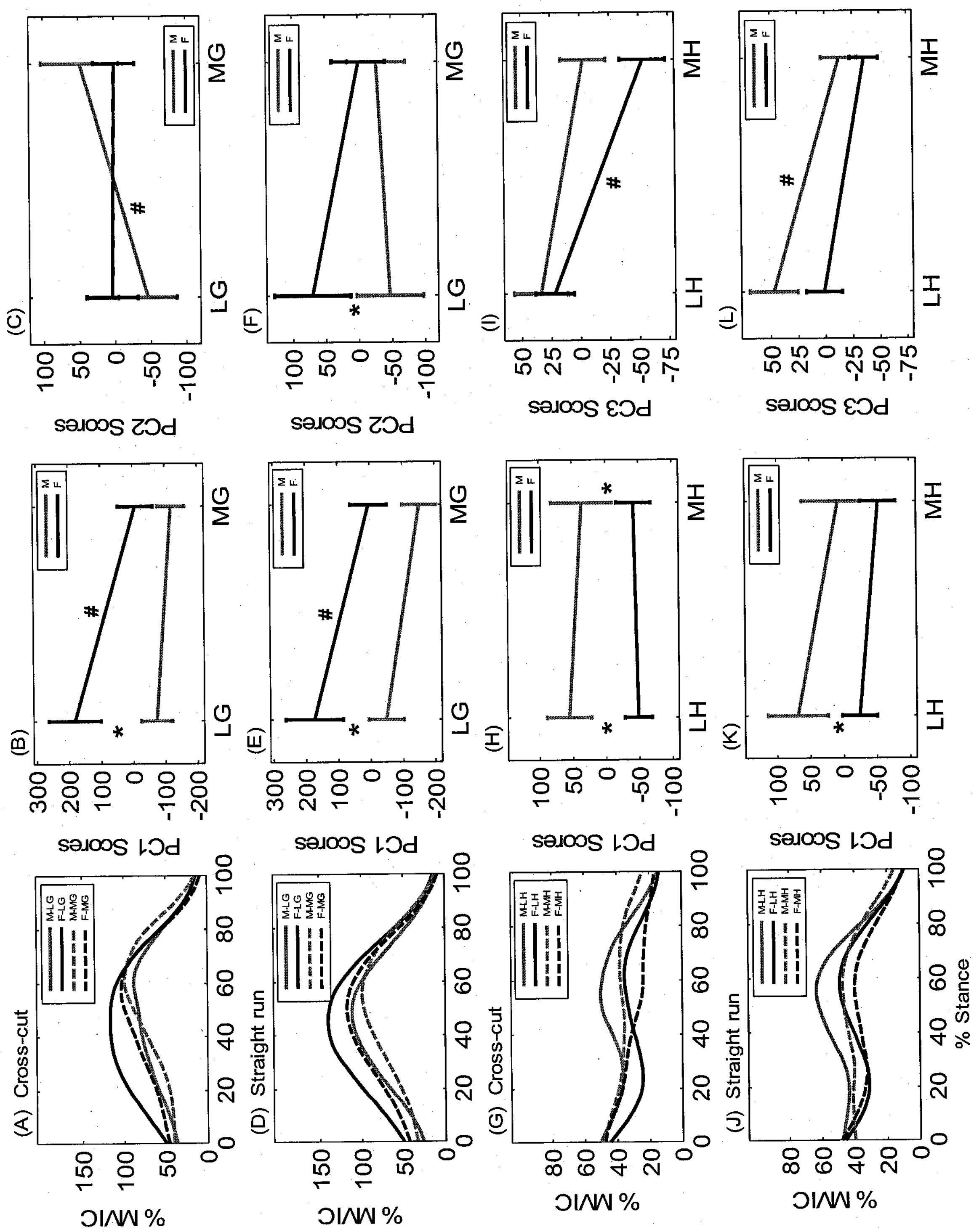
This study not only captured biomechanical and neuromuscular differences between male and female elite adolescent soccer players during unanticipated athletic maneuvers, but was also able to relate most of the differences between genders to ACL injury risk factors for females. To better replicate a game-like situation where the ACL is more likely to be damaged in a non-contact incident, the straight run and cross-cut maneuvers analyzed in this paper were both performed in an unanticipated manner. Unlike other studies addressing preplanned or unanticipated athletic maneuvers related to ACL injuries, this study also simultaneously compared kinematics and kinetics of the hip, knee and ankle as well as the neuromuscular activation patterns of 7 muscles surrounding the knee. Numerous differences previously identified in the literature as being ACL injury risk factors for females were identified in addition to other differences that have not been previously reported in the literature.

5.6 Acknowledgements

The authors would like to thank Nike, Inc. Sports Research Laboratory (Beaverton, Oregon) and NSERC for financial support and Soccer Nova Scotia for their cooperation and help in subject recruitment.

Figure 5.1. Male and female mean gastrocnemii and hamstring muscle activation waveforms for the stance phase of the cross-cut and straight run and corresponding PC score means

Left column includes male and female group means of the MVIC normalized ensemble average activation waveforms during stance for **A)** LG and MG of the cross-cut, **D)** LG and MG of the straight run, **G)** LH and MH of the cross-cut and **J)** LH and MH of the straight run. Center and right columns include male and female PC score group means with standard error of the means for **B)** PC1 (magnitude during early to mid-stance) and **C)** PC2 (magnitude during late stance) for LG and MG of the cross-cut, **E)** PC1 (magnitude during early to mid-stance) and **F)** PC2 (magnitude during late stance) for LG and MG of the straight run, **H)** PC1 (magnitude throughout stance) and **I)** PC3 (magnitude/shape during early and mid-stance) for LH and MH of the cross-cut and **K)** PC1 (magnitude throughout stance) and **L)** PC3 (magnitude/shape during early and mid-stance) for LH and MH of the straight run. For the PC score plots, * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).


(A) Cross-cut
(B)
(C)
(D) Straight run
(E)
(F)
(G) Cross-cut
(H)
(I)
(J) Straight run
(K)
(L)
% MVIC
% Stance
PC1 Scores
PC2 Scores
PC3 Scores
M-LG
F-LG
M-MG
F-MG
M-LH
F-LH
M-MH
F-MH
M
F
LG
MG
LH
MH

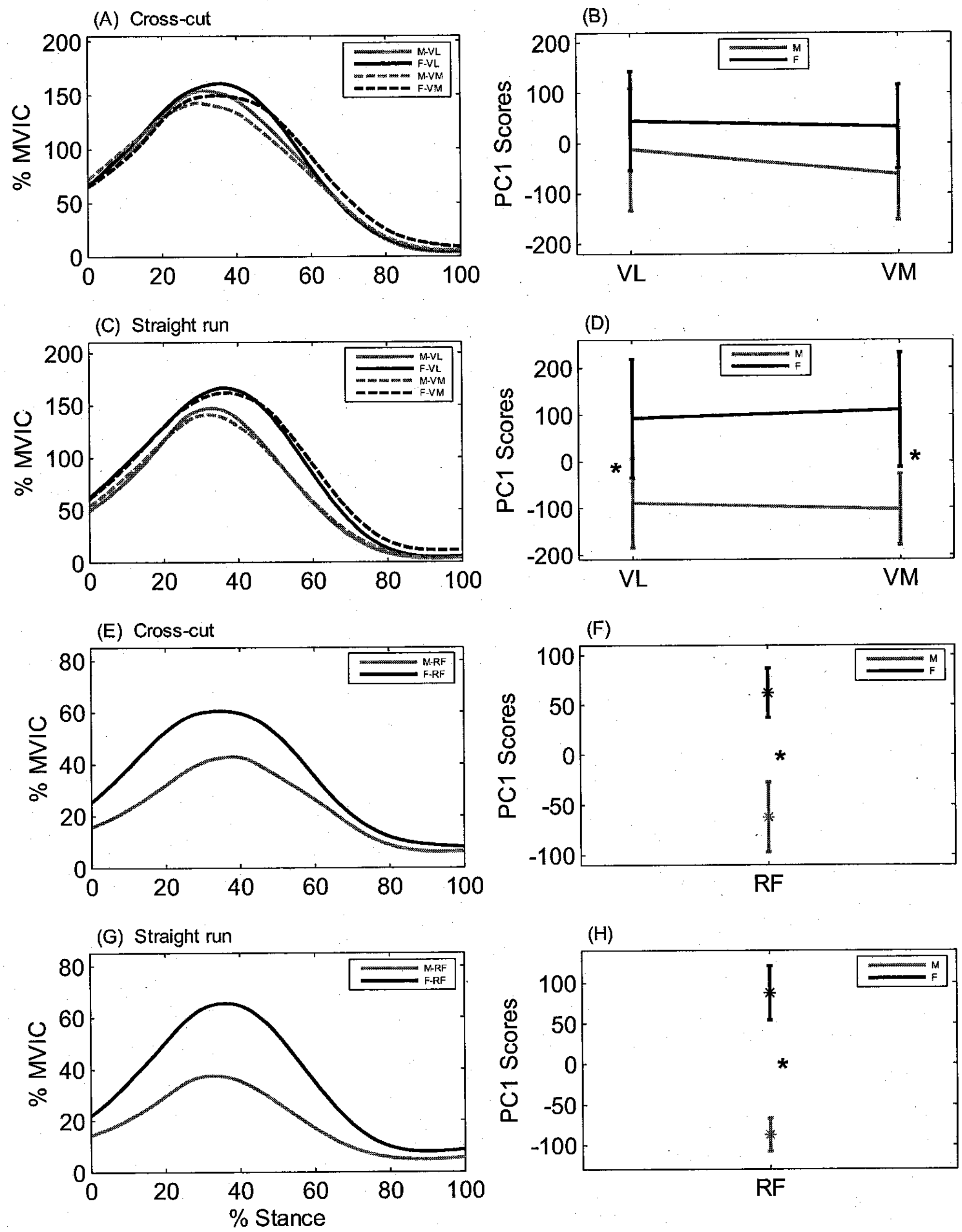


Figure 5.2. Male and female mean quadriceps muscle activation waveforms for the stance phase of the cross-cut and straight run and corresponding PC score means Left column includes group means of the MVIC normalized ensemble average activation waveforms during stance for **A)** VL and VM of the cross-cut, **C)** VL and VM of the straight run, **E)** RF of the cross-cut and **G)** RF of the side-cut. Right column includes male and female PC1 score (magnitude throughout stance) group means with standard error of the means for the **B)** VL and VM of the cross-cut, **D)** VL and VM of the straight run, **F)** RF of the cross-cut and **H)** RF of the straight run. For the PC score plots, * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).

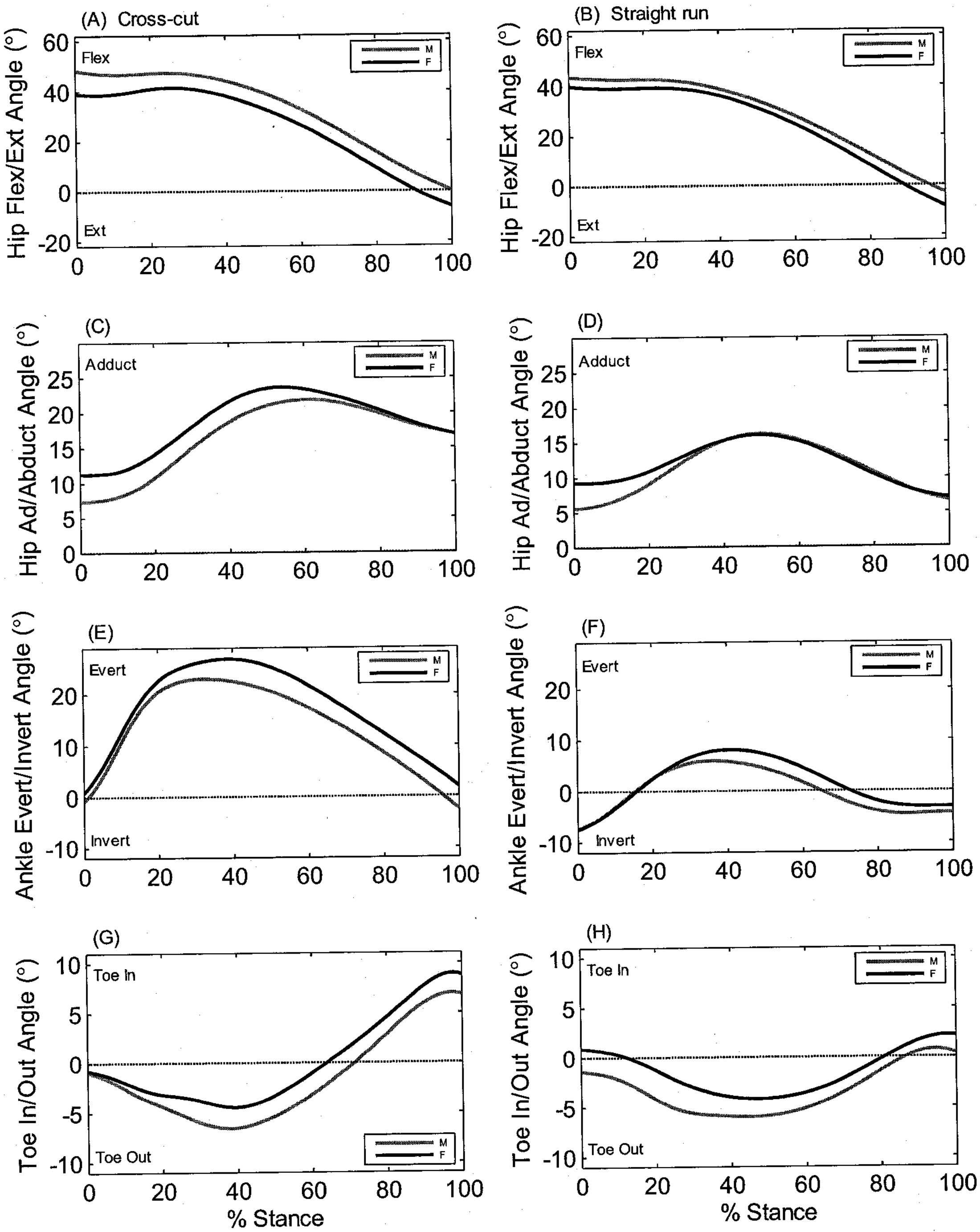


Figure 5.3. Male and female mean joint angle waveforms for the stance phase of the cross-cut and straight run

Left column corresponds to cross-cut and right column corresponds to straight run. **A)** and **B)** represent hip flexion/extension, **C)** and **D)** represent hip adduction/abduction, **E)** and **F)** represent ankle eversion/inversion and **G)** and **H)** represent toe in/toe out angle.

