

A Comparison of Risk Factors Between a Cutting Task and a Stop-Jump as it Relates to the
Non Contact Anterior Cruciate Ligament Injury

Uranie P. Browne

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial
fulfillment of the requirements for the degree of Master of Science in the Department of
Biomedical Engineering (School of Medicine).

Chapel Hill
2007

Approved by:

Henry Hsiao, Ph.D

Bing Yu, Ph.D

Michael Gross, PT, Ph.D

©2007
Uranie P. Browne
ALL RIGHTS RESERVED

ABSTRACT

Uranie P. Browne: A Comparison of Risk Factors Between a Cutting Task and a Stop-Jump as it Relates to the Non Contact Anterior Cruciate Ligament Injury
(Under the direction of Henry Hsiao, Bing Yu, and Michael Gross)

This study compared lower leg biomechanical differences specifically at the knee while performing jump stop and cutting tasks. This was done because of the need to better understand the specific mechanisms that contribute to non contact ACL tears. Much of the focus has been on non contact ACL tears while performing a stop-jump task. This study examined at the mechanisms of a cutting task as it relates to the incidence of non contact ACL tears. We found that the mechanisms of the cutting task are biomechanically different than the stop-jump task, suggesting the need to focus on the cutting task as a separate entity when looking at preventing non contact ACL tears. Overall, this new knowledge should help further research attempting to help reduce the incidence of non contact ACL ruptures.

DEDICATION

To my husband L. Kelsey Armstrong, my parents Clyde and Carol Browne, and my sister
Rashelle Browne.

ACKNOWLEDGEMENTS

I would like to express my deepest sincerity and gratitude to my masters committee. No one can ever imagine what superb guidance and support you have given me throughout the planning and preparation of this project. All of you were willing to assist me and stick by me when no one else seemed that they would. I will be forever in your debt, and hope that you are always shown the kindness and consideration that you have shown to me.

Before, during and after many trials and tribulations, there have been people who have continuously helped me to become a better person, challenged me to reach my potential, and to continue to persevere through to the completion of my masters thesis. They are my husband, L Kelsey Armstrong, my parents Clyde and Carol Browne, and my sister Rashelle Browne. I am particularly grateful to all of you as well as to my extended family and friends, who via phone calls, and packages always sent me well wishes, lighting up my day many times during this process, I love you all.

TABLE OF CONTENTS

LIST OF TABLES.....	ix
LIST OF FIGURES.....	x
Chapter	
I. INTRODUCTION.....	1
General Background.....	1
Statement of Problem.....	1
Research Questions.....	2
Operational Definitions.....	2
Assumptions/Limitations.....	3
Significance of Study.....	4
The Injury.....	4
II. REVIEW OF LITERATURE.....	6
Normal Lower Leg Articulation and Function.....	7
Normal Gait.....	7
Normal Knee Joint Movement.....	7
Normal Internal Knee Pathology.....	8
Lower Extremity Anatomy.....	8
The Anatomy of the Knee.....	8
Background on the ACL.....	10

The Non Contact ACL Injury and Possible Prevention Mechanisms.....	11
Potential Risk Factors.....	12
Effects of Hamstring and Quadricep Activation on ACL Loading.....	13
Effects of Knee Flexion Angle on ACL Loading	13
Effects of Knee Joint Resultant Flexion/Extension Moment, Anterior Tibial Shear Force, Internal/External Rotation Moment, and Varus/Valgus Moments on ACL Loading.....	14
Effects of Vertical Ground Reaction Force and Posterior Ground Reaction Force on ACL loading.....	16
Effects of ACL Elevation Angle on ACL Loading.....	16
Effects of Landing Techniques on ACL Loading.....	17
Effects of Tibial Tilting Angles on ACL Loading.....	17
Effects of Patellar Tendon Angles on ACL Loading.....	18
Biomechanical Analysis.....	18
Video, Marker Placement, and Force Plate Analysis.....	18
Summary.....	19
III. METHODS.....	21
Subjects.....	21
Equipment.....	21
Experimental Procedure.....	22
Data Collection.....	24
Data Reduction.....	24
Data Analysis.....	26
IV. RESULTS.....	27

V. DISCUSSION.....	37
Effect of Knee Flexion Angles for Cutting Compared to the Stop-Jump.....	37
Effect of Knee External Rotation Moment for Cutting Compared to the Stop-Jump.....	38
Effect of the Vertical Ground Reaction Forces and Tibial Tilting Angles for Cutting Compared to the Stop-Jump.....	38
Effect of the Posterior Ground Reaction Force for Cutting Compared to the Stop-Jump.....	39
Effect of Knee Valgus Moment for Cutting Compared to the Stop-Jump.....	40
Overall Differences in Resultant Data when Comparing Cutting on the Right and Left Legs.....	40
VI. CONCLUSION.....	42
REFERENCES.....	43

LIST OF TABLES

Table

1. Comparison of Knee Flexion Angles at the Peak Posterior Ground Reaction Force Among Tasks	28
2. Comparison of Vertical Ground Reaction Forces at the Peak Posterior Ground Reaction Force Among Tasks.....	28
3. Comparison of Tibial Tilting Angles at the Peak Posterior Ground Reaction Force Among Tasks.....	29
4. Comparison of Knee Valgus Moments at the Peak Posterior Ground Reaction Force Among Tasks.....	29
5. Comparison of Knee External Rotation Moments at the Peak Posterior Ground Reaction Force Among Tasks.....	30
6. Comparison of the Peak Posterior Ground Reaction Forces Among Tasks.....	30

LIST OF FIGURES

Figure

1. Marker Placement for Standing Static Trial Calibration	22
2. Knee Flexion Angles at Peak Posterior Ground Reaction Force.....	31
3. Vertical Ground Reaction Force at the Peak Ground Reaction Force.....	32
4. Tibial Tilting Angle the Peak Ground Reaction Force	33
5. Knee Valgus Moment the Peak Ground Reaction Force.....	34
6. Knee External Rotation Moment the Peak Ground Reaction Force.....	35
7. Peak Ground Reaction Forces.....	36

CHAPTER 1

INTRODUCTION

General Background

Knee ligament injuries are common among athletes, especially severe ligament injuries requiring surgeries, such as non contact anterior cruciate (ACL) injuries. Recent NCAA injury statistics, noted that female athletes were six times more likely to incur an ACL injury than their male counterparts. (8,29) Numerous studies have focused on explaining why women are more prone to ACL injuries, attributing the phenomenon to ovulation, larger Q angle and/or inherent muscle and ligament weakness, particularly during stop-jump tasks. The stop-jump task has been studied simply because it is one of the movements in which non contact ACL injuries frequently occur. However, another potentially dangerous movement in which non contact ACL injuries frequently occur is side cutting. Although the stop-jump task has been extensively studied, to date there are few studies that have examined the mechanical similarities and differences between the two motions, helping to further determine the potential cause of a non contact ACL injuries.

Statement of Problem

The objective of this study is to further investigate the lower extremity movement patterns and risk factors related to non contact ACL injuries by comparing the lower extremity kinematics and kinetics between a preplanned cutting task and a preplanned stop-jump task. We compared specific outcome variables of the cutting task to known results of the same variables for the stop-jump task to make the necessary comparisons and supply the answers to the following research questions.

Research Questions

The study will answer the following research questions:

- RQ1. Is the amount of peak posterior ground reaction force in the side cutting task the same as the stop-jump task?
- RQ2. Are the knee flexion angle, vertical ground reaction force, tibia tilting angle, knee external rotation moment, knee joint resultant valgus moment at the peak posterior ground reaction force in the side-cutting task the same as those in the stop-jump task?
- RQ3. Is there a significant difference in the same variables between cutting on the right or left legs?

The answers to these research questions will provide information for the prevention of non contact ACL injuries.

Operational Definitions

Cutting movement : a deceleration followed by an abrupt change in direction with one foot in the stance phase.

Stop-jump: a vertical deceleration done when landing on two feet at the same time.

Pre-planned cutting maneuver: advanced knowledge as to the direction that one will cut.

Assumptions/Limitations

The assumptions made for this project were as follows...

1. Previous data collected involving knee kinematics and kinetics for the stop-jump maneuver were accurate.
2. The previous stop-jump data was an average of the values of the right and left legs. We did this because a Yu et al. (2005) study concluded that stop-jump data between the left and right sides were about the same. This enabled us to compare single leg movements for both data groups.
3. We matched the activity levels for the cutting subject group to the stop-jump subject group and normalized each data set for weight differences.
4. From the Simonsen et al. (2000) (cutting) study and the Yu et al. (2006) (stop-jump), we were able to compare specific factors of the resultant data for previous stop-jump studies to the current cutting data results. This was because both studies noted that the ACL is at maximum strain when peak ground reaction forces were seen. Each of the values of the chosen variables were compared at that specific point in time.
5. We were also limited in the choice of comparison variables since the stop-jump data collection had already been completed. We had to match our variables to the ones noted in the previous study.

Significance of study

The ligamentous structures about the knee provide critical support and stability for function in athletic and occupational endeavors. During gait, the ACL tightens with internal tibia rotation, whereas during external rotation, it becomes lax. (10) It is already known through previous studies that ACL loading is at its highest when the peak ground reaction force is seen during a stop-jump task. (12, 32) Therefore, looking at the cutting task would enable a comparison of distinct variables at a point where non contact ACL injuries have been thought to occur at the peak ground reaction force. The outcome of this study will determine how similar or different the effects of stop-jump and cutting are on the ACL.

