Comparison of Lower Extremity Biomechanics between Female Division I Gymnastic, Lacrosse, and Soccer Athletes

Christin R. Chamberlain

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Approved by:

Darin Padua; PhD, ATC-L

Bill Prentice; PhD, PT, ATC-L

Alex Creighton; MD

Chris Hirth; MA, PT, ATC-L

Melanie McGrath; MA, ATC-L

ABSTRACT

CHRISTIN CHAMBERLAIN: Comparison of Lower Extremity Biomechanics between
Female Division I Gymnastic, Lacrosse, and Soccer Athletes
(Under the direction of Darin Padua)

Studies have shown that females are more likely to suffer non-contact anterior cruciate ligament injuries than males. The study consisted of eleven gymnastics, fifteen lacrosse, and twelve soccer athletes with no history of major lower extremity or anterior cruciate ligament injury one month prior to testing. Lower extremity kinematics, kinetics, and vertical ground reaction forces were collected from the dominant leg of each subject. Joint angles at initial ground contact for female gymnasts were significantly less than soccer athletes for knee and hip flexion. Gymnasts displayed significantly larger knee extension moments, hip flexion moments, anterior tibial shear forces, and vertical ground reaction forces. Female gymnastics athletes performed jump-landing and cutting maneuvers in such a way that may predispose them to anterior cruciate ligament injury. Our results suggest that further investigation is needed into differences in movement patterns and injury rates between female athletes to determine which athletes are at greater risk for injuring the anterior cruciate ligament.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Anterior cruciate ligament injury rates have been well researched in recent cross

gender studies. When compared to males participating in the same sports, female athletes

were approximately 6 times more likely to experience an ACL injury (Arendt & Dick, 1995;

Gray et al., 1985; Hutchinson & Ireland, 1995; Powell & Barber-Foss, 2000). A recent

epidemiological study of the NCAA examined anterior cruciate ligament injuries in men's

and women's basketball and soccer. The study utilized information gathered by the Injury

Surveillance System (ISS) between the years of 1990 to 2002 (Agel, Arendt, & Bershadsky,

2005). During this time 682 ACL injuries occurred in basketball (514 women and 168 men)

and 586 injuries in soccer (394 women and 192 men). For both sports, females sustained

significantly more ACL injuries than males; more specifically female soccer players had the

highest rate of ACL injuries.

Non-contact mechanisms for serious knee injury in women is three times more

prevalent than in men (Gray et al., 1985; Griffin et al., 2000; Zelisko, Noble, & Porter, 1982).

Studies have approximated that 70% of all ACL injuries in women's basketball and soccer

occur during non-contact cutting and jumping activities (Arendt & Dick, 1995; Griffin et al.,

2000). Agel et al. (2005) also observed that injuries in female athletes occurred

predominantly by a non-contact mechanism, when compared to males. According to the

current literature females participating in sports involving jump-landing and cutting maneuvers (i.e. soccer, basketball, gymnastics, and lacrosse) may be at greatest risk of sustaining an ACL injury.

Recent studies have supported the idea that female soccer athletes are at the highest risk of ACL injury. In a study by Agel et al. (2005), female soccer players sustained a total of 161 non-contact ACL injuries compared to 68 injuries for male soccer players. Also, the study found that female soccer athletes exhibited a significantly higher contact ACL injury rate compared to male soccer players and female basketball players. This recent epidemiological study has reinforced previous findings that women's soccer is the sport with the greatest risk of ACL injury (Agel et al., 2005; Arendt & Dick, 1995; Faude, Junge, Kindermann, & Dvorak, 2005; Hutchinson & Ireland, 1995; Powell & Barber-Foss, 2000).

Unlike soccer and basketball, in gymnastics the ACL injuries rates between male and female gymnasts do not differ (Dixon & Fricker, 1993). The lack of a gender bias in ACL injury rates in female gymnasts may suggest interesting information about how important the mechanism of injury is. Anterior cruciate ligament injuries are commonly associated with a twist at landing or hyperextension in elite gymnasts, which differs from the mechanisms of injury in most non-contact ACL injuries (Dixon & Fricker, 1993). Research has observed that the ankle accounted for 31.2% of total injuries, followed by the lower back (14.9%), and then the knee with 13.5% of injuries. The ankle and foot incurring the most injuries was consistent with previous reports for women's gymnastics (Dixon & Fricker, 1993; Lindner & Caine, 1990). These studies have failed to note any significant ACL injuries in women's gymnastics.

Women's Lacrosse is one of the fastest growing sports in the country. Between 1995 and 2001, approximately 70 new collegiate women's teams have been established. The average rate of injury at the collegiate level per 1000 athletic exposures for men and women was 10.8 and 3.8, respectively (Matz & Nibbelink, 2004). The higher injury rate in men's lacrosse can be attributed to being a full contact sport, where women's lacrosse limits contact between players. In a study involving 19 collegiate female lacrosse teams over two seasons, a total of 104 injuries occurred and of these injuries 47.7% of all injuries occurred to the head and face and 13% at the knee (Matz & Nibbelink, 2004). During the study, only 2 ACL reconstructions were performed during the 2 seasons, but it did not specifically indicate if any other ACL sprains occurred. Once again, studies have failed to note significantly higher ACL injury rates in female lacrosse athletes (Hinton, Lincoln, Almquist, Douoguih, & Sharma, 2005; Matz & Nibbelink, 2004). This lower injury rate in the literature may signify some specific movement strategies or training differences between gymnastics, lacrosse, and soccer, sports that involve jump-landing and side-step cutting maneuvers.