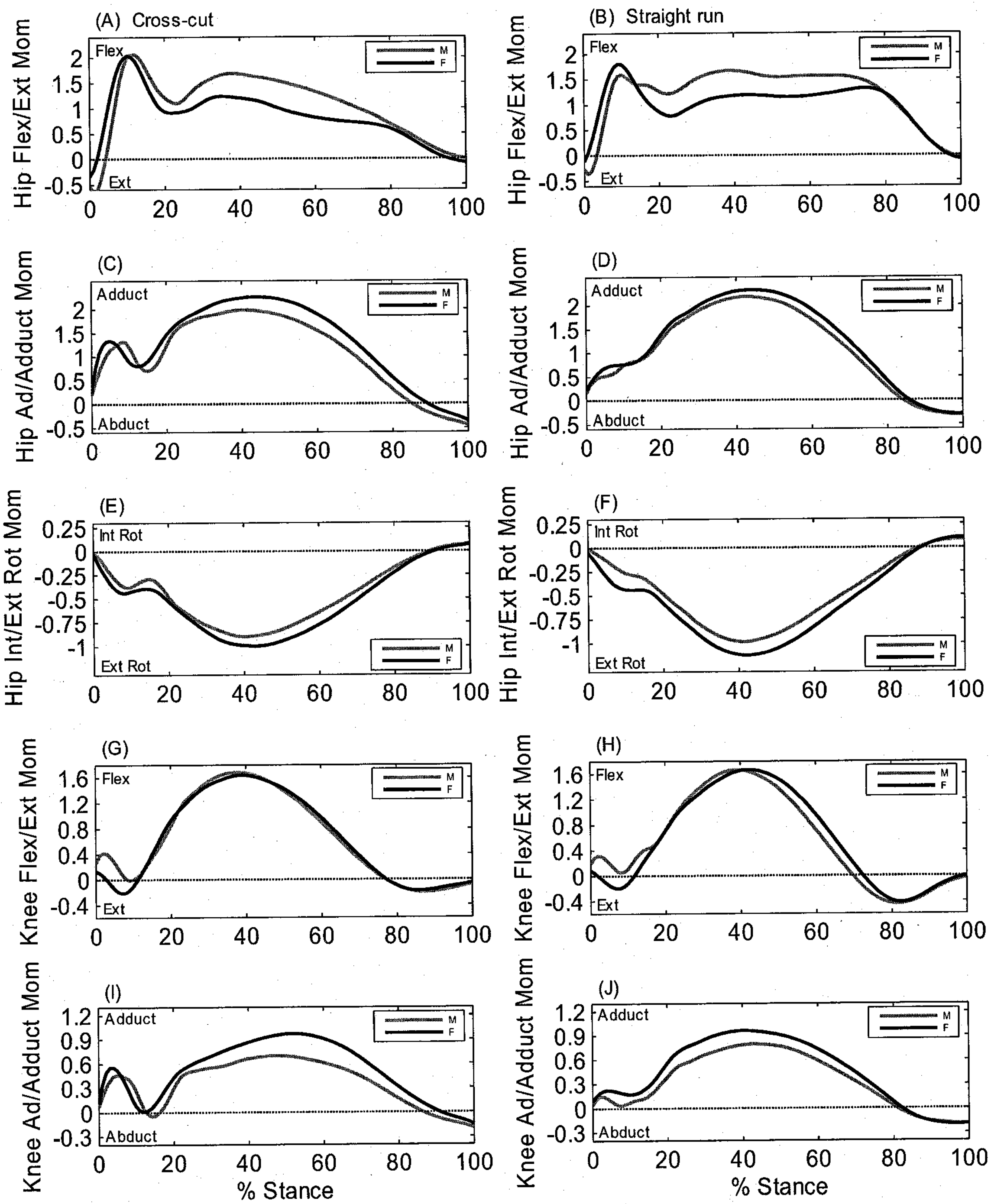


Figure 5.4. Male and female mean joint moment waveforms for the stance phase of the cross-cut and straight run

Left column corresponds to cross-cut and right column corresponds to straight run. **A)** and **B)** represent hip flexion/extension, **C)** and **D)** represent hip adduction/abduction, **E)** and **F)** represent hip internal/external rotation, **G)** and **H)** represent knee flexion/extension and **I)** and **J)** represent knee adduction/abduction moment.

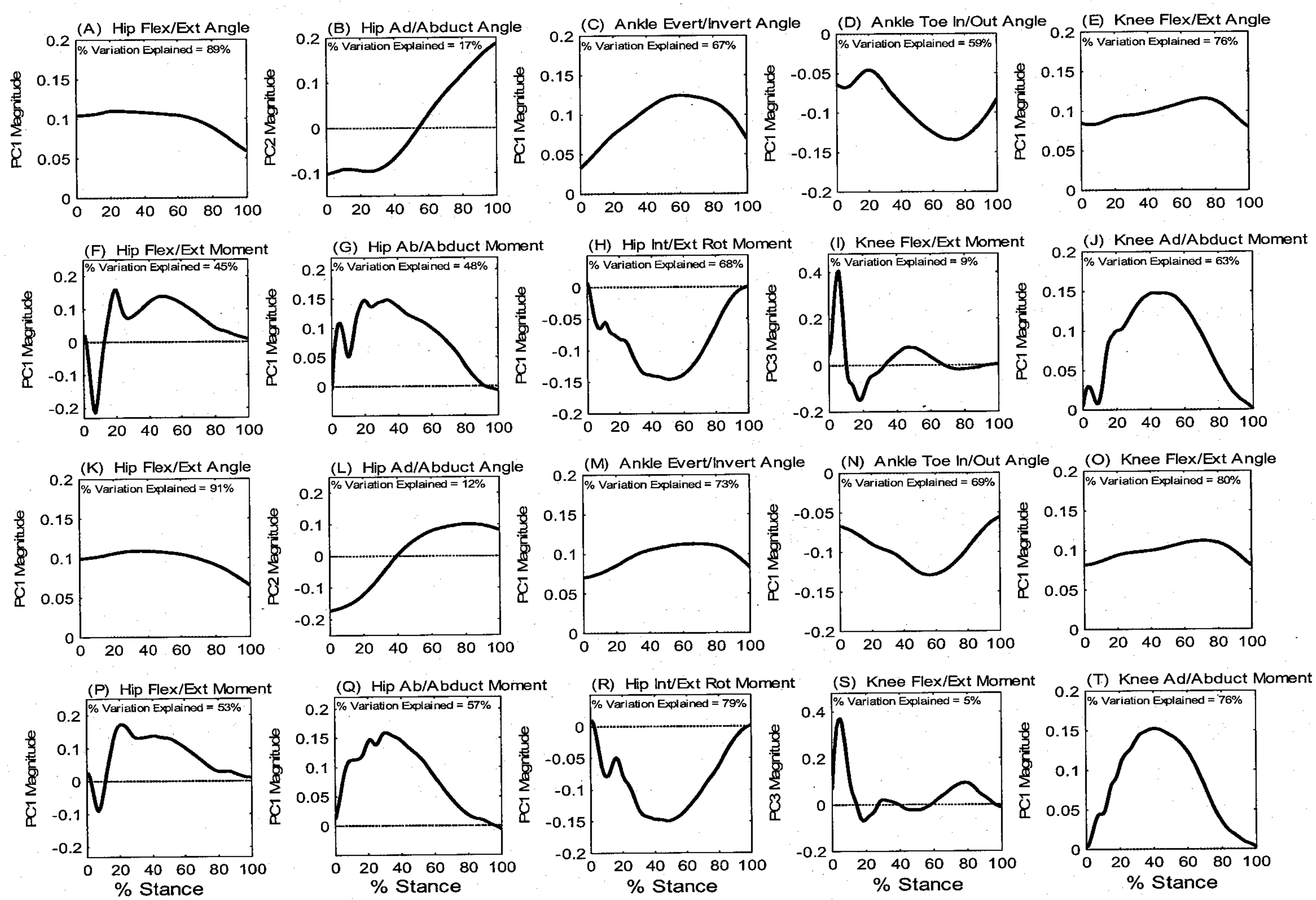


Figure 5.5. Cross-cut and straight run PC waveforms for kinematic and kinetic measures reported in Table 5.3
Each of the 20 plots include an individual PC waveform and the total variation explained by that specific PC. Plots **A)** to **J)** represent the cross-cut and plots **K)** to **T)** represent the straight run.

Table 5.1.
Descriptive and approach speed mean (SD) data for male and female subjects

	Male	Female	P value
Anthropometrics			
Age (yrs)	17.0 (0.6)	16.7 (1.0)	0.19
Height (m)	1.77 (0.05)	1.65 (0.07)	**<0.0001**
Weight (kg)	69.6 (6.6)	60.8 (5.5)	**<0.0001**
BMI (kg/m^2)	22.1 (1.7)	22.4 (1.8)	0.63
Cutting Characteristics			
Cross-cut approach speed (m/s)	3.45 (0.13)	3.48 (0.08)	0.44
Straight run approach speed (m/s)	3.55 (0.11)	3.53 (0.12)	0.62
Soccer Experience			
Years Played (yrs)	10.7 (1.7)	9.8 (2.1)	0.15

Student t-tests used to test for differences between genders. Statistically significant differences in bold ($p<0.05$).

Table 5.2.
Interpretation and p-values for the muscle activation PC waveforms during the cross-cut and straight run

Muscle Model	PC	Interpretation	Cross-cut Gender Comparison p-value		Cross-cut Med/Lat Comparison p-value		Straight Run Gender Comparison p-value		Straight Run Med/Lat Comparison p-value	
Gastrocnemii (LG & MG)	PC1	Magnitude during early to mid-stance (≈ 0-70%)	Med site	0.43	Male	0.97	Med site	0.17	Male	0.62
			Lat site	**<0.001**	Female	**0.009**	Lat site	**0.002**	Female	**0.02**
	PC2	Magnitude during late stance (≈ 50-100%)	Med site	0.48	Male	**0.04**	Med site	0.99	Male	0.86
			Lat site	0.40	Female	1.0	Lat site	**0.03**	Female	0.30
Hamstrings (LH & MH)	PC1	Magnitude throughout stance	Med site	**0.05**	Male	0.91	Med site	0.16	Male	0.16
			Lat site	**0.006**	Female	1.0	Lat site	**0.01**	Female	0.75
	PC3	Magnitude comparison between early and mid-stance	Med site	0.07	Male	0.28	Med site	0.59	Male	**0.01**
			Lat site	0.94	Female	**0.003**	Lat site	0.07	Female	0.19
Quadriceps (VL & VM)	PC1	Magnitude throughout stance	Med site	0.68	Male	0.92	Med site	**0.01**	Male	1.0
			Lat site	0.89	Female	1.0	Lat site	**0.02**	Female	1.0
Quadriceps (RF site only)	PC1	Magnitude throughout stance	-	**<0.001**	-	-	-	**0.006**	-	-

Repeated measures ANOVA with Tukey adjusted post-hoc pairwise comparisons used to test for gender and medial/lateral site differences in PC scores for the 3 muscle groups. For the RF, Student t-tests used to test for gender differences in PC scores. Statistically significant differences in bold ($p<0.05$). Med=medial, Lat=lateral

Table 5.3.
Interpretation, gender means, standard error of the means and p-values for the kinematic and kinetic PC waveforms during the cross-cut and straight run

Gait Measure	PC	Biomechanical Interpretation	Gender Comparisons of PC					
			Cross-cut			Straight Run		
			Male	**Female**	**p-value**	**Male**	**Female**	**p-value**
Joint Angles								
Hip Flex/Ext	PC1	Magnitude throughout stance	32.8 (17.3)	-32.8 (18.2)	**0.01**	17.7 (16.8)	-17.7 (15.7)	0.13
Hip Ad/Abduct	PC2	Amplitude/Range of motion throughout stance	-5.9 (4.8)	5.9 (4.5)	0.08	-5.7 (3.3)	5.7 (2.9)	**0.01**
Ankle Evert/Invert	PC1	Magnitude throughout stance	-18.0 (6.7)	18.0 (8.6)	**0.002**	-8.3 (8.8)	8.3 (9.2)	0.20
Ankle Toe In/Out	PC1	Magnitude throughout stance	8.5 (6.9)	-8.5 (7.5)	0.10	9.1 (6.2)	-9.1 (5.8)	**0.04**
Knee Flex/Ext	PC1	Magnitude throughout stance	-10.8 (16.6)	10.8 (14.8)	0.34	-6.1 (17.8)	6.1 (11.9)	0.57
Joint Moments								
Hip Flex/Ext	PC1	Magnitude throughout stance	1.70 (0.87)	-1.70 (0.63)	**0.003**	1.59 (0.85)	-1.59 (0.59)	**0.004**
Hip Ad/Abduct	PC1	Magnitude throughout stance	-1.02 (0.64)	1.02 (0.67)	**0.03**	-0.54 (0.62)	0.54 (0.63)	0.23
Hip Int/Ext Rot	PC1	Magnitude throughout stance	-0.41 (0.41)	0.41 (0.31)	0.12	-0.56 (0.42)	0.56 (0.30)	**0.04**
Knee Flex/Ext	PC3	Magnitude during early stance (≈ 0-12%)	0.43 (0.28)	-0.43 (0.29)	**0.04**	0.36 (0.19)	-0.36 (0.20)	**0.01**
Knee Ad/Abduct	PC1	Magnitude throughout stance	-0.87 (0.54)	0.87 (0.56)	**0.03**	-0.63 (0.54)	0.63 (0.50)	0.10

T-tests used to test for gender differences in the PC scores for the kinematic and kinetic waveforms. Statistically significant differences are shown in bold ($p<0.05$).

Chapter 6 - Male and Female Adolescent Soccer Players Demonstrate Different Neuromuscular Patterns During the Pre-contact and Early Stance Phase of Unanticipated Running and Cutting Maneuvers

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6.1 Introduction

The primary function of the anterior cruciate ligament (ACL) at the knee is to resist anterior translation and internal rotation of the tibia with respect to the femur.[130] The ACL also influences overall knee joint function and stability and injury to this ligament most often occurs during a dynamic landing, a fast deceleration or a quick change in directions during sporting activities such as soccer, basketball, volleyball or handball.[21,99,160] The non-contact event leading up to the injury is generally unanticipated in nature, with the athlete distracted and having to make last second decisions (i.e. throwing/catching a ball or avoiding an opposing player) prior to executing the actual landing or direction change. Approximately 70-80% of all ACL injuries involve no physical contact or direct blow to the knee at the time of injury[153] and females unfortunately have a non-contact ACL injury rate 2-8 times higher than their male counterparts.[1,8,128] Using the motion laboratory to analyze landing or cutting maneuvers and comparing the biomechanics and neuromuscular response between genders offers a unique opportunity towards identifying risk factors that could be contributing or related to the higher ACL injury rate observed in females.

From a biomechanical or neuromuscular perspective, it is not clearly understood why an athlete can injure their ACL when performing a maneuver that is so similar to maneuvers that they have performed safely and repeatedly in the past. Laboratory studies have begun using light guiding systems to force the athletes to make last second decisions as to which direction to cut in the laboratory, better replicating the unanticipated nature of a true game-like scenario where the ACL is most likely to be injured.[16,17,60,167] Besier et al.[16,17] measured knee mechanics and the neuromuscular response of muscles surrounding the knee during unanticipated running and cutting maneuvers and showed that knee joint loads are greater than those experienced for similar but preplanned maneuvers. They also noted that selective co-activations of the quadriceps and hamstrings were used for joint stabilization of the preplanned maneuvers, whereas generalized co-activations of the same muscle groups were used for the unanticipated maneuvers. Ford et al.[60] and Pollard et al.[167] used unanticipated maneuvers to identify gender differences in lower limb kinematics and/or kinetics, however, neither study made neuromuscular comparisons between genders for the unanticipated maneuvers. Ford et al.[60] found gender differences in knee abduction angles and maximum ankle inversion and eversion angles, whereas Pollard et al.[167] reported females having significantly smaller peak hip abduction angles than males during the randomly cued cutting trials.