The Injury

Overall body positioning is important when trying to prevent non contact ACL injuries. Previous studies have reported that 71-78 % of anterior cruciate ligament injured patients described non contact mechanisms of injury. (2) During deceleration, just after initial ground contact, the quadriceps and hamstrings are attempting to control knee movement or tibia movement at the proximal end. (29) In general, it has also been shown that large quadriceps muscle force along with small knee flexion angles increase the threat of an ACL tear. (2,7,16,18) At the same time, the internal knee ligaments are trying to also help to control movements at the knee. Soon after initial contact, the body pushes onto the ground at its highest force (peak ground reaction force) in order to sustain continued deceleration of the body. Knee flexion angles also are important when

discussing non contact ACL prevention. Previous studies suggest that a decreased knee flexion angle results in an increase in ACL loading. (45, 34, 24, 34).

Deceleration of the body is needed when one is simply trying to stop after moving or simply change directions. Both the stop-jump task and the cutting task do just that, although differently. During cutting, the foot turns to the direction of the positional change and then the body follows. (46) For stop-jump, there is usually no directional change thus the foot and the rest the body are facing the same direction in the same plane. When non contact injuries occur in stop-jump, the body is usually not in this ideal position. In order to prevent non contact ACL tearing we would need to see what causes its excessive loading during the deceleration process. Since both tasks exhibit different types of deceleration behaviors we examined their similarities and differences, helping us to further understand the reasons behind the devastating injury of a non contact ACL tear.

While much has been written on non contact anterior cruciate ligament injuries during stop-jump, little attention has been given or paid to understanding the mechanism of the injury during cutting. A comparison between these two very common dynamic movements in regards to ACL strain or prevention of non contact ACL tears, also has rarely been discussed in the literature until now. In particular, a comparison by way of the related timing seen at the peak vertical ground reaction force for each dynamic task has rarely been discussed if at all.

CHAPTER 2

REVIEW OF LITERATURE

Overall body positioning is important when trying to prevent non contact injuries during a preplanned movement, particularly while performing a cutting or stop-jump task. During preplanned movements, one usually has enough time to align ones self properly or at least in the most comfortable or non-taxing way in an effort to prevent injury. This section will first provide information on the body's natural lower leg mechanics and articulations. Then potential risk factors will be addressed as well as an explanation of the biomechanical analysis needed to draw a proper conclusion.

During gait, there is a relationship between biomechanical abnormalities of the foot and ankle complex and knee pathologies. These abnormalities may relay stresses to any area proximal or distal to it. The foot, knee and ankle joints may function as a closed or open system based upon the weight bearing status of the lower extremity. During the load bearing phase of the gait cycle, the lower extremity functions in a closed chain manner. It is believed that in this closed kinetic chain position that variable degrees of knee flexion and varus/valgus movements may be linked to internal knee strain. The study is divided into the following areas; the effects of knee flexion on non contact ACL injuries, the effects of varus/valgus moments, vertical ground reaction forces, tibia tilting ankles and knee external rotation moments on non contact ACL injuries, the importance

of peak ground reaction force on ACL loading, and the overall mechanics of cutting vs. stop-jump on non contact ACL loading. In the following section, we describe normal lower leg articulation then go into a description of lower leg articulation during dynamic events, cutting and stop-jump. This information is provided with the intention to provide background for understanding the potential risk of irregular lower leg physiology. Afterwards, a more detailed explanation of the significance of knee flexion angle, varus/valgus movements and peak ground reaction force will be further explained.

Normal Lower Leg Articulation and Function

Normal Gait

Gait is divided into two phases: stance and a swing phase. The stance phase is further divided into three phases: contact, midstance and propulsion. The contact phase begins with heel strike and ends with the foot flat on the ground. The midstance phase is the period between foot flat and heel lift. Propulsion is thus the period between heel lift and toe-off. During normal gait, initial heel contact is on the lateral aspect of the calcaneus. Afterwards the tibia rotates internally until about half way through midstance, then rotates externally during the second half of midstance through to propulsion. The area that this project will be focusing on is the period just after initial contact when peak ground reaction force occurs.

Normal knee Joint Movement

The motion of the knee joint itself is also an important component of the gait cycle. The knee is in full extension prior to heel strike and it flexes approximately 15-20

degrees during most of the contact phase. During midstance, knee extension is initiated with the foot flat and continues until immediately prior to heel lift.

Normal Internal Knee Pathology

The ligamentous structures about the knee provide critical support and stability for knee function in athletic and occupational endeavors, as well as the activities of daily living. During gait, the Anterior Cruciate Ligament (ACL) tightens at the beginning of the stance phase, whereas towards the end, it becomes lax. An investigation of the biomechanics of the ACL found that varus movements in the knee increases ACL strain. Inoue et al. also supported the importance of the ACL in resisting the varus/valgus movement of the knee joint, especially during cutting (28).

Lower Extremity Anatomy

The Anatomy of the Knee

The knee is a synovial, hinge joint that carries almost the entire body weight bearing when acting bipedally. Although it is the largest joint of the body, it only comprises of four bones, the femur, patella, tibia and the fibula. The main articulation is between the femur and the tibia. In general, 90% of the weight the body produces during gait is transferred through the tibia. This is important because in essence one has to balance their weight mostly on the tibia. This not only makes it the main articulation at the knee but also at the foot/ankle complex. Any amount of residual energy transferred from the foot to the tibia will automatically be transferred to the knee complex and vice

versa. As mentioned before, when the lower leg acts as a closed chained system, this is precisely what occurs.

Three of the four bones are considered long bones while the other bone, the patella, is a sesamoid bone. This bone is important because it is contained within the tendon of the quadriceps muscle and acts to increase the efficiency of the quadriceps muscle.

There are many muscles that are seen to have insertions around the knee area. However in regards to contributing to actual knee movement there are basically two sets of muscles that do the job, the quadriceps and the hamstrings.

The quadriceps muscle group mainly acts as knee extensors and all attach to the tibia via the patellar tendon. They consist of the rectus femoris, vastus medialis, vastus lateralis and the vastus intermedius. The hamstring muscle group not only acts to flex the knee but it also has a role in internally and externally rotating the tibia during the weight bearing/closed chain system. It consists of the biceps femoris, semitendinosus, semimembranosus, sartorius and gracilis muscles.

There are also important ligaments found in the knee's internal structure that serve to help stabilize the knee. The first two are the medial and lateral collateral ligaments, which help stabilize the medial and lateral sides of the knee. Another one is the posterior cruciate ligament, which helps prevent posterior translation of the tibia on the femur and helps to reduce the rotation of the femur on the tibia. Last is the anterior cruciate ligament (ACL), which helps to prevent anterior displacement of the tibia on the femur as well as to also reduce the rotation of the femur on the tibia. This was the ligament we focused on throughout this study.

Background of the ACL

The ACL originates at its proximal attachment along the posterosuperior lateral aspect of the intercondylar notch and transverses anteroinferiorly and slightly medially to the distal attachment at the anterior tibia eminence. The ACL holds the femur and the tibia together and helps keep the knee bending on its proper axis. In a knee with a stretched or loose ACL, a sudden unexpected shifting forward of the tibia relative to the femur may occur during the weight-bearing phase of a physical activity such as pivoting or changing direction, causing the knee to feel as if it has buckled or given way. A combination of weight-bearing and twisting stress, plus quadriceps muscle contraction stress being placed on the knee can also occasionally cause a healthy ACL to tear suddenly.

The anterior cruciate ligament provides important support against anteroposterior translational as well as rotational forces on the knee. The ligament has been described as isometric, maintaining an overall straight appearance and course, although the individual sections may tighten and relax separately. The sprain, as well as more focal partial tearing, may involve primarily two of the three functional bands. Most, if not all, complete ACL tears are repaired with complete reconstruction for the active individual. Since most tears are midsubstance complete tears, it affects the ACL entirely. Therefore another force (rotational) has to exist since the ACL ruptures at one time. The internal rotation force needed to counteract the external rotational force created by the posterior ground reaction force is the culprit. While many have concluded that there is a relationship between abnormal biomechanics and lower extremity pathology, information

on the effect of lower kinetic chain forces on knee ligament instabilities specifically the ACL, is limited.

In general, when the knee is less constrained, knee stability is reduced and the ACL becomes the dominant ligament for resisting valgus knee motion. This result is because the ACL controls coupled anteroposterior translations and axial tibia rotations to a greater degree than does the medial collateral ligament (MCL), another knee ligament, especially at small knee flexion angles.

The Non Contact ACL Injury and Possible Prevention Mechanisms

The mechanism of ACL injury is often described as non contact. A non contact ACL tear almost always involves a rapid deceleration, of the knee joint. Sometimes the knee is not stable during a rapid deceleration owing to forces from the hip and ankle placing the knee in a weak position. Seemingly, the ACL is most vulnerable when the knee is pointing inwards and the foot is pointing outwards while the torso is falling forwards. Therefore, one common action that can lead to an ACL tear is when restarting movement after stopping suddenly. The quadriceps and hamstrings are attempting to still control the deceleration of the knee, just before take-off however, the current gait phase still places an overload on the ACL. The sudden pull in the reverse direction then becomes too much for the ACL to handle and ruptures.

Previous studies have reported that 71-78 % of ACL injured patients described non contact mechanisms of injury. It has been suggested that excessive internal tibia rotation and inherent knee joint laxity may predispose an athlete to sustaining an ACL

injury. The frequent incidence of non contact ACL injuries has led researchers to study whether some athletes are predisposed to this type of injury.

Following heel strike, the quadriceps, in association with limb inertia, produce a force that results in anterior tibia displacement and internal rotator torque. The ACL, hamstrings, and menisci act to resist this anterior and rotator displacement. The hamstrings are only effective in doing so at knee flexion angles larger than thirty degrees.

While much has been written on injury to the ACL, little attention has been devoted to understanding the mechanism of injury. A greater understanding of the mechanics of injury is needed in order to prevent and improve treatment of injuries to the ACL.

There have been some notions as to what can be done in the way of prevention of ACL injuries. Hip weakness can exacerbate the anatomical alignment problems. Additional movement at the knee can occur too far and too fast if the hip abductors and the hip external rotators are not functional. The static pelvic position has been shown to influence the rate of ACL injury. Weak lower abdominals and poor muscular control can lead to a forward pelvic tilt, or sway-back position. This forward pelvic tilt also allows for more internal knee movement than normal when the pelvis is held in neutral alignment. Strengthening the body core muscles, gluteus medius, external hip rotators, lower abdominals and obliques should increase stability and help control knee internal rotation, thus reducing ACL injury risks.

Potential Risk Factors

Effects of Hamstring and Quadricep Activation on ACL Loading

Strong quadriceps and hamstrings have also been seen as being crucial for ACL prevention. However, over training the quadriceps compared to hamstrings is detrimental, since the hamstrings must cooperate with the quadriceps during knee joint decelerations to assist the stabilizing role of the ACL. It has been shown that athletes with good hamstring/quadriceps strength ratios suffer fewer non contact ACL injuries, but only at larger knee flexion angles. Strong ankle and calf muscles also help control the knee joint decelerations and help provide more stability from the ankle. Along with good all-around leg, hip and trunk strength, the coordination of the muscular recruitment is important for knee injury prevention. Neuromuscular coordination must occur optimally for the knee joint to be safely controlled. Thus, coordination drills and proprioceptive training are equally as important as muscular strength training in preventing ACL injury since most sporting movements, such as stop-jump and cutting, are very rapid. Stop-jump and cutting movements, at times, involve little knee flexion movement but require large deceleration forces. For effective ACL injury prevention training, knee deceleration movements such as landing, cutting, hopping etc., should be included as separate drills.

Effects of Knee Flexion Angle on ACL Loading

As explained above, due to the anatomy found at the knee, a greater quadriceps force results in a greater patella tendon force. At certain knee flexion angles, the force transferred through the patella tendon has been proven to create greater anterior tibia translation, putting more strain on the ACL. (2, 7, 16, 17, 18) Another way that this was

shown was by Huberti et al. (1984), and Buff et al. (1988) when they found that the patella tendon force to quadriceps force ratio changes with knee flexion angles.(11, 27) In particular, the ratio (Patella tendon force/quadriceps force) is greater than one at knee flexion angles lower than thirty degrees. This is important because it would imply that at smaller knee angles, there is an increased potential to strain the ACL due the increased potential of higher patella tendon force even if the quadriceps forces are lowered. This coincides with other various studies which noted that greater quadriceps muscle force with smaller knee flexion angles seemed to magnify the existence of ACL strain. (2, 7, 16, 18).

Effects of Knee Joint Resultant Flexion/Extension Moment, Anterior Tibial Shear Force, Internal/External Rotation Moment and Varus/Valgus Moments on ACL Loading

During an investigation of the effects of anterior tibia shear forces, knee valgus/varus, internal/external rotation moments at the knee, Markolf et al. (1995) showed that anterior shear force on the tibia generated significant ACL loading.(34) Also this study showed that knee valgus/varus and internal rotation moments also result in the same effect only when the ACL was loaded by the anterior shear force at the proximal end of the tibia. This is significant for several reasons, first it suggests that varus/valgus moments at the knee combined with anterior shear force increases ACL loading more so than anterior shear forces combined with knee external rotation moment and anterior shear forces acting alone on the knee. Also knee varus and internal rotation moment loading loaded the ACL more than either moment separately and knee valgus and external rotation loaded the ACL more than either moment separately. This study also showed that the anterior shear force, knee valgus/varus and internal rotation moments

increased the ACL loading as the knee flexion angle decreased. All of this suggests that tibia anterior shear loading is the major mechanism that loads the ACL during a stop jump task. Nunley et al. (2003) showed in their study that a more extended knee, i.e. smaller knee flexion angle, increases the anterior shear force found at the knee, which as mentioned above, would also increase the load on the ACL.(45) They also suggested that females, on average, had an anterior shear force 13.2% more than their male counterparts with the same knee flexion angle.

McLean et al. (2003,2004) studied the effect of ACL loading during a side cutting task using a stochastic and a forward dynamic model to simulate the task.(39,40) Although there were some limitations in the model, they still concluded that knee valgus moments were the major loading factor of the ACL in the non sagittal plane. Fleming et al.'s 2001 study looked at in vivo ACL strains by attaching it to a fixture that allowed for independent application of anter-posterior shear forces, valgus/varus moments and internal- external moments. (19) The knee angle was fixed at 20 degrees during the test. The results showed that anterior shear force and the knee internal rotation moment increased ACL loading while knee valgus/varus and external rotation moments had little effect on ACL strain independently.

Hewett et al. also did a longitudinal study in 2005 showing that injured female athletes had significant increases in overall knee valgus angle moments compared to non injured females.(26) This result caused them to propose that knee valgus angles had the most significant influence on ACL loading. Ford et al. (2003) and Kernozek et al. (2005) also showed that female subjects had greater valgus angles than their male counterparts during the drop jump, an activity similar to the stop jump.(21,31) This seemingly would

concur with the Hewett et al. conclusion concerning knee valgus angles and ACL loading. Since it is not agreed upon which factor is the most influential when comparing cutting to the stop jump task, in loading ACL strain we will be looking at all of them during our study.

Effects of Vertical Ground Reaction Force and Posterior Ground Reaction Force on ACL Loading

We have discussed the importance of knee angles as it relates to forces seen at the knee, particularly with smaller knee flexion angles. At smaller knee flexion angles, greater vertical ground reaction forces as well as greater posterior ground reaction forces are also seen. A large vertical ground reaction force and a large posterior ground reaction force results in a large external knee flexion moment which causes the knee to bend. This activates the quadriceps to produce an internal knee extension moment to balance out the external force applied. When the quadriceps fire, it also increases patellar tendon force which in turn increases anterior tibial shear force thus increasing ACL loading. It is important to note that peak vertical ground reaction force and the peak posterior ground reaction force occurred at about the same time as when the maximal ACL strain was noted. (12, 32) Also a study by Yu et al. (2006) showed that peak posterior ground reaction forces and peak knee extension moment occurred almost at the same time as the peak vertical ground reaction force.(52) With this knowledge, we will be able to compare the cutting task with the stop-jump task by looking at what is happening at the time of the peak vertical ground reaction force for each task.

Effects of ACL Elevation Angle on ACL Loading

Decreasing the knee flexion angle increases the ACL loading as well by increasing the ACL elevation angle. The line of action of the ACL was determined using the most anterior attachment point on the tibia and femur. A decrease of knee flexion angle results in a more vertical line of action of the ACL and increases the ACL elevation angle, which in turn increases ACL strain because it is less able to counteract any possible anterior shear forces present at the knee. (34,35)

Effects of Landing Techniques on ACL Loading

Landing on the heels requires larger quadriceps demand in order to bring the trunk forward (Griffin et al., 2000) and to balance the exaggerated external knee flexion moment. This large quadriceps force is then transferred to the patellar tendon which creates a large proximal tibial anterior shear force increasing ACL strain, especially at smaller knee flexion angles. It has been shown that the more anteriorly placed center of pressure predicted greater plantar flexion moment and less knee extensor moment. (35) Therefore, landing on the forefoot may be a protective landing style for the non contact ACL injury while landing on the heels may possibly increase the ACL loading.

Effects of Tibial Tilting Angle on ACL Loading

Landing on the heels exaggerates the external knee flexion moment for specific tibial tilting angles. Landing on the heels with the knee joint center anterior to the center of pressure, i.e. at more positive tibial tilting angles enables both the vertical and posterior ground reaction forces to produce external knee flexion moments. This external

knee flexion moment would create a similar pattern for producing increased ACL strain as seen above (35)

Effects of the Patellar Tendon Angle on ACL Loading

Decreasing the knee flexion angle increases the ACL loading by increasing the patellar tendon-tibial shaft angle and the proximal tibial anterior shear force. Nunley et al. (2003) found that the patellar tendon-tibial shaft angle was inversely related to the knee flexion angle. The more extended knee, therefore, increased the patellar tendon-tibial shaft angle, which would increase the proximal tibial anterior shear force. The increased proximal tibial anterior shear force would increase the ACL loading and ACL strain based on the ACL loading mechanism. (24,44).