Detailed review articles have been published summarizing various intrinsic and external risk factors thought to be linked to the gender bias of non-contact ACL injuries.[72,80,95,164] Most cutting-related studies making biomechanical and neuromuscular comparisons between genders have only focused on the stance phase of the maneuvers.[60,127,138-140,167,191] How the body and muscles of the lower limb respond and adapt to unanticipated maneuvers prior to the planting foot making contact with the ground and how this response varies between males and females is also of interest for understanding non-contact ACL injuries. Muscle activation has been shown to enhance the stiffness of the knee and thus improve the overall stability of the joint.[65] Studies focusing on the feed forward response of the muscles around the knee prior to the foot contacting the ground are less prevalent than studies focusing on the muscular response during stance. Since the ACL is usually injured in early stance just after initial contact with the ground,[21] focusing on the neuromuscular response and differences between genders for the period of time just prior to initial contact and during early stance should provide valuable information towards understanding both the non-contact mechanisms of ACL injuries and the gender bias associated with this injury.

A few studies have reported on the neuromuscular response of the muscles of the lower limb prior to foot contact for a side-cut maneuver; however, no comparisons between males and females were made in any of these studies.[14,16,39,192] DeMont and Lephart[48] compared male and female lower limb muscle activity prior to initial contact during pre-planned downhill walking and running and the only difference detected was greater medial hamstring activity in females compared to males for the walk. Zazulak et al.[227] analyzed the pre-contact phase of a pre-planned landing maneuver and demonstrated that females had greater rectus femoris activity than males. Studies focusing on the early stance phase of cutting maneuvers are also sparse, with Sigward and Power[191] having one of the only studies to compare quadriceps and hamstrings activity between genders during the early stance phase (first 20% of stance) of a side-cut maneuver. While no differences between genders were reported for hamstring activity, the female athletes did have greater average quadriceps activity, normalized to maximum voluntary isometric contraction (MVIC), in comparison to the male athletes. Higher quadriceps activity has been reported in other studies to be a risk factor for ACL injuries since contracting the quadriceps at flexion angles less than approximately 45° can increase ACL strain.[9,19]

For highly demanding tasks such as running, cutting and landing, musculature support is particularly important during the early stance phase when impact forces can be high and the ACL is most likely to be damaged in a non-contact manner.[21,160] Using elite adolescent male and female soccer players, the purpose of this study was to make gender comparisons of the muscle activation waveforms for the 3 main muscle groups crossing the knee during the pre-contact and early stance phase of 3 different unanticipated running and cutting maneuvers. The waveforms were analyzed by applying principal component analysis (PCA) to the muscle activation patterns[91,92,112] and it was hypothesized that neuromuscular differences would be identified between the male and female athletes. The 3 maneuvers analyzed included an unanticipated straight run, a side-cut and cross-cut and the 3 muscle groups included the quadriceps, hamstrings and gastrocnemii. In addition to gender differences, medial-lateral muscle site differences for each of the 3 muscle groups were also evaluated, with the objective of using all the identified differences to help identify and explain ACL injury risk factors and improve on the current understanding as to why females are more prone to ACL injuries than their male counterparts.

6.2 Methods

6.2.1 Subjects

Twenty-one healthy male and 21 healthy female elite adolescent soccer players were recruited from the Nova Scotia Provincial and Canada Games youth soccer teams to participate in this study. The means and standard deviations for age, height and body mass of the male subjects were 17.0±0.6 yrs, 1.77±0.05 m, 69.6±6.6 kg, respectively, and 16.7±1.0 yrs, 1.65±0.07 m, 60.8±5.5 kg, respectively, for the female subjects. All participants were required to be injury free at the time of testing, having not sustained a previous major injury to either lower extremity. If the participants ever experienced an ankle sprain, at the time of testing they had to be at least one-year post injury and be pain free while participating in sports. Written consent was attained from all subjects and their respective guardians prior to testing, with the study's ethical approval being obtained from the Research Ethics Board for Health and Medical Sciences at Dalhousie University.

6.2.2 Experimental Design

The testing protocol involved a three dimensional (3D) motion and electromyographic (EMG) analysis of the lower limb for 3 unanticipated running and cutting maneuvers in the human motion laboratory at Dalhousie University, with this paper focusing only on the pre-contact and early stance EMG data. Prior to patient setup, the maneuvers were described, demonstrated and then practiced by each subject. The maneuvers included i) running straight, ii) running and then side-cutting at an angle between 35°-60° from the direction of approach (cutting to the left with the right foot planted on the force platform) and iii) running and cross-cutting at an angle between 35°-60° from the direction of approach (cutting to the right with the right foot planted on the force platform). LabVIEW (National Instruments Corporation, Austin, TX, USA) controlled infrared timing gaits ensured that the approach speed leading up to the execution of each maneuver was 3.5±0.2 m/s. A 3-light guiding system, also controlled by LabVIEW, randomly cued the subjects to make a last second decision and perform the maneuvers in a manner similar to a game-like scenario where the running and cutting maneuvers are unanticipated in nature. For the targeted approach speed, subjects had approximately half a second of reaction time to properly carry out the maneuvers. Testing continued until 5 acceptable trials were collected for each maneuver, with a trial being deemed acceptable once it was ensured that the approach speed and angle of cut were adequate and the entire right foot was planted on the force platform. While performing the maneuvers, each subject wore lycra shorts and their own indoor/turf soccer shoes. An ultra-thin stretchable stocking was also placed over the right leg during the dynamic tasks to prevent damage and entanglement of the EMG electrode and infrared marker wires.

Three dimensional motion data, ground reaction force data and EMG data were collected using an Optotrak motion analysis system (Northern Digital, Inc. Waterloo, ON, CA), an AMTI force platform (Advanced Medical Technology Inc. Watertown, MA, USA) and an eight channel surface AMT-8 EMG system (Bortec, Inc. Calgary, AB, CA), respectively. Because this paper focuses on the pre-contact and early stance muscle activation patterns, only the EMG methodology will be described in detail.

The surfaces of the skin where the electrodes were to be placed on the right leg were shaven and cleaned using alcohol. Using standardized placements based on specific anatomical landmarks, silver/silver-chloride pellet surface electrodes (0.79 mm^2 contact area, Bortec, Inc. Calgary, AB, Canada) were attached in a bipolar configuration (20 mm center-to-center) along the direction of the muscle fibers. The muscles that were measured on the right leg included the lateral gastrocnemius (LG), medial gastrocnemius (MG), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), lateral hamstring (LH) and medial hamstring (MH).[91,92,121] A reference electrode was placed on the tibial shaft and proper electrode placements were validated by palpating the different activated muscles and assessing the EMG recordings while the subjects performed a series of isolated movements.[108,188,217] The raw EMG signals were collected at 1000 Hz, preamplified (500 times) and further amplified (bandpass 10-1000 Hz, CMRR = 115 dB (at 60 Hz), input impedance ~ 10 GΩ). It was ensured that the ratio of the skin-electrode impedance to the input impedance of the amplifier was less than the 1% recommended ratio[216] by not taking any recordings within 10 minutes of electrode placement.[172]

Previous landing, running and cutting studies have represented the pre-contact phase as 50-250 msec prior to foot strike[14,16,48,49,56,203,227] and the electromechanical delay between EMG activity and the development of muscle tension has been reported to range between 20-100 msec.[20,29,218] Based on these studies, the pre-contact phase in the current study was chosen to be the 100 msec prior to foot strike. Data from the force platform was used to determine foot strike and foot off during the running or cutting maneuvers. The early stance phase has been represented differently throughout the literature and some of these early stance descriptions have included: i) the time from foot strike to the first trough in the resultant ground reaction force,[16-18] ii) a predetermined amount of time,[56,203] iii) the first 20-30% of the entire stance phase[89,191] or iv) the point from foot strike to the instant where knee flexion first reaches 40° of flexion.[167] We chose early stance to be the first 20% of stance because not all our subjects exhibited the first trough in the resultant ground reaction force, the first 20% of stance for the 3 maneuvers corresponded very closely with 40° of knee flexion and our previous PC analyses of the kinematic and kinetic data identified several joint moment differences between genders localized within the first 10-20% of stance.[113,114]

Six maximum voluntary isometric contraction (MVIC) exercises and an EMG subject bias trial were collected immediately after completing the running and cutting maneuvers. The bias trial was captured with the subject lying supine and completely relaxed for 3 seconds. The MVIC exercises elicited maximal activation amplitudes for the purpose of normalizing the running and cutting EMG data. Five of the 6 exercises were performed on a Cybex dynamometer (Lumex, Inc. Ronkonkoma, NY, USA) and these exercises included i) knee extension with knee flexed 45° while sitting upright, ii) simultaneous knee extension and hip flexion while sitting upright with knee flexed 45°, iii) knee flexion with knee flexed 45° while sitting upright, iv) knee flexion with knee flexed 55° while lying prone and v) plantar-flexion while sitting upright with ankle in neutral position and knee near full extension. The sixth exercise was a heel rise pushing against a resistance while standing upright. Each exercise was repeated twice with subjects being coached to produce a sustained and smooth maximum effort for 3 seconds. The Optotrak data acquisition unit captured all the EMG data at 1000 Hz and it was later processed in Matlab V7.0.4 (The MathWorks, Inc. Natick, MA, USA).

6.2.3 Data Processing and Analysis

All EMG data was bias corrected, converted to μV, full-wave rectified and low pass filtered at 6 Hz using a zero lag 4^{th} order Butterworth filter[215] in Matlab. A 100 msec moving window algorithm identified maximum EMG amplitudes for each muscle individually during the MVIC normalization exercises and these maximums were then used to amplitude normalize the running and cutting EMG data.[91] Ensemble average waveforms for a subject's 7 muscle sites were obtained by averaging 3 to 5 trials for each of the running and cutting maneuvers. The 100 msec pre-contact phase and early stance (first 20%) phase for every subject's ensemble average waveforms were represented separately by 101 data points for the PC analysis.

The ensemble average EMG waveforms were entered into the pattern recognition and multivariate analysis technique of PCA, a technique that in recent years has emerged as a popular tool for analyzing biomechanical[46,47,112,136,195,224] and neuromuscular[91-93,223] waveform data. For both the pre-contact and early stance phases, four separate analyses were carried out on the waveform data with gender and medial-lateral muscle site comparisons being performed on the gastrocnemii (LG and MG), hamstrings (LH and MH) and quadriceps (VL and VM) and only gender comparisons being performed on the RF. In the case of the hamstrings for the pre-contact phase, for example, there were 21 males and 21 females with each subject having a lateral and medial hamstring waveform entered into the analysis, giving a total of 84 separate waveforms. Every waveform consisted of 101 data points, thereby producing a 84x101 **X** data matrix. The mean value at each instance of time was subtracted from the **X** data matrix, producing a mean removed data matrix $\overline{\mathbf{X}}$. The covariance matrix, $\mathbf{C} = \overline{\mathbf{X}}\overline{\mathbf{X}}^T$, was calculated for $\overline{\mathbf{X}}$ followed by an eigenvector decomposition of the **C** matrix.[91] The decomposition was represented as $\mathbf{C}=\mathbf{T}\Lambda\mathbf{T}^T$ with the transform matrix **T** being a matrix of patterns or features (orthogonal eigenvectors or principal components (PCs)) and Λ being a diagonal matrix of the associated variances (eigenvalues). PCs are an orthogonal representation of the original variables in $\overline{\mathbf{X}}$ describing features of variation within the original waveforms. The percentage of total waveform variation that each PC captures determines the order in which the PCs are extracted, with the PCs describing the greatest amount of variation being extracted first. Every waveform in the model then gets scored based on its similarity to the set of PCs. The PC scores are calculated as $\mathbf{Z}=(\overline{\mathbf{X}})\,\mathbf{T}$, with the PC score being a measure of the distance a subject's waveform is from the mean of that particular PC. A waveform that is similar with a given PC receives a high PC score and the maximum and minimum waveforms based on the PC scores are used, in combination with the PC itself, to help interpret the feature of variation that the specific PC is describing.[46,103] The orthogonal nature of the decomposition allows the various PCs to capture different independent features of variation for the specific waveforms and then the corresponding PC scores can be used in statistical hypothesis testing.

6.2.4 Statistical Analysis

For all 3 maneuvers, Student t-tests were used to test for gender differences ($p<0.05$) in the PC scores of the RF activation waveforms for both the pre-contact and early stance phases. A 2-factor mixed-model ANOVA with Tukey adjusted post-hoc pairwise comparisons was used to simultaneously test for gender (between group) and medial-lateral site (within group) differences in the PC scores of the quadriceps (VL and VM), hamstrings (LH and MH) and gastrocnemii (LG and MG) muscle groups for the 2 phases of the 3 maneuvers. All statistical tests were performed in Matlab and Minitab (Minitab, Inc. State College, PA, USA).

6.3 Results

For both the pre-contact and early stance phases of all 3 maneuvers, the first 2 PCs of each muscle group analysis (gastrocnemii, hamstrings, quadriceps and RF) explained at least 97.6% of the total variance in the magnitude and shape of the muscle activation waveforms. PC1 captured the overall magnitude of the waveforms during each task and phase, with PC2 capturing a feature related to a shape or pattern change in the waveforms that was quite similar across all the analyzed maneuvers, phases and muscle groups. The ensemble average waveforms for males and females, expressed as a percent of MVIC, show both the pre-contact and early stance phases of the 3 maneuvers in Figures 6.1 and 6.2. In all the ensemble average plots, the pre-contact phase is expressed in msec and the early stance phase is expressed as percent stance. For plotting purposes, the early stance phase was scaled appropriately in the plots to visually coincide with the pre-contact phase.

For all the separate analyses, an individual waveform obtaining a high PC1 score corresponded to a large overall muscle activation magnitude and a low PC1 score corresponded to a small activation magnitude throughout the phase (pre-contact or early stance) being analyzed (Figures 6.2E, 6.3A, 6.3I, 6.4A and 6.4I). Related to the second PC, a waveform with a high PC2 score generally had a small activation magnitude early in the phase followed by an increase in magnitude as the phase progressed. A low PC2 score generally corresponded to a waveform that had a magnitude that decreased or remained constant for the progression of either the pre-contact or early stance phase (Figures 6.2D, 6.3E, 6.3M, 6.4E and 6.4M).

Significant gender differences and/or medial-lateral muscle site differences were captured for the hamstrings (LH and MH), gastrocnemii (LG and MG) and RF during the pre-contact and early stance phases of the side-cut, cross-cut and straight run. No significant differences, related to either the magnitude or shape, were captured for the quadriceps (VL and VM) throughout either phase of the 3 maneuvers. Two female VM waveforms for the quadriceps analysis and 3 male MG waveforms for the gastrocnemii analysis were removed from the PC and statistical analysis due to inadequate signal quality during the MVIC normalization trials.