Biomechanical Analysis

Video, Marker Placement and Force Plate Analysis

Marker placement is extremely important to identify joint angles and depends heavily on which motions that are being investigated. Two well-known marker sets are the Helen-Hayes and the Cleveland Clinic. The Helen-Hayes marker set uses wands for the markers on the thigh and calf. The Cleveland Clinic marker set uses markers set in triads, which are often identified by motion analysis systems as one single marker. Cutting motion studies, with the exception of Zeller et al.,(57) in 2003 and Ford in 2005,(21) have mainly focused on recording the activity of the lower extremities. Marker sets for studies looking at the sidestep cutting maneuver have placed the highest marker on the ASIS.(5,6,42,47,48,51,54) Foot, ankle, knee and hip marker placement is usually

done using the Helen-Hayes or Cleveland Clinic methods, using only one fifth metatarsal marker on the foot.

Studies have been done to examine the accuracy of skin-base markers.(3,52,53) A criticism of the skin-based markers is that the movement of the skin over the joint alters the position of the joint. Unfortunately, the only other option for evaluating joint movement is to use bone-pin markers and fixing it to the bone.

Both data sets for the cutting task and the stop-jump tasks have been collected using video to see kinematics and kinetics of the motion coupled with force plates to note the ground reaction forces, particularly vertical ground reaction forces. The video is a 2D creation created using reflective markers placed on the subjects. At least six cameras, sampled at 100hz- 240hz were used for both data collection sets in order to capture the medial/lateral and posterior /anterior views which will be needed for comparison purposes. (43,50,57) The force plates used to measure the ground reaction forces were sampled between 200hz to 2000hz. Due to these inherent sampling differences, both data sets were synchronized and normalized to get the appropriate data. (41,44,50,55)

Summary

It has been acknowledged that Q angle, hip width and musculature differences along with ovulation cycles have a factor in creating a non contact ACL injury specifically for females. The intent of this project is not only to narrow down the cause of a non contact ACL injury, but also to assess the need to increase the potential for further research using the cutting maneuver, concerning overall non contact ACL injury prevention. The ACL is in the position to stop tibia rotation and anterior tibia shear,

which occurs during landing adjustment. Again, the time when peak ground reaction occurs is where we will be concentrating the efforts of this study.

All six previously mentioned factors, are key to understanding the mechanisms of a potential injury to the ACL. We hope that by comparing the cutting maneuver to the stop-jump maneuver, it would allow for better overall prevention of non contact ACL tears.

CHAPTER 3

METHODS

Subjects

The Institutional Review Board at the University of North Carolina at Chapel Hill approved the use of human subjects for this study. Recreational athletes ranging in age from 18-35 who participated in competitive or organized sporting activities three or fewer times a week and exercised at least three hours a week were recruited using various methods, email, flyers etc. Subjects who were pregnant or simply had previous lower extremity injuries that required missing practice or games for more than three weeks within the last 6 months or had any current lower extremity injuries were excluded. A consent form was signed by each subject before testing.

Equipment

The equipment used in collecting the necessary data was the following.

- twenty-four reflective markers,
- eight video infrared cameras, recorded data at a rate of 120 frames per second
- two force plates, Bertec 4060A force plates (Bertec, Worthington, OH) were used, sampling at a rate of 1200 samples per second
- software,

- *Peak Motus video analysis system (Peak Performance, Englewood, Colorado),
- * MS3D65 and MSGraphics65 (version 6.5 Chapel Hill, North Carolina),
- * MSDR60 (version 6.0 Chapel Hill, North Carolina)

Experimental Procedure

The subjects were tested individually at scheduled times. The attire for the subjects included spandex shorts, shoes and socks (provided by each subject), and a sports bra for the female subjects. Prior to testing, twenty-four reflective markers were placed on each subject. The markers were placed on the right and left first and fifth metatarsals, right and left heels, right and left medial and lateral malleoli, right and left lateral tibia, right and left lateral and medial femoral condyles, right and left greater trochanters, anterosuperioilliac spines, acromioclavicular joints, the L4-L5 spinous process and one on the front of the right thigh to signify the right leg during data analysis

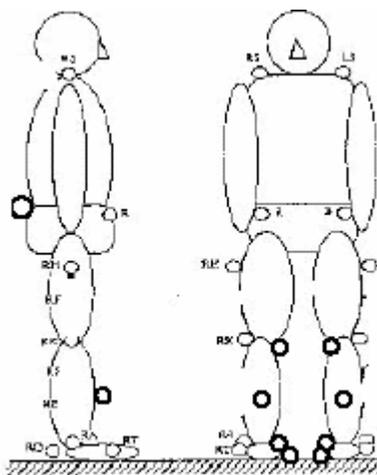


Figure 1: Marker placement for Standing Static Trial Calibration.

The standing trial data was collected first. Subjects were instructed to stand with one foot in each force plate, feet facing forward, shoulder width apart, with their arms crossed. This position was held for approximately two seconds and during this time, standing trial data was collected. Following the collection of data for the standing trial, the reflective markers on the right and left medial femoral condyle and malleoli were removed. The remaining markers were either pre-wrapped or taped down using either athletic tape or duct tape to ensure that they remained in place for the entire data collection process. The study was then explained to each subject. They were told that they would be running toward the white signal board and were instructed to respond to the lights on the signal board as follows: if the left light appeared the subjects were to plant their right foot entirely in the area of the two force plates and, to the best of their ability, turn along the black lines on the floor at a 45 degree angle to the left, or if the right light appeared, the subjects were to plant their left foot entirely in the area of the two force plates and, to the best of their ability, turn along the black lines on the floor, at a 45 degree angle to the right. This was demonstrated to the subjects so they could visualize the movements of the study, left turn or right turn. The subjects were told that with each trial, they would need to jog at a consistent pace, as if they were running about three miles, which would be monitored by the timers. They were told that they would be informed if they were outside their self-selected running speed range and the trial would be repeated. They were shown the location at which they would need to start each trial and were instructed that between each trial there would be at least a minute break. When it was time for the next trial, they would be told to “go when ready.” After the task was completely described, the subjects ran straight forward several times to establish a

comfortable speed which they could maintain throughout the data collection. With their running speed practice, the subjects also practiced the cutting motion in each direction, without responding to the signal lights. Upon malfunction of the lighting system, subjects were simply told which way to cut prior to the onset of movement. Since the lighting system also told the subjects which way to cut prior to running, there was no difference in the way the subjects reacted to either stimulus.

Data Collection

Each subject's performance of each condition was recorded using the eight infrared video cameras. The calibration area for the cameras was 1.4 meters deep by 2.0 meters wide by 2.6 meters high. The cutting maneuver was performed in this area. Synchronized with the eight infrared video cameras were two Bertec 4060A force plates (Bertec, Worthington, OH). The force plates measured ground reaction forces and moment data with a sampling rate of 1200 Hz. A Peak Motus video analysis system (Peak Performance, Englewood, CO) was used to synchronize the infrared cameras and force plate system; with the synchronization occurring when the subject first landed on the force plates. The Peak Motus system also synchronized the ground reaction forces and the video data. Two successful trials, one for each direction were collected per subject. A successful trial for data collection was defined as one during which the subject's planted foot was completely on the two force plates and the subject turned the correct direction with the correct leg planted.

Data Reduction

The Peak Motus video analysis system software was used to digitize the trajectories of the reflective markers. A successful trial for data digitization was defined as a trial where all the points were visible prior to the subject landing on the force plates and remained visible for the entire time the subject was on the force plates. Digitization began in the first frame in which all the points were visible and continued until the subject was completely off the force plates. A low-pass Butterworth digital filter with an optimum cutoff frequency was used on the raw three-dimensional coordinates.(56) Using the MS3D65 program, virtual landmarks were created using the standing trial and the timing trials which defined the center of the hip, knee, and ankle joints. MS3D65 Force Plate Model (version 6.5) software was used to find the ground-reaction forces, free moments and center of pressure location. An inverse dynamic process was used to find the joint resultant forces and moments at the knee joint for each successful digitized trial.(22) These estimates of the joint resultants and moments were made using MS3D65 MotionSoft Kinetic system software version 6.5. Euler parameters were used with the inverse dynamic procedure to estimate the segment angular velocities and accelerations.(13,23) Resultant forces and moment vectors of the knee were converted to the tibia reference frame. The estimated forces and moments of the knee were then further analyzed into kinematic motions for this study: vertical ground reaction force, peak posterior ground reaction force, valgus/varus and internal-external moments. The estimated joint resultant forces of the knee were normalized to the subject's body weight to allow for comparison among subjects. Joint resultant moments were normalized to both the subject's body weight and height. The stance phase was defined as the period from the point the subject's foot landed on the force plate until the foot completely left

the force plates. The stance phase was then divided into 100 time intervals. This division allowed normalization of 1% for each time interval of the stance phase. Data analysis was clearer when every trial is split into the same intervals.

Data Analysis

The data for each of the timing conditions were analyzed using the leg planted on the force plates during a sidestep cutting maneuver, producing joint kinematic, kinetic results. For statistical significance, a 0.05 level of Type I error was chosen. The overall Type I error rate was adjusted with the Bonferroni procedure. A t test design analyses was conducted for each dependent variable: knee external rotation moment, maximum knee flexion angle, peak posterior ground reaction force (GRF), and peak vertical ground reaction force, valgus/varus moments and tibia tilting angle. A t test was also used to compare the left and right preplanned cutting maneuvers to themselves and to the stop-jump maneuver.

CHAPTER 4

RESULTS

The empirical data used for this study were collected from 15 male and 15 female recreational athletes during the cutting task. The results of this study are described in three parts. The first are the results of the lower extremity motion patterns on ACL loading compared between cutting legs. The second are the results of the lower extremity motion patterns on ACL loading compared between the left cutting leg and the jump stop task. Lastly, are the results of the lower extremity motion patterns on ACL loading compared between the right cutting leg and the stop jump task. Each of the three sets of data was analyzed for both females and males separately.

The ranges of the knee flexion angle, vertical ground reaction force, tibia tilting angle, knee valgus/varus moment, and the knee external rotation moment at the peak posterior ground reaction force as well as the peak posterior ground reaction force during the cutting task were determined from the *in vivo* kinematic and kinetic data of the 15 male and 15 female subjects (Tables 1,2,3,4,5,6).

Table #1 Comparison of Knee Flexion Angle at Peak Posterior Ground Reaction Force Among Tasks

Task	Female	Male
Cut with left leg	18.89 ± 6.52	15.86 ± 9.92
Cut with right leg	15.85 ± 6.87	18.05 ± 8.61
Stop-jump (average of both legs) (#)	32.51 ± 8.25	36.70 ± 9.66

Table #2 Comparison of Vertical Ground Reaction Force at the Peak Posterior Ground Reaction Force Among Tasks

Task	Female	Male
Cut with left leg	1.64 ± 0.90	1.76 ± 0.56
Cut with right leg	1.83 ± 0.51	1.32 ± 0.63
Stop-jump	2.67 ± 0.95	2.16 ± 0.6

Table #3 Comparison of Tibial Tilting Angle at the Peak Posterior Ground Reaction Force Among Tasks (- posterior, + anterior)

Task	Female	Male
Cut with left leg	-18.09 ± 24.42	-13.12 ± 32.74
Cut with right leg	-19.92 ± 16.08	-13.03 ± 12.36
Stop-jump	-5.10 ± 6.45	-5.85 ± 5.62

Table #4 Comparison of Knee Valgus Moment at the Peak Posterior Ground Reaction Force Among Tasks

Task	Female	Male
Cut with left leg	0.06 ± 0.08	0.05 ± 0.06
Cut with right leg	0.07 ± 0.08	0.06 ± 0.06
Stop-jump	0.02 ± 0.05	0.01 ± 0.05

Table #5 Comparison of Knee External Rotation Moment at the Peak Posterior Ground Reaction Force Among Tasks

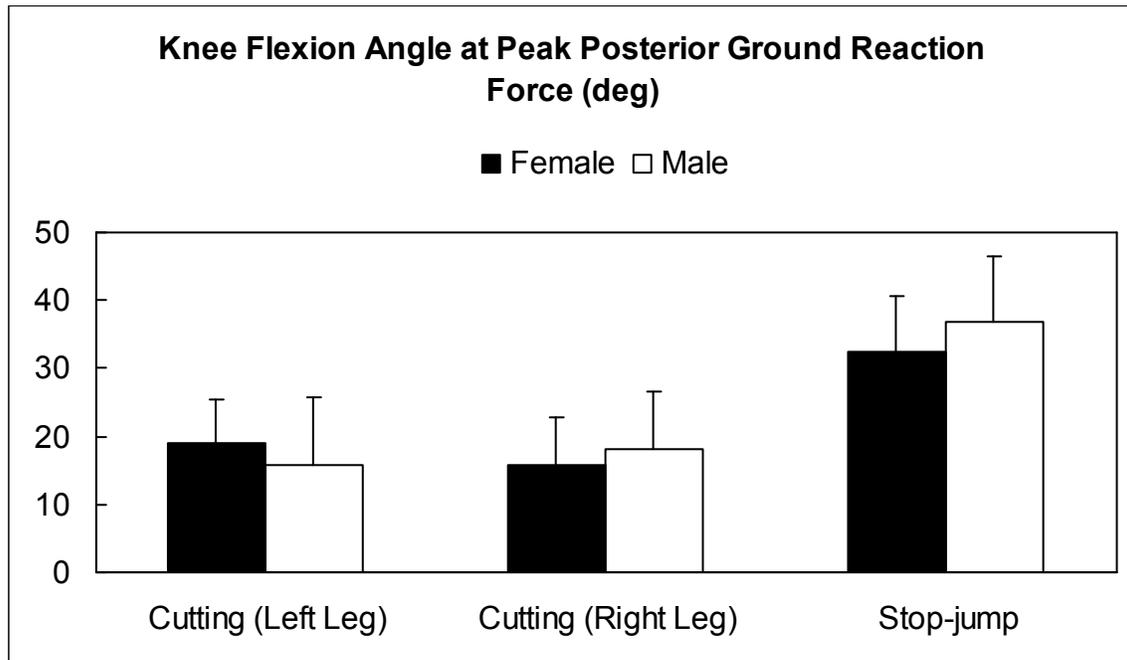
Task	Female	Male
Cut with left leg	0.13 ± 0.11	0.15 ± 0.09
Cut with right leg	0.14 ± 0.16	0.18 ± 0.12
Stop-jump	0.02 ± 0.05	0.01 ± 0.04

Table #6 Comparison of the Peak Posterior Ground Reaction Forces Among Tasks

Task	Female	Male
Cut with left leg	0.60 ± 0.29	0.85 ± 0.17
Cut with right leg	0.67 ± 0.32	0.57 ± 0.32
Stop-jump	1.16 ± 0.55	0.95 ± 0.34

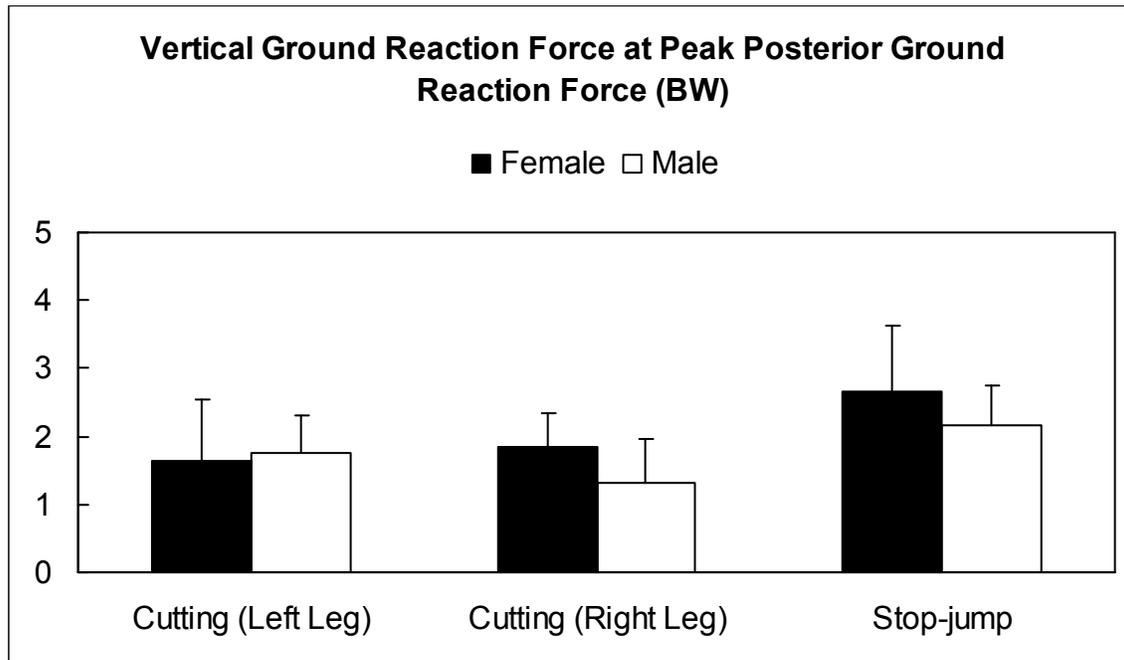
There was no significant difference in the knee flexion angle at the peak posterior ground reaction force between cutting with left and right legs for female and male subjects ($p = 0.08$, $p = 0.20$ respectively). Both female and male subjects had smaller knee flexion angles at peak posterior ground reaction force in the cuttings than in the stop-jump ($p = 0.01$).