6.3.1 Gastrocnemii Activation Waveforms

The ensemble average muscle activation waveforms for the gastrocnemii (Figure 6.1A, 6.1B and 6.1C) were analyzed and the identified differences varied across the 2 phases and 3 maneuvers (Figure 6.3 and Table 6.1). The waveforms plotted in the left hand column of Figure 6.3 represent individual waveforms corresponding to subjects receiving high and low PC1 and PC2 scores in the PC analysis. It is evident from Figures 6.3A and 6.3I, that PC1 captured an overall activation magnitude during the pre-contact and early stance phases, respectively. PC2 captured a shape change for both phases and Figures 6.3E and 6.3M demonstrate this for the pre-contact and early stance phases, respectively. The high and low PC score waveforms plotted in the left hand column of Figure 6.2 are for the straight run maneuver only. The same plots for the side-cut and cross-cut were similar to the straight run and therefore were redundant and not illustrated.

For the side-cut, only magnitude differences (PC1) were captured with the females having larger activation magnitudes than males for both the LG and MG throughout the duration of both the pre-contact (LG $p=0.03$; MG $p=0.04$, Figures 6.1A and 6.3B) and early stance phases (LG $p=0.002$; MG $p=0.007$, Figures 6.1A and 6.3J). The only difference detected for the cross-cut was a gender difference in the overall magnitude of the LG during early stance, with females experiencing greater muscle activity levels than males throughout the entire early stance phase ($p=0.006$, Figures 6.1B and 6.3K). LG magnitude differences between genders were also captured for the straight run (Figure 6.1C), during both the pre-contact (Figure 6.3D) and early stance phases (Figure 6.3L). Females had greater LG activity during the pre-contact ($p=0.03$) and early stance ($p=0.001$) phases compared to males and during the pre-contact phase only, males also had a medial-lateral imbalance with the MG being more activated than the LG ($p=0.03$). The only maneuver that demonstrated shape or pattern differences (PC2) in the waveforms was for the straight run with differences being detected during both phases (Figures 6.1C, 6.3H and 6.3P). Gender differences were captured for the pre-contact phase with females tending to have MG and LG activity that was relatively low in magnitude at 100 msec pre-contact and then as contact approached, the activity level increased to a greater magnitude (high PC2 score waveform in Figure 6.3E) compared to males (LG p=0.01; MG p=0.003). Males on the other hand, tended to have LG and MG activity levels that remained relatively constant throughout pre-contact and had a smaller activation magnitude (low PC2 score waveform in Figure 6.3E) compared to females at contact. For early stance, the only identified shape difference was between the MG and LG of the males, with the LG tending to be less active at contact compared to the MG and then as stance progressed to 20% stance, the activity level of the LG increased to a greater magnitude than the MG of the male subjects (p=0.006, Figure 6.1C, 6.3M and 6.3P).

6.3.2 Hamstring Activation Waveforms

Similar to the gastrocnemii analyses, PC1 captured an overall hamstring activation magnitude throughout the duration of each phase and PC2 was associated with a shape difference for both the pre-contact and early stance phases (Table 6.2 and Figure 6.4). While PC2 captured a very similar shape feature for the hamstrings compared to the gastrocnemii, the actual waveforms did differ slightly in overall shape, which is evident when comparing Figure 6.3E with Figure 6.4E and Figure 6.3M with Figure 6.4M. Again, for the hamstrings a large PC2 score corresponded to a low initial activation magnitude at the beginning of the phase that increased as the phase progressed. A low PC2 score corresponded to an activation profile that was more consistent and steady throughout the phase. The left hand column plots of the high and low PC score waveforms in Figure 6.4 are for the straight run and these are consistent with the same plots for the side-cut and cross-cut, which are not shown.

The only hamstring differences captured for the side-cut and cross-cut were gender differences in the shape or overall pattern of the activation waveforms (PC2) during the pre-contact phase of the 2 maneuvers (Figures 6.1D, 6.1E, 6.4F and 6.4G). Females tended to have greater hamstring activity occurring earlier in the pre-contact phase compared to males and as contact approached, males were reaching peak activations whereas females tended to be experiencing a reduction in hamstring activity. This difference between genders was statistically significant at the MH site for the side-cut (p=0.01, Figure 6.4F) and at the LH site for the cross-cut (p=0.04, Figure 6.4G) only, with gender differences being of comparable magnitude but statistically insignificant for both the LH site of the side-cut (p=0.14) and the MH site of the cross-cut (p=0.07). A lack of adequate power (side-cut LH power =0.18; cross-cut MH power =0.23) makes it difficult, however, to confidently conclude that these 2 differences do not exist.

The straight run demonstrated overall magnitude differences (PC1) in hamstring activity levels during the pre-contact phase and shape differences (PC2) between genders in the early stance phase. Throughout the pre-contact phase, males had less MH activity than females (p=0.0002, Figures 6.1F and 6.4D) and also a medial-lateral hamstring magnitude imbalance that was not present in females. The MH of males was less activated than the male LH throughout the duration of the pre-contact phase (p=0.01, Figures 6.1F and 6.4D). Related to the shape difference in early stance, females had lower PC2 scores than males for the LH and MH which corresponded to females tending to experience a reduction in hamstring activity as early stance progressed. Males, however, had hamstring activation waveforms that remained relatively constant throughout the early stance phase (LH p=0.007; MH p=0.03, Figures 6.1F and 6.4P).

6.3.3 Quadriceps Activation Waveforms

No differences were captured for the VM and VL muscle sites (Figure 6.1G, 6.1H and 6.1I), however, several differences were identified for the RF (Figure 6.2 and Table 6.3). A shape difference (PC2) was detected for the RF during the pre-contact phase of the side-cut (p=0.01) and cross-cut (p=0.01) maneuvers. At a 100 msec prior to contact, females generally had less RF activity than males but as foot contact approached, females tended to increase their RF activity to a greater extent and therefore at contact, females were activating their RF to a higher percentage of MVIC compared to males (Figure 6.2A, 6.2B and 6.2D). For the entire early stance phase, a magnitude difference (PC1) was captured with females having a greater activation magnitude than males for both the side-cut (p=0.02, Figures 6.2A and 6.2E) and cross-cut (p=0.005, Figures 6.2B and 6.2E).

RF differences were not identified for the pre-contact phase of the straight run, however, RF magnitude and shape differences were found between the male and female athletes during the early stance phase (Figure 6.2C). Females had greater RF activity throughout early stance (PC1, p=0.005) and also tended to be increasing their RF activity at a greater rate as early stance progressed, in comparison to the males (PC2, p=0.008).

6.4 Discussion

This study identified gender and/or medial-lateral muscle site differences in the activation patterns of the musculature surrounding the knee joint during the pre-contact and early stance phases of 3 unanticipated athletic maneuvers. Differences were present for the RF, both gastrocnemii and both hamstrings with no differences being captured for either the VL or VM. Focusing on the musculature response during the early stance phase of cutting or landing maneuvers is important because most non-contact ACL injuries occur during this period and contracting the musculature surrounding the knee has an important role related to joint stability and protecting the knee's ligamentous structures.[65] The muscular response prior to making contact with the ground (pre-contact phase) also has relevance to ACL injuries and how the body activates the musculature during this phase influences the ability of the knee to accept and dissipate forces, thereby helping to avoid injury to ligaments such as the ACL.

It is interesting that the RF differences captured between genders during the pre-contact phase of the side-cut and cross-cut maneuvers were not related to the magnitude of RF activity but rather to the overall shape or activation pattern of the RF prior to the athletes making contact with the ground. During the early pre-contact phase both genders had comparable RF activities; however, as the pre-contact phase progressed females increased their RF to a greater extent so that by foot contact, activity levels were greater for the females compared to the males. Although the mechanism is not clearly understood, it appears that the RF of the male and female athletes follows a different neuromuscular feed forward process with respect to how this muscle is pre-activated prior to the foot making contact with the ground during the cutting maneuvers.

Of the 3 quadriceps muscles analyzed in this study, the RF was the only muscle that demonstrated differences between the male and female athletes during the early stance phase of the 3 unanticipated maneuvers. Contracting the quadriceps can strain the ACL through an anterior pull on the tibia[9,19] and while it remains unclear if this force alone can injure the ACL, greater activation of the quadriceps in combination with other external loads pose as a potential risk factors for ACL injuries. A possible reason why gender differences were identified for the RF and not the VL or the VM may be because the RF is the only biarticulate quadriceps muscle and the greater RF activity observed in females may be related more to the hip joint rather than the knee. The corresponding kinematic and kinetic results for these same maneuvers, reported previously by our group,[113,114] have shown that females generate smaller hip flexion angles throughout the entire stance phase compared to males. Cutting or landing in a less erect posture is thought to reduce the loads at the knee and possibly help protect the ACL,[63,96,127] therefore one plausible explanation for females having the greater RF activity is to help increase hip flexion angles and avoid the potentially more dangerous erect posture. It is apparent from our work, however, that the females are not only experiencing increased RF activity but also decreased hip flexion angles compared to males throughout stance.[113,114] Both of these differences have been identified as ACL injury risk factors and may have contributing roles to the higher ACL injury rate seen in females compared to males.

Contracting the hamstrings and generating forces in this muscle group can increase joint stability and also reduce ACL strain at knee flexion angles greater than approximately 30°.[144,174] It has been suggested that increasing pre-activity of the hamstrings prior to experiencing a stressful load can help protect the integrity of the knee joint and surrounding structures[48] and this pre-activity would appear to be important, particularly during unanticipated maneuvers where a reduction in the response time can lead to a lack of appropriate postural adjustments and an increase in the loads experienced at the knee joint.[16] Although the identified hamstring differences in the current study varied between the 3 maneuvers, it was apparent from the mean ensemble average waveforms that hamstring activity generally peaked during the pre-contact phase in comparison to the early stance phase (Figure 6.1D, 6.1E and 6.1F), with the one exception being the male MH during the straight running maneuver. The peak hamstring activity prior to initial contact is likely contributing to the deceleration of the tibia as it comes into contact with the ground. The protective role of the hamstrings at initial contact for both the side-cut and cross-cut maneuvers may be small at initial contact and early stance as hamstring activity (LH and MH) is actually decreasing at this point.

With respect to hamstring gender comparisons in the current study, the only differences captured for the 2 cutting maneuvers were waveform shape differences, with no magnitude differences being identified during either phase. For the pre-contact phase of both cutting maneuvers, females tended to have hamstring activity peaking earlier than males and then as initial contact approached, females tended to be decreasing their hamstring activity for a longer period of time compared to males, who on average had just begun decreasing hamstring activity near initial contact. These gender differences were statistically significant for the MH during the side-cut and the LH during the cross-cut only. Comparable gender differences for the LH during the side-cut and MH during the cross-cut only were evident but these differences only approached statistical significance and lacked adequate power. The relevance of these pre-contact hamstring differences to the non-contact ACL injury gender bias is not completely understood and warrants further investigation but the differences indicate that, like the RF prior to initial contact, females do have different activation patterns compared to males. The muscle activation differences alone, or in combination with one another, may be affecting the female's overall ability of preparing for an unanticipated cutting maneuver during the pre-contact phase of the maneuver.

Hamstring differences were also captured for the unanticipated straight run, with males having less MH activity than females during the pre-contact phase of the run. DeMont and Lephart[48] identified a similar difference during the pre-contact phase of a straight walk, with females also having greater MH pre-activity than males. Whether this difference in MH provides females with improved joint protection or places them at greater risk of being injured is unknown. Unlike the side-cut and cross-cut, the straight run demonstrated shape differences in the hamstring activation waveforms during early stance. Hamstring activity (LH and MH) tended to be decreasing during this phase in females, whereas hamstring activity in males tended to be maintaining a more steady and consistent level of activity. The steady hamstring activity in males could be helping to better stabilize the knee joint, thereby providing more adequate protection for the ACL in comparison to the decreasing activation patterns demonstrated by the female athletes throughout the early stance phase.

The importance of the hamstrings and quadriceps with respect to knee joint stability and ACL injuries has been described throughout the literature;[2] however, the role the gastrocnemii muscle group plays at the knee remains less clear. Some researcher have suggested that the gastrocnemii help flex the knee and provide stability to the joint,[97,116] while others have shown that contracting this muscle group can increase ACL strain.[58,157] It has been demonstrated that forces generated by the gastrocnemii, using both a computer based model[157] and a differential variable transducer implanted on the ACL,[58] can increase the load on the ACL. Gastrocnemii pre-activity has also been compared between genders for downhill walking and running using EMG, with differences not being identified between males and females for either the LG or MG.[48] LG and MG pre-activity was also accessed in female ACL-deficient, ACL-reconstructed and control groups during functional activities such as walking, running, hopping and landing. Differences were captured for the LG only and although the differences varied based on the activities being analyzed, it did indicate that the gastrocnemii muscle group likely has a role related to knee joint stability and the ACL.[49] For the gastrocnemii activation waveforms in our study, we identified magnitude differences between genders for all 3 maneuvers and differences based on the shape of the activation profiles for the straight run only. Females demonstrated greater LG and MG activity compared to males for both the pre-contact and early stance phase of the side-cut maneuver. LG activity was also greater in females for the early stance phase of the cross-cut maneuver and the pre-contact and early stance phase of the straight run. Females demonstrated a more rapid increase in MG and LG activity than males during the pre-contact phase of the straight run which was evident by the shape feature captured by PC2. Non-contact ACL injuries in an Australian football population have been shown to be more prevalent during a side-cut maneuver in comparison to a cross-cut[38] and our gastrocnemii gender differences were most evident for the side-cut maneuver. The higher gastrocnemii activity seen in females during the pre-contact and early stance phases of the side-cut may be required by the females to enhance joint stability but at the same time may be placing the ACL under greater stress, thereby increasing the risk of the ligament being injured in the female population. The main role of the gastrocnemii appears to be later in stance when the ankle needs to be plantar-flexed during the propulsion phase of the cut. Because gender differences exist prior to initial contact and during early stance when ACL injuries are most likely to occur, it is felt that the gastrocnemii may also have an influence on protecting the knee and ACL while executing athletic maneuvers.

Gender and medial-lateral muscle site differences were effectively identified for the muscle activation waveforms of the RF, gastrocnemii and hamstrings during the unanticipated running and cutting maneuvers. These differences were associated with the overall magnitude and overall shape or pattern of the activation waveforms during both the pre-contact and early stance phases of the maneuvers. The combination of decreasing hamstring activity and increasing RF and gastrocnemii activity near initial contact, in combination with the gender differences identified for these muscles, could all be contributing factors to non-contact ACL injuries during cutting-related maneuvers.

6.5 Conclusion

This study is one of the few studies to identify neuromuscular differences between genders during the pre-contact and/or early stance phase of unanticipated running and cutting maneuvers. Making comparisons between male and female elite adolescent soccer players, magnitude differences in the RF and gastrocnemii as well as shape differences in the hamstring activation waveforms were identified and described in terms of being possible risk factors for ACL injury. These results suggest that female athletes are performing unanticipated running and cutting maneuvers with different neuromuscular control strategies compared to male athletes and these neuromuscular patterns could be contributing to the greater ACL injury rate observed in females compared to males. Attempting to modify these neuromuscular control strategies through preventative training programs could potentially reduce the incidence of ACL injuries, particularly in the female athletic population.

6.6 Acknowledgements

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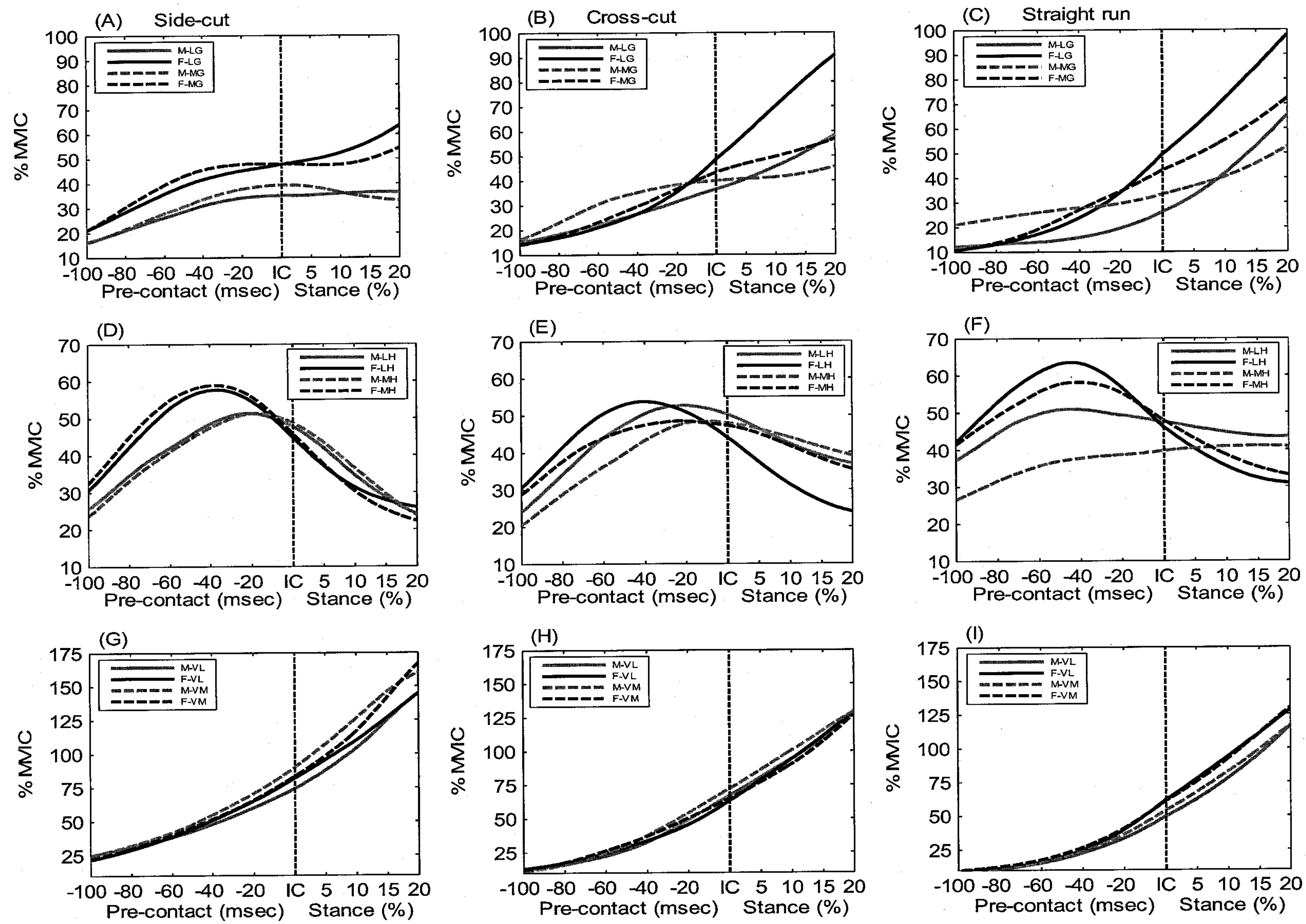
Figure 6.1. Male and female mean activation waveforms for the gastrocnemii, hamstrings and quadriceps showing the pre-contact and early stance phases of the three maneuvers

Plots for gastrocnemii (LG and MG) along top row, hamstrings (LH and MH) along middle row and quadriceps (VL and VM) along bottom row. Plots for side-cut down left column, cross-cut down center column and straight run down right column. Pre-contact phase expressed in msec (-100 msec to IC) and early stance phase expressed as % stance (IC to 20%).


(A) Side-cut
(B) Cross-cut
(C) Straight run
(D)
(E)
(F)
(G)
(H)
(I)
M-LG
F-LG
M-MG
F-MG
M-LH
F-LH
M-MH
F-MH
M-VL
F-VL
M-VM
F-VM
% MVIC
Pre-contact (msec)
Stance (%)
-100 -80 -60 -40 -20 IC 5 10 15 20

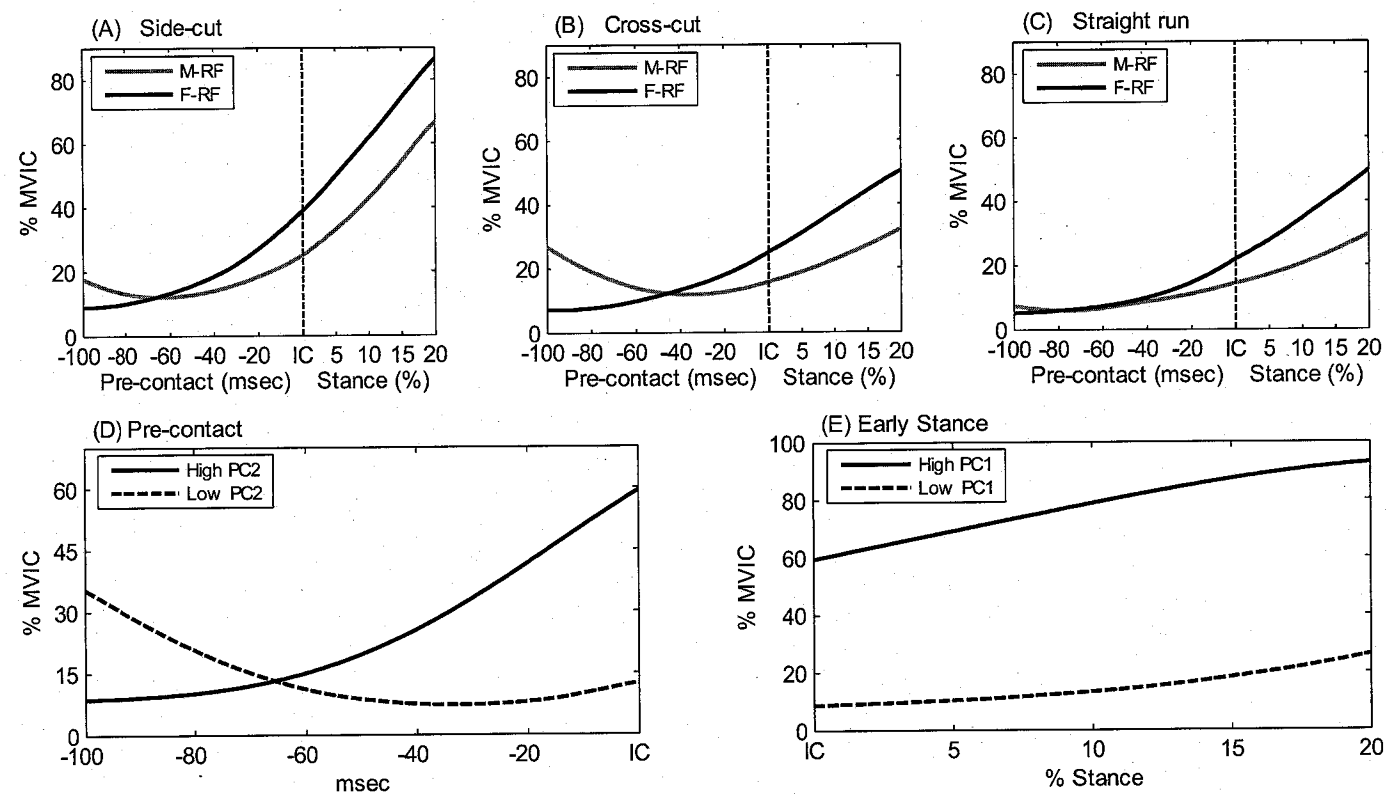


Figure 6.2. Male and female mean activation waveforms for the RF showing the pre-contact and early stance phases of the three maneuvers and waveforms of individuals with high and low PC1 and PC2 scores

Mean activation waveforms for the **A)** side-cut, **B)** cross-cut and **C)** straight run. **D)** Pre-contact RF waveforms for an individual with a high and low PC2 score. **E)** Early stance waveforms for an individual with a high and low PC1 score.

Figure 6.3. Gastrocnemii muscle activation waveforms of individuals with high and low PC scores along with the PC1 and PC2 score means of the males and females for the three maneuvers

Waveforms in first column are from the straight run: **(A)** Pre-contact waveforms for an individual with a high and low PC1 score, **(E)** Pre-contact waveforms for an individual with a high and low PC2 score, **(I)** Early stance waveforms for an individual with a high and low PC1 score, **(M)** Early stance waveforms for an individual with a high and low PC2 score. Second, third and fourth columns represent corresponding gastrocnemii PC score means with standard error of the means for the side-cut, cross-cut and straight run, respectively. * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).

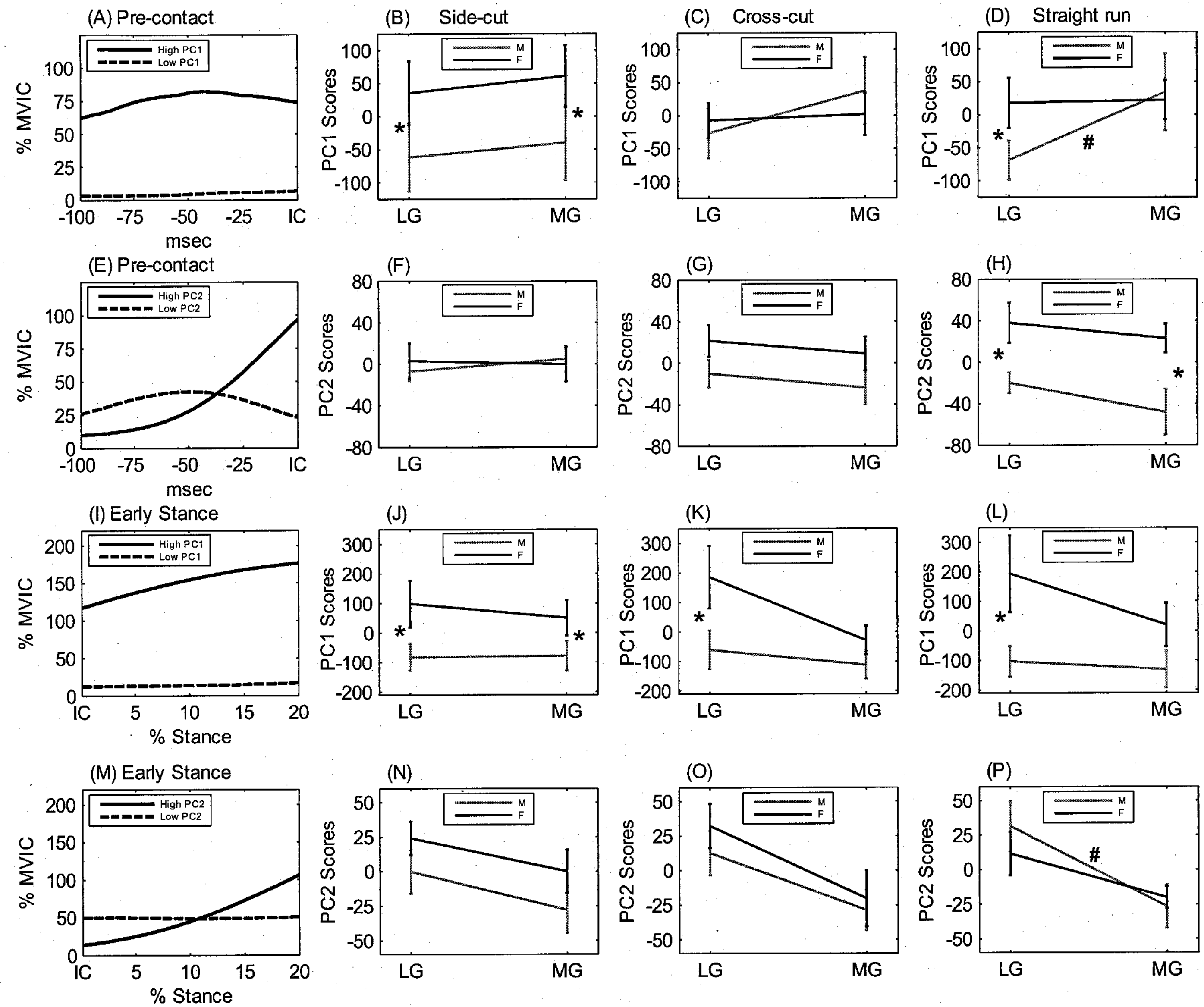

(A) Pre-contact
High PC1
Low PC1
% MVIC
msec
(B) Side-cut
(C) Cross-cut
(D) Straight run
M
F
PC1 Scores
LG
MG
(E) Pre-contact
High PC2
Low PC2
(F)
(G)
(H)
PC2 Scores
(I) Early Stance
% Stance
(J)
(K)
(L)
(M) Early Stance
(N)
(O)
(P)

Figure 6.4. Hamstrings muscle activation waveforms of individuals with high and low PC scores along with the PC1 and PC2 score means of the males and females for the three maneuvers

Waveforms in first column are from the straight run: **(A)** Pre-contact waveforms for an individual with a high and low PC1 score, **(E)** Pre-contact waveforms for an individual with a high and low PC2 score, **(I)** Early stance waveforms for an individual with a high and low PC1 score, **(M)** Early stance waveforms for an individual with a high and low PC2 score. Second, third and fourth columns represent corresponding hamstring PC score means with standard error of the means for the side-cut, cross-cut and straight run, respectively. * indicates a significant gender difference and # indicates a significant medial-lateral muscle site difference ($p<0.05$).