Figure 2 Knee Flexion Angle at Peak Posterior Ground Reaction Force



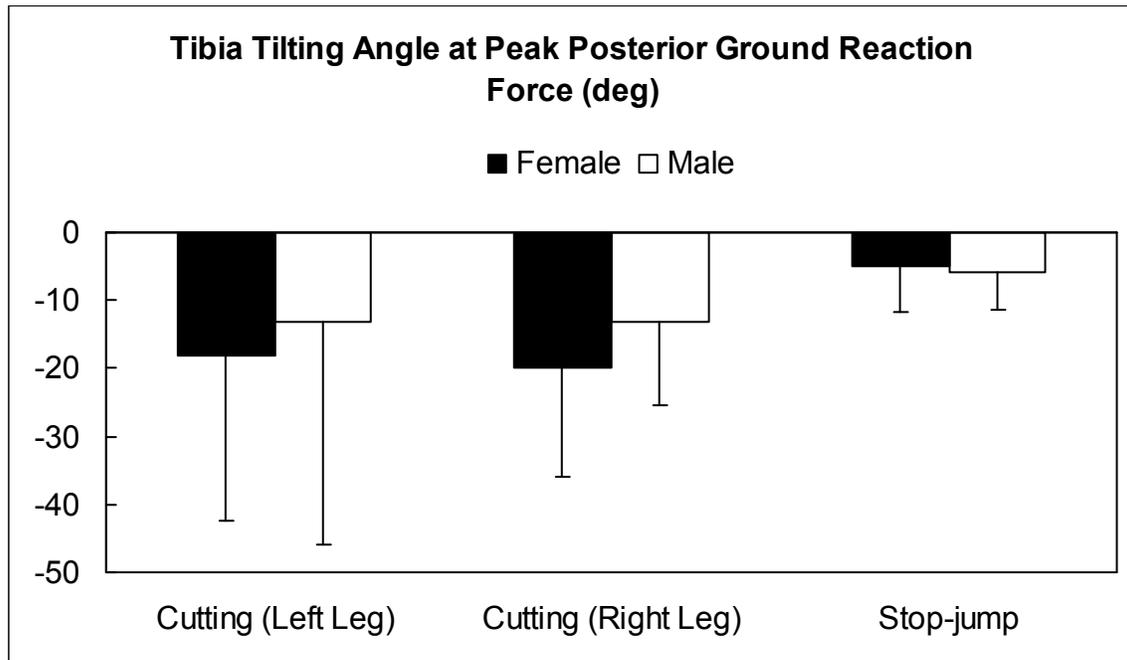
There was no significant difference in the vertical ground reaction force at the peak posterior ground reaction force between cutting with left and right legs for female subjects ($p = 0.5$). However the vertical ground reaction force for males was significantly greater when cutting left than right. ($p = .02$) Both female and male subjects had smaller vertical ground reaction forces at peak posterior ground reaction force in the cuttings than in the stop-jump ($p = 0.001$).

Figure 3 Vertical Ground Reaction Force at the Peak Ground Reaction Force



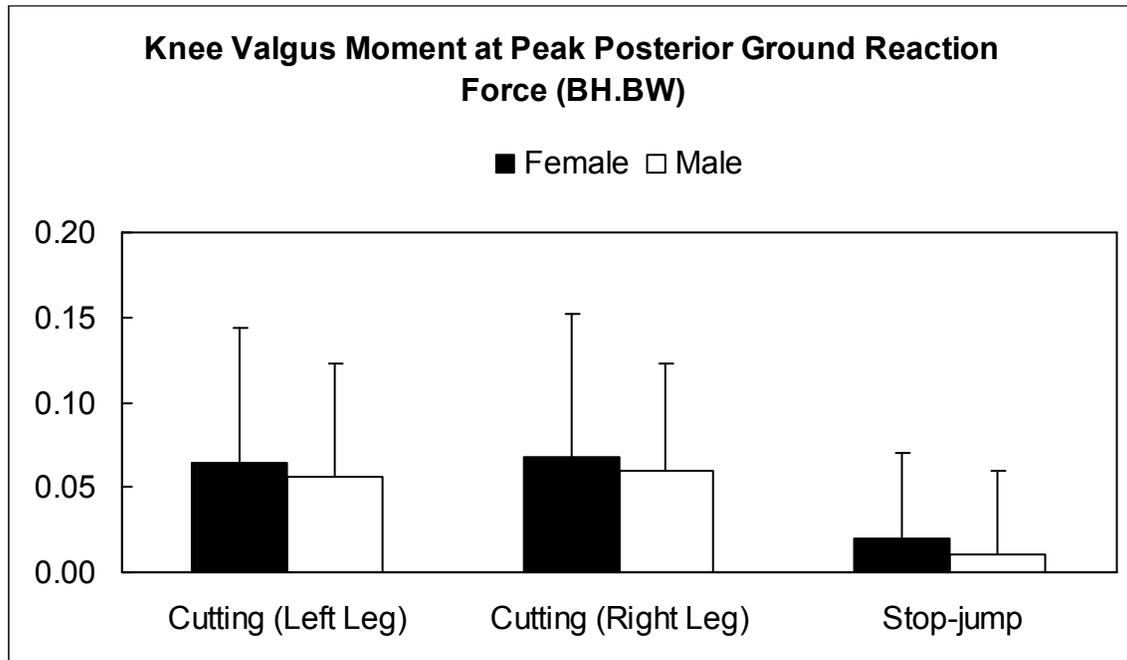
There was no significant difference in the tibia tilting angle at the peak posterior ground reaction force between cutting with left and right legs for female and male subjects ($p = 0.8$ and $p = .9$ respectively). Both female and male subjects had smaller tibia tilting angles at peak posterior ground reaction force when cutting on the right leg than in the stop-jump ($p = 0.001$, $p = .015$). Only the females had significantly smaller tibia tilting angles when cutting with the left leg ($p = .02$).

Figure 4 Tibial Tilting Angle at the Peak Ground Reaction Force



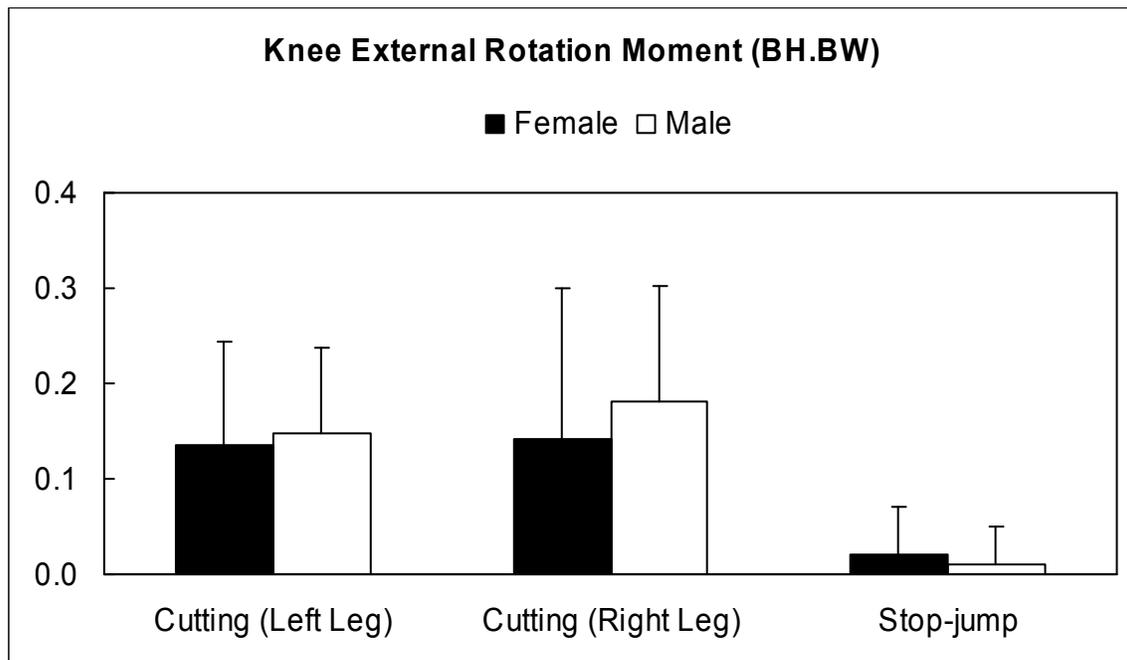
There was no significant difference in the knee valgus moment at the peak posterior ground reaction force between cutting with left and right legs for female and male subjects ($p = .9$). Both female and male subjects had larger knee valgus/varus moment at peak posterior ground reaction force when cutting on the right and left legs than in the stop-jump ($p = 0.015$ females, $p = .005$ left leg cut males, $p = .004$ right leg cut males).

Figure 5 Knee Valgus Moment at the Peak Ground Reaction Force



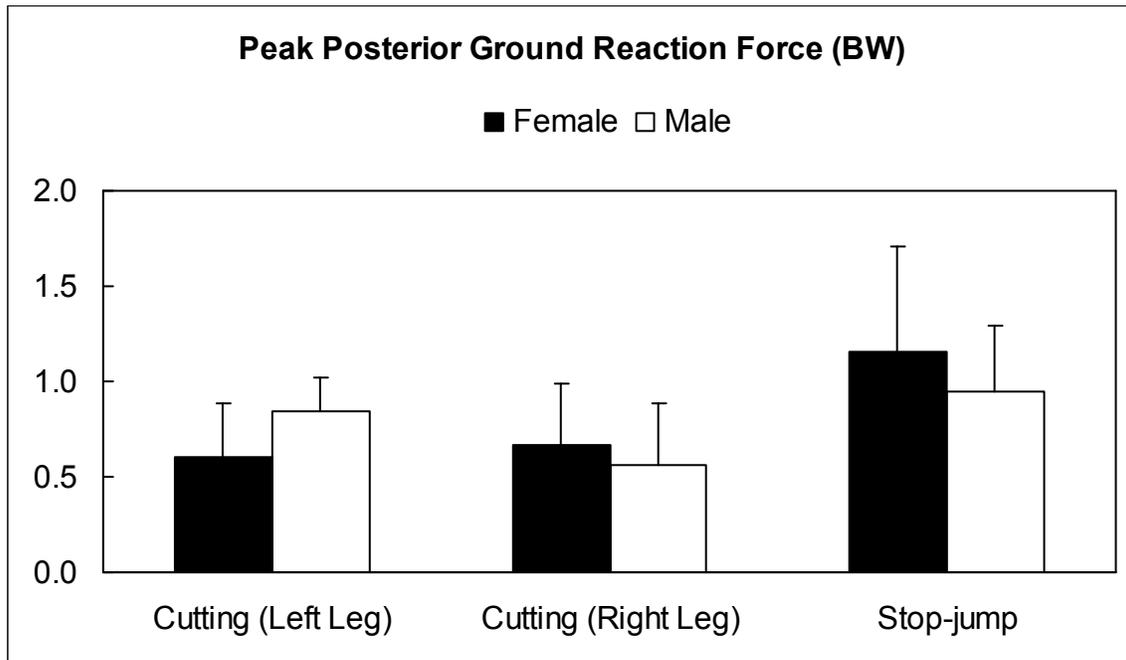
There was no significant difference in the knee external rotation moment at the peak posterior ground reaction force between cutting with left and right legs for female and male subjects ($p = .9$, $p = .2$ respectively). Both female and male subjects had larger knee external rotation moments at peak posterior ground reaction force when cutting on the right and left legs than in the stop-jump ($p = .001$).