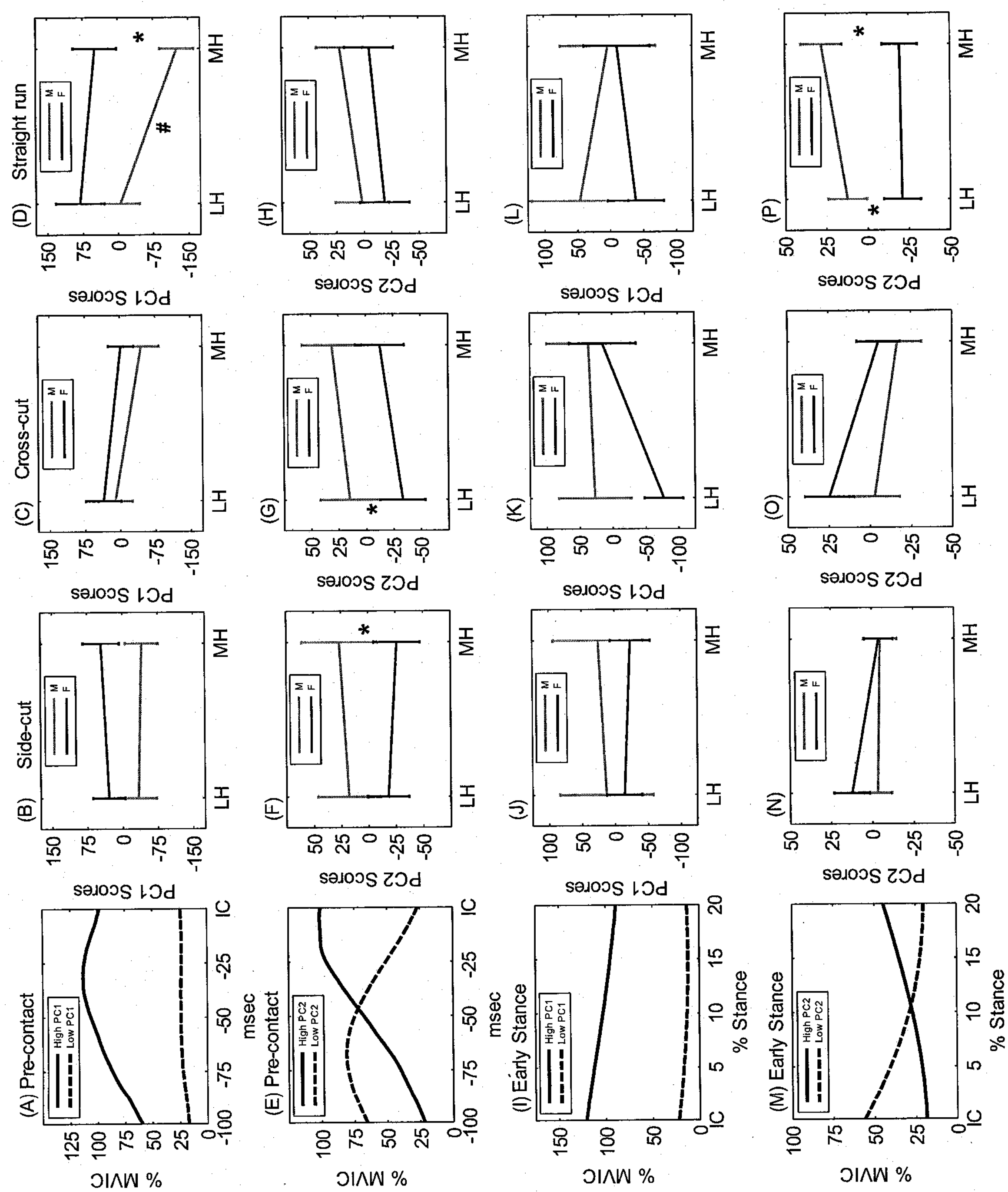

(A) Pre-contact
High PC1
Low PC1
% MVIC
msec
(B) Side-cut
(C) Cross-cut
(D) Straight run
PC1 Scores
M
F
LH
MH
(E) Pre-contact
High PC2
Low PC2
(F)
(G)
(H)
PC2 Scores
(I) Early Stance
% Stance
(J)
(K)
(L)
(M) Early Stance
(N)
(O)
(P)
IC

Table 6.1.
Gender and medial-lateral muscle site comparisons of gastrocnemii muscle activation PC waveforms for the pre-contact and early stance phase of the three maneuvers

Maneuver	PC	Feature described by PC	Pre-contact Phase: Gender Comparison p-value		Pre-contact Phase: Med-Lat Site Comparison p-value		Early Stance Phase: Gender Comparison p-value		Early Stance Phase: Med-Lat Site Comparison p-value	
Side-cut	PC1	Magnitude	Med site	**0.04**	Male	0.95	Med site	**0.007**	Male	0.99
			Lat site	**0.03**	Female	0.87	Lat site	**0.002**	Female	0.59
	PC2	Shape	Med site	0.99	Male	0.93	Med site	0.16	Male	0.19
			Lat site	0.83	Female	0.99	Lat site	0.18	Female	0.21
Cross-cut	PC1	Magnitude	Med site	0.82	Male	0.40	Med site	0.61	Male	0.98
			Lat site	0.96	Female	0.99	Lat site	**0.006**	Female	0.056
	PC2	Shape	Med site	0.49	Male	0.99	Med site	0.92	Male	0.17
			Lat site	0.22	Female	0.87	Lat site	0.71	Female	0.054
Straight run	PC1	Magnitude	Med site	1.0	Male	**0.03**	Med site	0.27	Male	0.99
			Lat site	**0.03**	Female	0.99	Lat site	**0.001**	Female	0.094
	PC2	Shape	Med site	**0.003**	Male	0.44	Med site	0.97	Male	**0.006**
			Lat site	**0.01**	Female	0.83	Lat site	0.35	Female	0.056

Repeated measures ANOVA used on PC scores for each phase, with Tukey adjusted post-hoc pairwise comparisons. Significant differences in bold ($p<0.05$). Med=medial, Lat=lateral.

Table 6.2.
Gender and medial-lateral muscle site comparisons of hamstring muscle activation PC waveforms for the pre-contact and early stance phase of the three maneuvers

Maneuver	PC	Feature described by PC	Pre-contact Phase: Gender Comparison p-value		Pre-contact Phase: Med-Lat Site Comparison p-value		Early Stance Phase: Gender Comparison p-value		Early Stance Phase: Med-Lat Site Comparison p-value	
Side-cut	PC1	Magnitude	Med site	0.32	Male	0.99	Med site	0.56	Male	0.99
			Lat site	0.41	Female	0.98	Lat site	0.87	Female	0.99
	PC2	Shape	Med site	**0.01**	Male	0.96	Med site	0.99	Male	0.99
			Lat site	0.14	Female	0.95	Lat site	0.27	Female	0.27
Cross-cut	PC1	Magnitude	Med site	0.69	Male	0.49	Med site	0.99	Male	0.99
			Lat site	0.92	Female	0.78	Lat site	0.11	Female	0.13
	PC2	Shape	Med site	0.066	Male	0.78	Med site	0.96	Male	0.76
			Lat site	**0.04**	Female	0.63	Lat site	0.29	Female	0.11
Straight run	PC1	Magnitude	Med site	**0.0002**	Male	**0.01**	Med site	0.99	Male	0.89
			Lat site	0.12	Female	0.83	Lat site	0.18	Female	0.71
	PC2	Shape	Med site	0.24	Male	0.49	Med site	**0.007**	Male	0.47
			Lat site	0.48	Female	0.77	Lat site	**0.03**	Female	0.99

Repeated measures ANOVA used on PC scores for each phase, with Tukey adjusted post-hoc pairwise comparisons. Significant differences in bold ($p<0.05$). Med=medial, Lat=lateral.

Table 6.3.

PC score gender means, standard error of the means and gender comparisons of the RF muscle activation PC waveforms for the pre-contact and early stance phase of the three maneuvers

Maneuver	PC	Feature described by PC	Gender Comparison p-value					
			Pre-Contact Phase			Early Stance Phase		
			PC Score Means (SEM) Male	PC Score Means (SEM) Female	p-value	PC Score Means (SEM) Male	PC Score Means (SEM) Female	p-value
Side-cut	PC1	Magnitude	-22.8 (17.8)	22.8 (24.4)	0.14	-91.5 (31.8)	91.5 (65.9)	**0.02**
	PC2	Shape	-24.5 (16.9)	24.5 (8.4)	**0.01**	4.9 (12.5)	-4.9 (8.6)	0.51
Cross-cut	PC1	Magnitude	36.2 (42.0)	-36.2 (9.3)	0.10	-74.3 (16.1)	74.3 (53.5)	**0.005**
	PC2	Shape	-25.3 (9.0)	25.3 (17.4)	**0.01**	-4.9 (5.9)	4.9 (5.2)	0.096
Straight run	PC1	Magnitude	-10.8 (17.3)	10.8 (16.4)	0.369	-71.6 (17.8)	71.6 (45.8)	**0.005**
	PC2	Shape	-8.7 (8.9)	8.7 (7.3)	0.14	-12.3 (3.6)	12.3 (8.0)	**0.008**

Student t-tests used to test for differences between genders in the PC scores for the RF waveforms. Statistically significant differences in bold ($p<0.05$).

Chapter 7 - Conclusion

7.1 Summary

The primary motivation for this thesis was to address the gender bias of females having a higher non-contact ACL injury rate compared to males during sporting activities where the ACL can be injured while performing maneuvers such as decelerating, cutting to change directions and landing from a jump. Twenty-one male and 21 female elite adolescent soccer players with no previous history of major injury to the lower limbs were recruited from the Nova Scotia Provincial Soccer Program to perform a series of unanticipated running and cutting maneuvers in the Dynamics of Human Motion Laboratory (DOHM) at Dalhousie University. A comprehensive analysis of the biomechanics of the hip, knee and ankle, as well as the neuromuscular response of the quadriceps, hamstrings and gastrocnemii, was done on the male and female athletes for the unanticipated maneuvers. The main aim of this study was to relate differences between genders and between medial-lateral muscle sites to non-contact ACL injury risk factors in order to improve upon the current understanding of the gender bias associated with this devastating and often career ending knee injury.

The introductory chapter of this thesis, chapter 1, provided a brief description on the statement of the problem, the rationale, the purpose, the objectives and the hypotheses for carrying out the study. ACL injuries are most often non-contact in nature[153] and injuring this ligament generally requires invasive reconstructive surgery and often leads to the early onset of knee osteoarthritis.[124,147,213] Numerous studies have identified various non-contact ACL injury risk factors by comparing different measures or characteristics between males and females;[59,60,78,120,127,167,191,226,227] however, no study to our knowledge has used unanticipated running and cutting maneuvers in the laboratory to simultaneously compare lower limb biomechanics (hip, knee and ankle) and neuromuscular patterns (quadriceps, hamstrings and gastrocnemii) between male and female elite adolescent athletes. Medial-lateral muscle site comparisons within a muscle group and gastrocnemii activation patterns have also not been extensively studied for cutting related maneuvers. These comparisons were therefore included in the current study to help with the understanding of the gender bias and risk factors related to non-contact ACL injuries during unanticipated cutting maneuvers.

A thorough review of the ACL literature relevant to this thesis was provided in chapter 2. This review supplied the necessary background required to understand the implications the gender bias in ACL injuries has on the female athletic population. The review summarized numerous studies that have focused on identifying risk factors for the purpose of trying to understand non-contact ACL injuries. Also reviewed in this chapter was the waveform analysis technique of principal component analysis (PCA), the technique which was used to analyze all the biomechanical and neuromuscular waveforms in this thesis. Chapter 3 outlined the methodology and recruitment of subjects along with all the steps related to subject setup, running and cutting testing protocols, instrumentation and acquisition, processing and analysis of all the data.

The results and main discussions from for this thesis are presented in chapters 4, 5 and 6 in the form of 3 manuscripts. The chapter 4 manuscript has been accepted for publication (January 22, 2007) in the *American Journal of Sports Medicine* and the chapter 5 and 6 manuscripts have been submitted and are currently under review with the *American Journal of Sports Medicine* and the *Journal of Electromyography and Kinesiology*. The 3 manuscripts discuss the findings from the biomechanical and electromyographic analysis as the male and female adolescent soccer players completed a series of randomly cued athletic maneuvers including an unanticipated straight run, side-cut and cross-cut in the motion laboratory. Lower limb biomechanics (kinetics and kinematics) and the neuromuscular response of the main muscle groups surrounding the knee were presented in chapter 4 for the entire stance phase of the unanticipated side-cut maneuver. Chapter 5 described the same biomechanical and neuromuscular measurements for the entire stance phase of the unanticipated cross-cut and straight run and chapter 6 discussed the neuromuscular findings during the pre-contact and early stance phases for all 3 unanticipated athletic maneuvers.

This thesis was driven by 5 main objectives and 4 main hypotheses that were outlined in chapter 1. The first objective was to simulate a scenario in the laboratory that more closely resembled a true game-like situation where the ACL is most likely to be injured during a cutting maneuver. The remaining 4 objectives corresponded with the 4 hypotheses, with the first 3 objectives related to quantifying lower limb biomechanics, the neuromuscular response and muscle strengths of the male and female adolescent athletes and the 3 hypotheses stating that gender and/or medial-lateral muscle site differences would exist for the corresponding objectives. The last objective and hypothesis stated that the identified biomechanical and neuromuscular differences during the unanticipated running and cutting maneuvers would provide insight into non-contact ACL injury risk factors and the gender bias of the injury. The findings for the 5 objectives and 4 hypotheses are summarized below.

7.1.1 Objective 1 – Unanticipated Running and Cutting Maneuvers

The first objective was to simulate unanticipated running and cutting maneuvers in the motion laboratory, which are thought to more closely resemble a true game-like scenario where the ACL is most often injured. This was successfully accomplished for all 42 athletes using a 3-light guiding system in the laboratory.

7.1.2 Objective 2 and Hypothesis 1 – Lower Limb Biomechanical Comparisons Between Genders

The second objective was to determine if biomechanical differences exist between genders at the hip, knee and ankle during the stance phase of the 3 maneuvers. Gender differences were found, providing support for my first hypothesis that biomechanical differences would exist between the male and female athletes during unanticipated running and cutting maneuvers. These differences were described in the 2 manuscripts presented in chapters 4 and 5. For the 3 maneuvers, kinematic differences were captured at the hip and ankle only with no kinematic differences identified at the knee.

The most notable kinematic difference was females having reduced hip flexion angles compared to males throughout the entire stance phase of the side-cut and cross-cut maneuvers. Females also demonstrated greater ankle eversion angles compared to males throughout the stance phase of the cross-cut maneuver only. Additional kinematic differences were captured for hip adduction angles, hip internal-external rotation angles and toe-out angles, with these differences varying across the 3 maneuvers.

For lower limb kinetics, again the most notable gender difference was at the hip with males generating greater flexion moments than females throughout the majority of stance for the straight run, cross-cut and side-cut. Females also demonstrated greater hip and knee adduction moments throughout stance for the cross-cut maneuver only. Other differences in hip, knee and ankle moments were also identified between the male and female athletes during the first approximate 12-20% of stance for the 3 athletic maneuvers.

7.1.3 Objective 3 and Hypothesis 2 – Neuromuscular Comparisons Between Genders and Between Medial-Lateral Muscle Sites

The third objective was to determine if gender and medial-lateral muscle site differences exist in the neuromuscular response of the quadriceps, hamstrings and gastrocnemii during the entire stance phase, early stance phase and pre-contact phase of the unanticipated maneuvers. Support for the second hypothesis was found by identifying differences between genders and/or between medial-lateral muscle sites within each of the 3 main muscle groups surrounding the knee for the different phases of the running and cutting maneuvers. Gender differences and medial-lateral differences for the entire stance phase were described in chapters 4 and 5 and the same differences but for the pre-contact and early stance phases were presented in the chapter 6 manuscript.