Figure 6 Knee External Rotation Moment at the Peak Ground Reaction Force



There was no significant difference in the peak posterior ground reaction force between cutting with left and right legs for female subjects ($p = .3$). However male subjects produced a larger peak posterior ground reaction force when cutting on the left leg than when cutting on the right leg. ($p = .001$) Both female and male subjects had smaller peak posterior ground reaction forces at peak posterior ground reaction force when cutting on the right leg than in the stop-jump ($p = .001$). However only females exhibited significantly smaller differences in the peak posterior ground reaction forces when cutting on the left leg. ($p = .001$)

Figure 7 Peak Ground Reaction Forces



CHAPTER 5

DISCUSSION

The implications of the results noted above are discussed below. Potential ACL tear risk factors for the cutting task compared to the stop-jump task as related to the results will be discussed as well as differences seen between some of the left and right leg cutting techniques.

Effect of the Knee Flexion Angles for Cutting Compared to Stop-Jump

The knee flexion angle affects the ACL loading. Decreasing knee flexion angle results in an increase in ACL loading while the other lower extremity kinematic and kinetic conditions are the same. Given that both males and females exhibited smaller knee flexion angles at the peak ground reaction force, previous studies would support the conclusion that the cutting movement possibly puts more strain on the ACL than stop-jump if based solely on this variable. However, the ACL is more likely at risk when landing at a small knee flexion angle accompanied by a large posterior ground reaction force. Another point is that ACL loading increases as the peak posterior ground reaction force increases. This indicates that a small decrease in knee flexion angle can dramatically increase the ACL loading if lands with large peak posterior ground reaction force than that lands with small peak posterior ground reaction force. Our result showed

that there actually was not a larger peak posterior ground reaction force when cutting. Possible implications of this will be discussed later on in this section.

Effect of the Knee External Rotation Moment for Cutting Compared to the Stop-Jump

Previous literature has noted that during when the knee flexion angle increases, the peak knee external rotation moment also increases to counteract tibia anterior shear forces. Our results showed that there was a significant increase in the amount of knee external rotation moments while cutting for both males and females than during stop-jump. It is also important to note that males, cutting left or right, exhibited more knee external rotation moments than females. Given that internal knee rotation moments are seen as detrimental to the ACL, looking at this variable alone would suggest that cutting protects the ACL more so than stop-jump and the males seemingly protect their ACL while cutting than females.

Effect of the Vertical Ground Reaction Force for Cutting Compared to the Stop-Jump.

Literature has noted that the vertical ground reaction force produces an external knee flexion moment if an individual lands with the tibia titled forward with the knee joint center anteriorly located to the center of pressure. The vertical ground reaction force also produces an external knee rotation moment if the tibia is tilted backward in such a way that the knee joint center is posterior to the center of pressure. The external knee rotation moment produced by the vertical ground reaction force reduces the demand for internal knee rotation moment and quadriceps muscle force. The results of our study show that both male and female subjects exhibited smaller tibia tilting angles, smaller

vertical ground reaction forces and smaller peak posterior ground reaction forces then exhibited during the stop-jump task. These results combined indicate that a large vertical ground reaction force may not necessarily be a risk factor for non contact ACL injuries because the landing styles and tibia tilting angle seemingly affects the role of the vertical ground reaction forces on the ACL loading.

Effect of the Posterior Ground Reaction Force for Cutting Compared to the Stop-Jump

Literature has shown that the moment as which peak posterior ground reaction force occurs is an important factor to ACL loading. Although important, the effect of peak posterior ground reaction force on the ACL loading depends on the knee flexion angle. The rate of ACL loading increases as the peak posterior ground reaction force increases. This rate of increase of the ACL loading also increases as the knee flexion angle decreases. The smaller the knee flexion angle is, the greater the effect of the peak posterior ground reaction force on ACL loading is. A small increase in the peak posterior ground reaction force can cause a large increase in the ACL loading at a small knee flexion angle. This is what we see as the results of this study, a smaller overall peak posterior ground reaction force coupled with even smaller knee flexion angles. This supports the fact that cutting is also a potentially detrimental movement when a non contact ACL injury is concerned. The main factors that control ACL strain, knee flexion and the amount of the peak posterior ground reaction force still apply for cutting as they do for stop-jump, the difference may be that for cutting, both variables decreased by a similar ratio, making the amount of ACL strain still equal to that seen during stop-jump.

Effect of the Knee Valgus Moments for Cutting Compared to Stop-Jump

In general, a cutting maneuver increases the pressure on the medial side of the knee (48). Therefore it would make sense to see a larger knee valgus/varus moments at the peak posterior ground reaction force when cutting as opposed to the stop-jump task, as our results showed. Previous studies have shown that increasing the knee valgus moment puts the ACL at a greater risk of injury (38,39). Also, the closer the knee joint is to full extension, the greater the torque the ACL must restrict possible valgus/varus movement, which could explain the continued possible detriment to the ACL while cutting. Considering its significant increase while cutting when compared to stop-jump, this may suggest that the of knee valgus moment is more so a critical factor in determining the likelihood of a non contact ACL tear when cutting then while stop-jump.

Overall Differences in Resultant Data when Comparing Cutting on the Right and Left Legs

Previous studies have shown no difference between cutting on the left or right leg when looking at cutting maneuvers (21,42). Our study partially concurs with this given that for three out of the six measured variables, knee external rotation moments, knee valgus/varus moments, and knee flexion angles, there was no significant difference between cutting on the left or right legs. When compared to the jump stop task, the cutting task exhibited significantly smaller knee flexion angles as well as smaller peak posterior ground reaction forces, except when males cut on their left leg, as mentioned earlier. Along with that, there were smaller vertical ground reaction forces seen as well as smaller tibia tilting angles, except when males cut with the left leg. Why we continued

to see a discrepancy with males cutting with their left legs, i.e. cutting to the right, is not conclusive. It could possibly be due to left leg dominance although there is nothing in this study or previous literature that could corroborate that.

CHAPTER 6

CONCLUSION

Knee flexion angles and peak posterior ground reaction forces are two important risk factors for the risk of non contact ACL injuries during the jump stop task. What did increase during cutting was the amount of knee valgus moments and knee external rotation moments as compared to the stop-jump task. All of this taken into consideration, it seems as if knee flexion angles and peak posterior ground reaction forces along with the increase of the valgus and knee external rotation moments are more of a factor when determining the extent of the possibility of an ACL injury while cutting. This shifts the focus from looking at the actual residual forces, such as vertical ground reaction forces, in the x and y plane combined with positioning as done for the stop-jump task to focusing more on alignment/positioning and the potential third dimensional force, moments, acting on the knee. Inherently, we would be able to make the case that the mechanisms for cutting and stop-jump, although similar, are in fact different, and must be treated as such for future applications.

REFERENCES

- 1 Allen, C. R.; Livesay, G. A.; Wong, E. K., and Woo, S. L. Injury and reconstruction of the anterior cruciate ligament and knee osteoarthritis. Osteoarthritis Cartilage. 1999 Jan; 7(1):110-21
- 2 Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E: The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. Am J Sports Med 1984; 12(1): 8-18.
- 3 Benoit, D.L., Ramsey, D.K., Lamontagne, M., Xu, L., Wretenberg, P., Renstrom, P. Effect of Skin Movement Artifact on Knee Kinematics During Gait and Cutting Motions Measured In Vivo. Gait Posture. Oct27, 2005.
- 4 Benvenuti, F., Stanhope, S.J., Thomas, S.L., Panzer, V.P., Hallett, M. Flexibility of Anticipatory Postural Adjustments Revealed by Self-Paced and Reaction –Time Arm Movements. Brain Res. 761:59-70, 1997.
- 5 Besier, T.F., Lloyd, D.G., Ackland, T.R. Muscle Activating Strategies at the Knee during Running and Cutting Maneuvers. Med Sci Sports Exerc. 35(1):119-127, 2003.
- 6 Besier, T.F., Lloyd, D.G., Cochrane, J.L., Ackland, T.R. External Loading of the Knee Joint during Running and Cutting Maneuvers. Med Sci Sports Exerc. 33(7):1168-1175, 2001.
- 7 Beynon BD, Fleming BC, Johnson RJ, Nichols CE, Renstrom PA, Pope MH: Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. Am J Sports Med 1995; 23(1): 24-34.
- 8 Biondino, C. R. Anterior cruciate ligament injuries in female athletes. Conn Med. 1999 Nov; 63(11):657-60
- 9 Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr.: Mechanisms of anterior cruciate ligament injury. Orthopedics 2000; 23(6): 573-8.
- 10 Borsa, M9 P. A.; Lephart, S. M.; Irrgang, J. J.; Safran, M. R., and Fu, F. H. The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. Am J Sports Med. 1997 May-1997 Jun 30; 25(3):336-40
- 11 Buff HU, Jones LC, Hungerford DS: Experimental determination of forces transmitted through the patello-femoral joint. J Biomech 1988; 21(1): 17-23.

- 12 Cerulli G, Benoit DL, Lamontagne M, Caraffa A, Liti A: In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. Knee Surg Sports Traumatol Arthrosc 2003; 11(5): 307-11.
- 13 Chao, E.Y. Justification of Triaxial Goniometer for the Measurement of Joint Rotation, J Biomech. 13: 989-1006, 1980.
- 14 Chappell JD, Yu B, Kirkendall DT, Garrett WE: A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. Am J Sports Med 2002; 30(2): 261-7.
- 15 Colby, S. Francisco, A., Yu, B., Kirkendall, D., Finch, M., Garrett, W. Electromyographic and Kinematic Analysis of Cutting Maneuvers. Am J Sports Med. 28(2):234-240, 2000.
- 16 DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W: Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. Am J Sports Med 2004; 32(2): 477-83.
- 17 Draganich LF, Vahey JW: An in vitro study of anterior cruciate ligament strain induced by quadriceps and hamstrings forces. J Orthop Res 1990; 8(1): 57-63.
- 18 Durselen L, Claes L, Kiefer H: The influence of muscle forces and external loads on cruciate ligament strain. Am J Sports Med 1995; 23(1): 129-36.
- 19 Fleming BC, Renstrom PA, Ohlen G, et al.: The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. J Orthop Res 2001; 19(6): 1178-84.
- 20 Ford KR, Myer GD, Hewett TE: Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc 2003; 35(10)
- 21 Ford, K.R., Myer, D.G., Toms, H.E., Hewett; T.E. Gender Differences in the Kinematics of Unanticipated Cutting in Young Athletes. Med Sci Sports Exerc. 37(1):124-129, 2005.
- 22 Greenwood, D.T. Principles of Dynamics. Englewood Cliffs, NJ, Prentice-Hall, 2nd edition: 389-392, 1987. 155
- 23 Haug, E.J. Intermediate Dynamics. Englewood Cliffs, NJ, Prentice-Hall, 1st edition:198-206, 1992.
- 24 Herzog W, Read LJ: Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. J Anat 1993; 182 (Pt 2): 213-30.
- 25 Hewett TE, Myer GD, Ford KR, et al.: Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk

- in female athletes: a prospective study. Am J Sports Med 2005; 33(4): 492-501.
- 26 Hewett TE: Neuromuscular and hormonal factors associated with knee injuries in female athletes. Strategies for intervention. Sports Med 2000; 29(5): 313-27.
 - 27 Huberti HH, Hayes WC, Stone JL, Shybut GT: Force ratios in the quadriceps tendon and ligamentum patellae. J Orthop Res 1984; 2(1): 49-54.
 - 28 Inoue, M., McGurk-Burleson, E., Hollis, J. M., and Woo, S. L. Treatment of the medial collateral ligament injury. I: The importance of anterior cruciate ligament on the varus-valgus knee laxity. Am J Sports Med, 15(1):15-21. (1987)
 - 29 Ireland, M. L. The female ACL: why is it more prone to injury? Orthop Clin North Am. 2002 Oct; 33(4):637-51
 - 30 Kadaba, M.P., 57 Ramakrishnan, H.K., Wootten, M.E. Repeatability of Kinematic, Kinetic and Electromyographic Data in Normal Adult Gait, J Ortho Res. 7: 849-860, 1989.
 - 31 Kernozek TW, Torry MR, H VANH, Cowley H, Tanner S: Gender differences in frontal and sagittal plane biomechanics during drop landings. Med Sci Sports Exerc 2005; 37(6): 1003-12; discussion 1013.
 - 32 Lamontagne M., Benoit D. L., Ramsey D. K., Caraffa A., Cerulli G., What can we learn from in vivo biomechanical investigations of lower extremity? Proceedings of XXIII International Symposium of Biomechanics in Sports, Beijing, China, 2005.
 - 33 Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH: Gender differences in strength and lower extremity kinematics during landing. Clin Orthop Relat Res 2002(401): 162-9.
 - 34 Li G, Defrate LE, Rubash HE, Gill TJ: In vivo kinematics of the ACL during weight-bearing knee flexion. J Orthop Res 2005; 23(2): 340-4.
 - 35 Lin, Connie. A Stochastic Biomechanical Model for Risk and Risk Factors of Sustaining Non-Contact ACL Injuries. University of North Carolina at Chapel Hill. 2006
 - 36 Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL: Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res 1995; 13(6): 930-5.
 - 37 Massitti, S. Desperately Seeking Stability. Impact Magazine Mar/Apr 30-31, 1996. www.fitter1.com/education/stability.html

- 38 Matsumoto, H., Suda, Y., Otani, T., Niki, Y., Seedhom, B.B., Fujikawa, K. Roles of the Anterior Cruciate Ligament and the Medial Collateral Ligament in Preventing Valgus Instability. J Orthop Sci. 6:28-32, 2000.
- 39 McLean SG, Huang X, Su A, Van Den Bogert AJ: Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. Clin Biomech 2004; 19(8): 828-38.
- 40 McLean SG, Su A, van den Bogert AJ: Development and validation of a 3-D model to predict knee joint loading during dynamic movement. J Biomech Eng 2003; 125(6): 864-74.
- 41 McLean, S.G., Lipfert, S.W., VandenBogert, A.J. Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. Med Sci Sports Exerc. 36(6):1008-1016, 2004.
- 42 McLean, S.G., Neal, R.J., Myers, P.T., Walters, M.R. Knee Joint Kinematics during the Sidestep Cutting Maneuver: Potential for Injury in Women. Med Sci Sports Exerc. 31(7):959-968,1999.
- 43 McLean, S.G., Huang, X., van den Bogert, A.J. Association between Lower Extremity Posture at Contact and Peak Knee Valgus Moment during Sidestepping: Implications for ACL injury. Clin Biomech. 20:863-870, 2005.
- 44 Myer, G.D., Ford, K.R., McLean, S.G., Hewett, T.E. The Effects of Plyometric Versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics. Am J Sports Med. 34(3):445-455, 2006.
- 45 Nunley, R. M., Wright, D. W., Renner, J. B., Yu, B., and Garrett, W. E. Gender comparison of patella tendon-tibial shaft angle with weight-bearing. Res Sports Med, 11:173-185. 2003.
- 46 Patla, A.E., Adkin, A., Ballard, T. Online Steering: Coordination and Control of Body Center of Mass, Head and Body Reorientation. Exp Brain Res. 129:629-634, 1999.
- 47 Pollard, C.D., McClayDavis, I., Hamil, J. Influence of Gender on Hip and Knee Mechanics during Randomly Cued Cutting Maneuver. Clin Biomech. 19:1022-1031, 2004.
- 48 Schot, P., Dart, J., Schuh, M. Biomedical Analysis of Two Change-of-direction Maneuvers while Running. J Ortho Sports Phy Ther. 22(6):254-258, 1995.
- 49 Semonian, R. H.; Denlinger, P. M., and Duggan, R. J. Proximal tibiofibular subluxation relationship to lateral knee pain: a review of proximal tibiofibular joint pathologies. J Orthop Sports Phys Ther. 1995 May; 21(5):248-57.

- 50 Sigward, S.M., Powers, C.M. The Influence of Gender on Knee Kinematics, Kinetics and Muscle Activation Patterns during Side-Step Cutting. Clin Biomech. 21:41-48, 2006.
- 51 Stacoff, A., Steger, J., Stussi, E., CREinschmidt, C. Lateral Stability in Sideward Cutting Movements. Med Sci Sports Exerc. 28(3):350-358, 1996.
- 52 Taylor, W.R., Ehrig, R.M., Duda, G.N., Schell, H., Seebeck, P., Heller, M.O. On the Influence of Soft Tissue Coverage in the Determination of Bone Kinematics using Skin Markers. J Orthop Res. 23(4):726-34, Jul. 2005.
- 53 Waite, J.C., Beard, D.J., Dodd, C.A.F., Murray, D.W., Gill H.S. In Vivo Kinematics of the ACL-Deficient Limb during Running and Cutting. Knee Surg Sports Traum Arthrosc. 13:377-384, 2005.
- 54 Wojtys, E.M., Ashton-Miller, J.A., LKHuston L.J. A Gender-Related Difference in the Contribution of the Knee Musculature to Sagittal-Plane Shear Stiffness in Subjects with Similar Knee Laxity. J Bone & Joint. 84A(1):10-16, 2002. 161
- 55 Yu B, Lin CF, Garrett WE: Lower extremity biomechanics during the landing of a stop-jump task. Clin Biomech 2006; 21(3): 297-305.
- 56 Yu, B., Gabriel, D., Nobel, L. Estimate of Optimum Cutoff Frequency for a Low-Pass Digital Filter. J App Biomech. 15: 318-329, 1999.
- 57 Zeller, B.L., McCrory, J.L., Kibler, B., Uhl, T.L. Difference in Kinematics and Electromyographic Activity Between Men and Women during the Single-Legged Squat. Am J Sports Med. 31(3):449-456, 2003.