In chapters 4 and 5 where PCA was used to analyze the muscle activation waveforms for the entire stance phase, differences were captured for all 3 muscle groups with the most notable differences being identified for the gastrocnemii during early to mid-stance. For all 3 athletic maneuvers, females demonstrated greater lateral gastrocnemius activity than males during early to mid-stance. Females also exhibited a medial-lateral gastrocnemii imbalance that was not present in males for the same portion of stance, with the lateral gastrocnemius being more highly activated than the medial gastrocnemius. For the side-cut maneuver only, females also generated a greater overall magnitude in medial gastrocnemius activity compared to males for the early to mid-stance phase.

For the 3 quadriceps muscles, females had greater rectus femoris activity throughout stance compared to males for all 3 maneuvers. Vastus medialis and vastus lateralis activity levels differed between genders for the straight run only, with females having greater activity levels than males throughout stance.

Gender differences in activation magnitudes of the hamstrings throughout the entire stance phase were identified for the unanticipated cross-cut and straight run only. Males demonstrated greater activity levels for the lateral hamstrings during the cross-cut and straight run compared to females and greater activity levels for the medial hamstrings during only the cross-cut maneuver. Additional gender and medial-lateral muscle site differences related to the overall shape of the hamstrings activation patterns were also captured for the 3 maneuvers.

Neuromuscular differences during the pre-contact and early stance of the maneuvers were presented in chapter 6 and the application of PCA was effective in capturing gender and medial-lateral muscle site differences related primarily to either the overall magnitude or general overall shape of the activation patterns throughout the 2 phases analyzed. One of the main findings was that the overall magnitude of rectus femoris activity was greater in females compared to males during the early stance phase of the 2 cutting maneuvers but this magnitude difference was not present during the pre-contact phase. During the pre-contact phase, however, a difference in the overall shape of the rectus femoris activation pattern was captured between genders. Females tended to have a greater magnitude than males 100 msec prior to initial contact and then as initial contact approached and the phase progressed, females increased their rectus femoris activity levels to a greater extent in comparison to the male athletes. While differences were not captured for the vastus medialis or vastus lateralis, other significant differences were also identified for the gastrocnemii and hamstring muscle groups. The side-cut maneuver had females demonstrating greater medial and lateral gastrocnemii activity compared to males for both the pre-contact and early stance phases. For the hamstrings, a gender difference in the overall activation waveform pattern or shape and not in the overall magnitude was captured for the pre-contact phase. This difference was significant for only the medial hamstring during the side-cut maneuver and for the lateral hamstring during cross-cut maneuver. Females tended to have greater activity earlier in the pre-contact phase and reached a peak activation magnitude earlier compared to males. Later in the pre-contact phase, however, males tended to have the greater hamstring activity in comparison to the female athletes.

7.1.4 Objective 4 and Hypothesis 3 – Lower Limb Strength Comparisons Between Genders

The fourth objective of this thesis was to determine if strength differences exist between genders for knee extension, knee flexion and ankle plantar-flexion by measuring the torque generated on a Cybex dynamometer. These findings were presented in chapter

4 and it was determined that males produced greater torques than the females for all 4 exercises, therefore supporting the first part of the third hypothesis. It was also hypothesized that the torque ratio of knee flexion to knee extension would be greater in males compared females; however, this part of the hypothesis was rejected as no gender differences were identified for the ratios of these torque measures. It has been suggested in the literature that individuals with a low ratio of knee flexion to knee extension strength are at a greater risk for sustaining a significant knee injury.[214]

7.1.5 Objective 5 and Hypothesis 4 – Relate Differences to Non-contact ACL Injury Risk Factors and Gender Bias

The final objective and hypothesis was to use the biomechanical and neuromuscular differences to improve on the current understanding of the gender bias and risk factors associated with non-contact ACL injuries. Many of the differences between the male and female athletes were explained in terms of being risk factors towards the higher non-contact ACL injury rate seen in females compared to males. Contracting the quadriceps at relatively small flexion angles can increase the load experienced by the ACL[9,174] and contracting the hamstrings at larger flexion angles has been shown to reduce the strain experienced by the ACL.[144,174] Although results varied across the 3 unanticipated maneuvers, females in general demonstrated increased quadriceps activity and reduced hamstring activity in comparison to the male athletes. These activation patterns in combination with females having higher activated gastrocnemii and medial-lateral gastrocnemii imbalances that were not present in males, might possibly be affecting joint stability and be placing the ACL at greater risk of being injured while performing the cutting maneuvers. The role of the gastrocnemii in knee joint stability is not as clearly understood as the role of the quadriceps and hamstrings and it has been shown that contracting the gastrocnemii muscle group can increase ACL strain.[58,157] This study represents one of the first to propose gender differences in gastrocnemii function as a possible non-contact ACL injury risk factor and thereby warrants further investigations.

The muscle activation differences identified between genders during the pre-contact phase were in general related to a difference in the overall pattern or shape of the activation pattern. These differences in activation patterns were particularly evident for the hamstrings and rectus femoris and while the relevance of these differences to the non-contact ACL injury gender bias is not entirely understood, it does suggest that females are using different neuromuscular strategies compared to males in *preparing* themselves for the stance phase of the unanticipated cutting maneuvers.

The importance of the musculature and biomechanics at the hip for controlling and protecting the knee and ACL has been suggested throughout the literature.[181,228] The findings from this thesis showed that females side-cut and cross-cut with reduced hip flexion angles and this more erect posture could be contributing to greater loads at both the knee and thereby potentially in the ACL as well. Males also generated greater hip flexion moments than females and while further research is warranted, this greater overall moment magnitude combined with the greater flexion angles in males, could be helping to increase hip joint stability and thereby be placing the ACL in a reduced state of being injured. Several gender differences in joint kinetics were also identified during the first 20% of stance, which corresponds approximately to the period of stance where non-contact ACL injuries generally occur with the knee close to full extension.[21,160] It still remains unclear as to whether these early stance gender differences in hip flexion-extension, hip internal-external rotation, hip adduction-abduction, knee flexion-extension, knee adduction-abduction and ankle eversion-inversion moments have a direct influence on the gender bias associated with non-contact ACL injuries. However, the significance of these findings may be in their timing, pointing to the importance of investigating the early stance phase.

Attempting to link the gender differences identified for lower limb biomechanics with the gender differences identified for the EMG muscle activation patterns during the dynamic athletic maneuvers is difficult to do, mainly because the measured EMG activation levels during dynamic tasks are not necessarily related linearly to the forces generated by the corresponding muscles.[106,230] If one makes the general assumption, however, that higher muscle activity levels correspond to greater force generation, then one can more easily attempt to relate the biomechanical and neuromuscular findings to one another with the goal of enhancing the current understanding of the gender bias in ACL injury rates.

Pertaining to the results from this thesis, females generally performed the cutting maneuvers with less hip flexion, less hamstring activity, greater rectus femoris activity and greater gastrocnemii activity compared to males. One plausible explanation of how these differences could be linked to one another and related to the ACL gender bias is with respect to the sagittal plane for the hip and knee. Compared to males, females might possibly be having greater rectus femoris activity throughout stance to help increase hip flexion and avoid cutting in a more erect posture. Small flexion angles or an erect posture tends to generate higher impact forces[63,204] and thereby greater forces at the knee. The increased rectus femoris activity could also be producing an internal knee extension moment that would have to be balanced by an opposing internal flexion moment generated by the hamstrings and/or the gastrocnemii muscle groups. From an ACL injury perspective, it would likely be more beneficial if females were able to create the internal flexion moment by further contracting the hamstrings. The increased hamstring activity and forces generated by this muscle group would therefore be pulling posteriorly on the tibia and helping to reduce the loads on the ACL. This was not found to be the case in our study, however, with females actually having greater gastrocnemii activity for both cutting maneuvers during early to mid-stance and reduced hamstring activity for the cross-cut maneuver compared to the male athletes. The combination of greater quadriceps (rectus femoris in particular) activity, greater gastrocnemii activity and reduced hamstrings activity in females while cutting could all be contributing to greater loads in the ACL based on previous studies showing that i) forces generated by the gastrocnemii can increase ACL strain,[58,157] ii) forces generated by the quadriceps can pull the tibia anteriorly and strain the ACL[9,19,174] and ii) forces generated by the hamstrings can decrease ACL loads.[144,174] While further research is warranted and transverse and frontal plane biomechanics can not be ignored for non-contact ACL injuries, the description above does represent one plausible explanation of how gender differences in hip angles and activation patterns of the quadriceps, hamstrings and gastrocnemii could all be contributing collectively towards the greater non-contact ACL injury rate seen in females compared to males.

7.2 Implications

The knowledge gained from this thesis should have direct implications on a number of areas related to non-contact ACL injuries and the gender bias associated with this injury. It is well known that females are 2-8 times more likely than males of sustaining a non-contact ACL injury[1,8,128] and many of the biomechanical and neuromuscular differences identified between the male and female athletes for the unanticipated maneuvers were successfully related to previously identified or newly identified risk factors for non-contact ACL injuries. Risk factors such as greater quadriceps activity and reduced hamstring activity have been identified in the literature for preplanned cutting maneuvers.[127] This thesis represents one of the first studies to show that many of the potential risk factors present during preplanned maneuvers are also evident for unanticipated maneuvers, which are maneuvers thought to more closely resemble a true game-like scenario where the ACL is commonly injured.

Many of the biomechanical differences identified between genders in this thesis were at the hip joint, which has implications on the importance of focusing at the hip when addressing risk factors and mechanisms for non-contact ACL injuries. Although muscle activation patterns were not measured at the hip in the current study, the biomechanical differences suggest that females may not be adequately controlling the hip during cutting-related maneuvers and they may therefore be placing their knee and ACL at greater risk of injury in comparison to the male athletes. Future studies need to address the interaction of the biomechanics and neuromuscular response at the hip during cutting-related maneuvers and determine how the loads at the knee and in the ACL are affected by the responses at the hip.

Also unique to this study were the simultaneous comparisons of the muscle activation patterns between genders and between medial-lateral muscle sites for each of the 3 main muscle groups crossing the knee. Differences between genders varied for the lateral and medial muscle sites and medial-lateral imbalances were also identified for the hamstrings and gastrocnemii across the 3 maneuvers. The imbalances and differences for the medial and lateral muscle sites has implications with respect to the possible importance of selective activations of the medial and lateral muscle sites for controlling higher adduction-abduction and internal-external rotation loads at the knee during unanticipated cutting-related maneuvers. The gastrocnemii and hamstrings have medial and lateral insertions at the knee as opposed to the quadriceps muscles that insert centrally into the patella and extend the knee through the patellar tendon. The insertions for the gastrocnemii and hamstrings are at a more advantageous position for controlling out of sagittal plane movements and loads and this may explain why medial-lateral muscle site differences were captured for the gastrocnemii and hamstrings and not for the quadriceps. Because the ACL has a role in controlling movements and loads in the frontal and transverse plane, it is important that the response of both the medial and lateral muscle sites be considered when trying to understand i) stability at the knee, ii) the mechanisms for non-contact ACL injuries and iii) potential ACL injury risk factors, particularly in females.

Many of the gender and/or medial-lateral muscle site differences captured and identified as ACL injury risk factors in this thesis are potentially modifiable and this has direct implications on preventative training regiments or intervention programs aiming to reduce the number of non-contact ACL injuries in sport. Neuromuscular and proprioceptive training programs such as those proposed by Hewett et al.[79] and Mandelbaum et al.[129] have been able to reduce the incidence of ACL injuries and the findings from this thesis could be used to help improve these current intervention programs. The unanticipated cutting maneuver testing protocol developed in the current study could also have implications in a long term study that attempts to assess the effectiveness of current and newly developed ACL preventative training programs.

7.3 Limitations

One of the difficulties and limitations associated with almost any motion analysis study is the inherent errors that can be introduced when using markers on the skin to represent the movement of the underlying bone. Motion analysis errors have been shown to be associated with kinematic crosstalk,[104,166,171,173] soft tissue artifact,[117] hip joint center miscalculation,[201] anatomical landmark misplacement[45] and instrumentation errors.[35] These errors were minimized by having the same person place all the markers meticulously on the subjects during the data collection. Optimization routines and filtering techniques were also applied to the marker data to minimize the associated errors.

PCA has proven to be a powerful technique for analyzing biomechanical and neuromuscular waveforms,[33,46,47,91,92,112,136,195,224] however, the technique also has limitations related to ease of interpretability and the ability to quantify identified waveform differences. PCA objectively extracts waveform features based on the variability in the dataset but interpreting these features from a biomechanical or neuromuscular basis can be both subjective and difficult at times. Gender and medial-lateral muscle site differences were tested by statistically comparing the generated PC scores from each PC analysis. The limitation with this technique is that the identified differences in PC scores can not be quantified with respect to the units that the waveforms are reported in. Regardless of the limitations, PCA still serves as an effective alternative to a parameter based analysis of waveforms and has several advantages such as its ability to reduce the dataset and the ability to identify discriminatory features that may not have been obvious or apparent if only a parameter based analysis was used.

While electromyography provided valuable information on muscle function during the athletic maneuvers, the technique does have some limitations associated with it. Signal crosstalk between adjacent muscles has been reported to be a problem when measuring muscle activity;[198,217] however, precautions were taken so as to minimize these potential errors. Careful attention was made to electrode placement and a series of manual muscle tests were employed to ensure electrodes were properly placed and crosstalk minimized. The muscles analyzed in this study also tend to be the larger muscles in the body, making the distance between different muscles larger and thereby helping to reduce crosstalk. Most athletes had low levels of adipose tissue and this would have also helped with minimizing crosstalk. Another limitation with electromyography can be amplitude normalizing the signals and being able to elicit maximum voluntary isometric contractions for each muscle. Fortunately all the athletes were of a high caliber and very motivated, making it easier to get consistent maximum contractions. And while the muscle activation levels during dynamic maneuvers can be greater than the activation levels obtained during the maximum voluntary isometric contractions, this normalization technique has been recommended over other normalization techniques for making comparisons between subjects and muscles.[25,110] Caution most also be used when attempting to compare muscle activity to force production by the muscles as it has been shown in the literature that the relationship between activity level and force generation is not linear during dynamic tasks.[106,230]

A further limitation related to this study was the variability introduced into this study due to differences in the technique in which athletes performed the unanticipated running and cutting maneuvers. While the angle of cut, the approach speed and foot placement on the force platform were all carefully monitored and controlled throughout the cutting maneuvers, the athletes were asked to cross-cut and side-cut in a manner that felt natural to them. It was qualitatively apparent from observing all the cutting trials that some of the athletes used different techniques in order to successfully execute the maneuvers. This was a limitation because the individual cutting styles most likely increased the variability in the dataset, therefore making it more difficult to detect differences between genders and/or between medial-lateral muscle sites. It was felt, however, that having the athletes cut naturally the way they did, rather than in a more controlled manner, more closely approximated a true game-like scenario where the athlete is most likely to injure the ACL from a non-contact cutting-related maneuver.

7.4 Conclusions

Exploring and identifying potential risk factors for non-contact ACL injuries and gaining insight into the gender bias associated with this devastating knee injury were the motivating factors for conducting the research presented in this thesis. Biomechanical and neuromuscular differences of the lower limb were identified between genders and also between medial-lateral muscle sites in an elite adolescent soccer population during an unanticipated straight run, cross-cut and side-cut maneuver. A light guiding system in the laboratory forced the athletes to perform the maneuvers in an unanticipated manner, which is believed to more closely approximate a game-like scenario where the ACL is most apt to be injured. Many of the differences captured across the 3 maneuvers were identified as potential risk factors for non-contact ACL injuries.

The majority of the biomechanical differences identified between genders were at the hip and with these differences, it appears that females could be controlling their hips in a manner that is tending to place the knee and subsequently the ACL at greater risk of being injured compared to their male counterparts. Numerous gender differences in joint moments were also captured during the first 20% of stance for the 3 maneuvers. While these moments during early stance were small compared to mid-stance and appear to not be of a magnitude great enough to injure the ACL, the significance of this finding could be the timing in which the differences were captured, which was during early stance when the ACL has been shown to be most prone to a non-contact injury.[21,160]

Also unique to this study was the simultaneous comparison of muscle activation patterns between genders and between medial-lateral muscle sites using the waveform analysis technique of PCA. Between the male and female athletes, different medial-lateral imbalances were identified for both the hamstrings and gastrocnemii muscle groups. The most notable imbalance was seen in the female gastrocnemii for all 3 maneuvers, with the lateral site being more activated than medial site. It was suggested that this imbalance could be contributing to instability at the knee and also be placing the female ACL at greater risk of being injured. While not evident for all maneuvers, females also tended to have greater quadriceps activity, particularly for the rectus femoris, and reduced hamstring activity compared to males throughout the stance phase of the unanticipated maneuvers and similar findings have been previously noted in the literature for preplanned maneuvers.[127] The combination of these neuromuscular differences between genders could be placing the female knee in a less stable state and contributing to the gender bias in non-contact ACL injuries. Gender and medial-lateral muscle differences for the hamstrings, gastrocnemii and rectus femoris were also captured during the pre-contact and early stance phases of the 3 unanticipated maneuvers, suggesting that females are using different neuromuscular control strategies than males to prepare themselves for executing unanticipated athletic maneuvers.

This study successfully and simultaneously compared lower limb biomechanics and neuromuscular activation patterns of the muscles surrounding the knee during unanticipated running and cutting maneuvers. Numerous differences were captured between genders and between medial-lateral muscle sites and this represents the first study to compare neuromuscular activation patterns between genders for unanticipated cutting-related maneuvers.

7.5 Future Research

The findings from this study and how the identified differences relate to non-contact ACL injuries and the gender bias associated with the injury will serve as the foundation for future research initiatives aimed at preventing and reducing the incidence of non-contact ACL injuries.

The current study captured several biomechanical differences between genders at the hip; however, the neuromuscular response of the hip musculature was not measured during the unanticipated maneuvers. It has been stated in the literature that the hip may have an important role in controlling the loads experienced by both the knee and ACL during dynamic tasks.[181,227,228] It is therefore warranted that future research be carried out to determine if hip muscle activation patterns differ between genders during the unanticipated cutting maneuvers and if identified differences can be related to ACL injury or risk factors associated with the injury. Core strength has been shown to have an important role in injury prevention[119] and therefore measuring muscle activation patterns of the core during unanticipated cutting may also enhance the current understanding of the gender bias of ACL injuries.

The findings from the current and past studies can be used to help design and improve upon preventative training regiments aimed at reducing the incidence of non-contact ACL injuries. Ideally, an unanticipated cutting maneuver study in the laboratory should be carried out that involves measuring and comparing the biomechanical and neuromuscular response of the body between genders prior to an intervention. After the intervention program has been implemented, each individual could be re-tested to determine how the biomechanical and neuromuscular measures change between the 2 genders as a result of the preventative training program. The findings from a study of this magnitude and nature could provide significant insight into the ACL injury gender bias and provide a means for reducing the frequency of this injury, particularly in the female population.

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Appendix A - Consent Form

Consent Form

Knee Mechanics and Muscular Function During Cutting Maneuvers

Gender Difference in Non-Contact ACL Injury Rates

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Contact Person

Please contact Scott Landry or Kelly McKean (contact information above) in the event of any unusual occurrences or difficulties related to the research, or to receive more information or clarification about the study procedure at any time.

Introduction

We invite you to take part in a research study at Dalhousie University. Taking part in this study is voluntary and you may withdraw from the study at any time. The study is described below and the risks or discomfort that you might experience during the study are also explained. Participating in the study might not help you, but we might learn things that will help others. You should discuss any questions you have about this study with the people who explain it to you.

Purpose of the study

This research proposal addresses the forces and muscle activity around the knee during non-contact sports. Many knee injuries occur during non-contact sports involving cutting movements (running forward and turning to the side quickly). The most severe of these injuries is tearing of the anterior cruciate ligament (ACL). The ACL is a small ligament inside the knee that provides knee stability. While this injury is common in males and females, females tear their ACL 2-8x more than males. This risk is also greater with higher levels of competition. For example in Nova Scotia, at least 7 female soccer players on the Under 17 and Under 16 provincial soccer teams have actually torn their ACL within the past year. To our knowledge none of the boys in the same age group have had this injury. The forces and muscular activity that may contribute to this gender difference are not well understood. The position of the knee and the forces on the knee during athletic activity may be different between males and females and this may place the ACL under greater strain. Also, the muscles of the front and the back of the thigh play a major role in stabilizing the knee. The pattern and timing of when these muscles turn on can also increase the load that the ACL experiences. Our hypothesis is that females experience differences in forces, angles and muscular control of the knee and this places their knee in a weaker state. If these differences can be detected it will help us understand why females are at greater risk for ACL injuries. It will also help develop training programs to prevent ACL injury.

Study Design

The study is designed to compare the knee joint orientation, loading and muscle activity during running and cutting movements between a group of healthy male and female soccer players. We will measure the forces between the foot and the ground, the angle of the knee joint and the activity patterns of the leg muscles throughout running and cutting activities. This data will be measured and averaged for each subject. Data from the male group will be compared to the female group.

Who Can Participate in the Study

Two groups of subjects are invited to participate in this study: a group of healthy female soccer players, and a group of healthy male soccer players. You may participate in the study if you are between the ages of 14 and 18 years, have no history of surgery to your legs and no pain in your legs.

Who will be Conducting the Research

The principal investigators of this study are Scott Landry and Kelly McKean. They are graduate students in the School of Biomedical Engineering, working under the supervision of Dr. Cheryl Hubley-Kozey, Dr. Kevin Deluzio (School of Biomedical Engineering) and an orthopaedic surgeon, Dr. William Stanish.

What you will be asked to do

You will be asked to run along a 3-5 meter walkway and then cut to the side at about halfway down the walkway. We will also ask you to run straight the entire length of the walkway. A brief training session with demonstrations and practice trials will be conducted prior to the trials and this will allow you to get used to the movements. We will monitor you in a number of ways while you run down the walkway so that we can measure movement characteristics of your body during the activity. First, special cameras will be used to record your movement across the walkway. We will tape small markers over your ankle, calf, knee, thigh, hip, and shoulder. The cameras are able to follow the motion of these markers with a high level of accuracy. Second, small electrodes (little metal discs that pick up the activity from working muscles) will be placed on 7 sites on your thigh and calf to measure muscle activity. The parts of your skin where electrodes will be placed, will be lightly rubbed with an alcohol swab and if necessary shaven with a new disposable hand held razor. Once the cutting and running trials are completed, you will be asked to perform 6 different leg exercises. You will be asked to produce a maximum effort for three seconds for each exercise. These will be repeated twice and you will have at least 1 minute rest in between trials. The testing will be done in the Dynamics of Human Motion Laboratory (DOHM) at Dalhousie University. It will take 2 hours of your time.

Possible Risks and Discomforts

The risks associated with this study are minimal. However, there is a small risk of fatigue, muscle soreness or injury from the walkway trials and maximal muscle contractions. The risk of ACL injury will be much smaller than in a regular game situation since the trials will be collected in a controlled environment and your muscles will not be tired. You will not be asked to take part in the trials until you have had a days rest since your last game. You may rest at any time during the testing, or withdraw from the study if you feel the need. In case of an emergency the primary investigators are CPR and first aid certified. All known precautions have been performed to reduce any potential risk to you as a result from participating in the study.

Possible Benefits

We do not expect this study to have any direct benefit to you. However, the study may help identify gender differences in sports movements that can be modified to decrease the risk of sports injuries in the future. In addition, in previous gait studies performed by the principal investigators, subjects have been interested in learning about their movement patterns. Please feel free to ask any questions that you may have.

Compensation

In exchange for participating in this study you will be paid $20. This amount will be paid regardless of whether you complete the study activities or not.

Knee Mechanics and Muscular Function During Cutting Maneuvers
Gender Difference in Non-Contact ACL Injury Rates

Confidentiality

Your privacy will be safeguarded at all times. A subject number will be assigned to each participant and that number will be used to link to the data that we collect. Identifying information about you will not be used in any way.

Questions

If you have any questions regarding the study, please do not hesitate to contact Scott Landry or Kelly McKean at (902) 494-1686 or (902) 494-7186.

Signature

I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I hereby consent to take part in this study. However, I realize that my participation is voluntary and that I am free to withdraw from the study at any time. Should I decide to withdraw, I will inform Scott Landry or Kelly McKean of my decision.

Subject Signature ____

Date ____________________

I have read the explanation about the study above and agree to allow my son/daughter to participate.

Subject Name (Please Print) ________________________________

Parent/Guardian Signature ________________________________

Date __________

In the event that you have any difficulties with, or wish to voice concern with any aspect of your participation in this study, you may contact the Human Research Ethics/ Integrity Coordinator at Dalhousie University's Office of Human Research Ethics and Integrity for assistance: (902) 494-1462

Appendix B - Questionnaires Related to Participation, Previous Injuries and Menstrual Cycle

Knee Mechanics and Muscular Function During Cutting Maneuvers
Gender Difference in Non-Contact ACL Injury Rates

Subject #: ________________ Date: ________________

Teams Playing for: ______________________________ Position: ______________________________
Yrs Playing Soccer: ______________________________ Yrs on Provincial Team: ________ Teams: ______________________
Total # of games played per week (including all teams played for): Winter________________Summer________________
Total # of training sessions per week (including all teams played for): Winter________________Summer________________
Length of time of training sessions (i.e. 1.5 hours): Winter________________Summer________________

Other sports currently playing (this year): ________________________
Total # of games played per week: Winter________________Summer________________
Total # of training sessions per week: Winter________________Summer________________
Length of time of training sessions: Winter________________Summer________________

Other Sports Played (ever): ________________________

Have you ever had any type of surgery on your legs (this includes feet, ankles, shins, calves, knees, thighs, hips)? Y N
If yes, what type of surgery? ____
When was the surgery? ____

Have you suffered **any other leg injuries** in the past (i.e. broken bones, stress fractures, sprains, strain, muscle pulls, ligament/tendon damage)?
Y N

If yes, please complete the following for each injury:

	Injury (diagnosis)	**Date injury occurred**	**Diagnosed by**		
i.e	Hamstring Strain	May 2003	☑ physician	☐ other health professional	☐ self
1.			☐ physician	☐ other health professional	☐ self
2.			☐ physician	☐ other health professional	☐ self
3.			☐ physician	☐ other health professional	☐ self
4.			☐ physician	☐ other health professional	☐ self

Do you currently have any leg pain? Y N

PLEASE REMEMBER THAT <u>ALL</u> PARTS OF THIS QUESTIONNAIRE ARE OPTIONAL.

There is research that suggests there is a link between the menstrual cycle and ACL injuries in female athletes.

If you feel comfortable, please answer the following optional questions:

When was the last time you began your period? Please circle the date.

May 2004

Sun	Mon	Tue	Wed	Thu	Fri	Sat
2	3	4	5	6	7	1/8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

June 2004

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

July 2004

Sun	Mon	Tue	Wed	Thu	Fri	Sat
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

Generally, are your periods regular? **Y N**

Appendix C - Principal Component Analysis Applied to Biomechanical and Neuromuscular Data

Data Structure

- X = n x p matrix of original observations and variables

  $X = [\vec{x}_1, \vec{x}_2 ...... \vec{x}_p]$

  where $\vec{x}_i$ = a vector of n subjects' observations at one point, *i*, in the phase
  $i = 1, ... p$

- p = the number of original variables

  $p = (p_1, p_2 .... p_{101})$

- n = the total number of original observations (2 or 4 groups)

  $n = n_1 + n_2 + n_3 + n_4$

  where n_1 = the number of male subjects, lateral site
  n_2 = the number of female subjects, lateral site
  n_3 = the number of male subjects, medial site
  n_4 = the number of female subjects, medial site

  $\overline{X} = [\vec{x}_1 - \overline{x}_1, \vec{x}_2 - \overline{x}_2 ...... \vec{x}_p - \overline{x}_p]$

Principal Component Analysis (PCA)

The Covariance Matrix

- C = the p x p covariance matrix of the mean subtracted dataset

$$C = \mathrm{Cov}(\overline{X})$$

$$C = \begin{bmatrix} s_1^2 & s_{12} & . & s_1^2 \\ s_{12} & s_2^2 & . & . \\ . & . & . & . \\ s_{1p} & s_{2p} & . & s_p^2 \end{bmatrix}$$

Where s_i^2 = variance of the variable x_i

s_{ij} = covariance of the variables x_i and x_j

Decomposition of Eigenvectors (PCs) and Eigenvalues

- T = p x p orthonormal matrix whose clolumns are eigenvectors or PCs of C

$$T = [\vec{u}_1, \vec{u}_2 ......\vec{u}_p] = [\overrightarrow{PC}_1, \overrightarrow{PC}_2 ......\overrightarrow{PC}_p]$$

- Λ = p x p diagonal matrix of eigenvalues

$$\Lambda = T^T CT$$

$$\mathbf{\Lambda} = \begin{bmatrix} l_1 & 0 & . & 0 \\ 0 & l_2 & . & . \\ . & . & . & . \\ 0 & 0 & . & l_p \end{bmatrix}$$

and $l_1 > l_1 > ..... > l_p$

Percent Variation Explained by Each PC

- pct = percent of the total variation in the data explained by each PC

$$pct_p = \frac{l_p}{Tr(C)} 100$$

where $Tr(\mathrm{C})$ = the sum of the eigenvalues

$$Tr(\mathrm{C}) = Tr(\Lambda) = \sum l_1 \ldots l_p$$

Calculating Z Scores

- Z_k = n x k matrix of transformed observations or Z scores

$$Z_k = (\overline{X})T_k$$

$$Z_k = [z_{n,1}, z_{n,2} \ldots z_{n,k}]$$

where k = number of retained PCs
z_n = subject Z score or variance in subjects waveform for given PC

Interpretation

The original variables or dataset, $\underset{nxp}{\overline{X}}$, is described by $\underset{1xp}{T}$ features of variation and reduced to $\underset{1xk}{T}$ features of variation, where k < p. The variance in these features is described by the newly transformed observations $\underset{nxk}{Z}$.