Presently, organizations like the National Collegiate Athletics Association (NCAA) have collected valuable data on injuries and have made a portion of the data available for public use. The data compiled by the NCAA includes information for 16 collegiate sports. Among the variables collected by the Injury Surveillance System (ISS) are both injury type and severity of injury for sports including Women's Gymnastics, Lacrosse, and Soccer. Women's gymnastics Division I-III for the 2002-2003 seasons reported 9 ACL injuries in 22,317 exposures, a rate of 0.404 per 1000 exposures. During the 2003-2004 season a total of 4 ACL injuries in 15,084 exposures were reported for an injury rate of 0.26 per 1000 exposures. The average injury rate of the two seasons was 0.347 per 1000 exposures. While

3

the injury rate for gymnastics is greater than soccer (0.33) as reported by Agel et al., it should

be noted that the average number of exposures in a soccer season 162,000. Thus, women's

gymnastics injury rates are particularly sensitive to seasons with abnormally large numbers

of ACL injuries due to fewer collegiate participants and exposures. During the same two

seasons (2002-2004), women's lacrosse reported 9 ACL injuries in 94,586 exposures and 8

ACL injuries in 84,349 exposures, respectively. The injury rate for 2002-2003 was 0.09 and

0.09 per 1000 exposures for 2003-2004. For these two seasons, women's lacrosse suffered

significantly fewer ACL injuries per 1000 exposures than gymnastics and soccer.

Epidemiological studies has lead to other research into the identification of risk

factors that are responsible for higher ACL injury rates in female athletes (Dufek & Bates,

1991; Hewett, 2000; Kolt & Kirkby, 1999; Lephart, Ferris, & Fu, 2002; McLean, Huang, &

van den Bogert, 2005; McLean, Neal, Myers, & Walters, 1999; Shelbourne, Davis, &

Klootwyk, 1998). Several theories for the increased risk of ACL injury in female athletes

have been proposed, but research has yet to clearly support these theories. Many studies have

examined the contribution of both intrinsic and extrinsic factors. Intrinsic factors consist of

anatomical or hormonal differences that may influence the risk of knee injury. Extrinsic

factors include biomechanical and neurological factors (Griffin et al., 2000; Hewett, 2000;

Hutchinson & Ireland, 1995). Notable differences in intrinsic and extrinsic factors have been

observed when comparing males and females. For example, female athletes have been found

to have an increased Q-angle, which may be associated to an increase valgus alignment at the

knee (Hutchinson & Ireland, 1995). The greater valgus alignment may increase strain on the

ACL, MCL, and medial joint capsule. Also, a study that compared the intercondylar notch

width of men and women with intact anterior cruciate ligaments, unilateral ACL tears, and

bilateral ACL tears (Shelbourne et al., 1998). Researchers found that femoral intercondylar notch width was wider in men than women and that a narrower notch width was observed in participants who sustained an ACL tear when compared to the control group.

These differences may partially explain the increase in ACL injuries of female athletes. But, these factors cannot adequately explain the cause of injury specifically in female basketball and soccer (Agel et al., 2005; Arendt & Dick, 1995). While intrinsic factors may predispose athletes to injury, research has not overlooked the role of dynamic movement strategies. Studies have focused on the functional effect of extrinsic factors through biomechanical analysis of the lower extremity, in particular the knee. These research projects examine the influence of the gender on biomechanics of the lower extremity (Arendt & Dick, 1995; Dufek & Bates, 1991; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Powell & Barber-Foss, 2000; Zelisko et al., 1982). Cross-gender biomechanical analysis research has investigated the biomechanical difference between males and females during cutting and jumping maneuvers to better understand the observed gender differences in ACL injury rates. Previous research focused on biomechanical factors such as leg stiffness, joint kinematics and kinetics, ground reaction forces, and muscle activity. Leg stiffness during side-cutting and jump-landing tasks has been found to be significantly larger in male athletes (Chappell, Yu, Kirkendall, & Garrett, 2002; Granata, Padua, & Wilson, 2002; Granata, Wilson, & Padua, 2002; Lephart, Ferris, Riemann et al., 2002). Also, males were found to have a greater degree of knee flexion at the time of landing. Vertical ground reaction forces were similar between genders once normalized for body mass and it has been theorized that adjustments in stiffness are made at different joints to normalize these forces. By identifying biomechanical differences,

researchers are becoming more educated and aware of the potential gender-specific factors that may put female athletes at greater risk for injury in sports like soccer.

Another important part of biomechanical analysis is to create "game-like" situations to increase the validity of findings to sports participation. Athletes are often required to make spontaneous, unplanned movements to elude opposing players. When sports movements are anticipated by the athlete postural adjustments and reflex responses have been observed (Besier, Lloyd, & Ackland, 2003). These compensatory responses lead to better body position during movement. (Besier, Lloyd, Ackland, & Cochrane, 2001) compared males performing both an anticipated and unanticipated cutting maneuver. The study observed unanticipated knee moments that were twice the magnitude of the anticipated condition. Besier and others believe that analysis of unanticipated cutting maneuvers closely simulates the motion and torque in the lower extremity during sports activities. The findings reinforce the use of unanticipated side-cutting maneuvers during laboratory testing to mimic conditions seen during activity. It is notable that gymnastics is an exception, due to the fact that all movements are anticipated or planned.

Researchers are now charged with the task of determining if differences may also exist in the sports-specific movement strategies and type of training that female athletes undergo during athletic participation in various sports. These movement strategies may be an important factor in ACL injury rates. Hence, it is important for research to not only examine the biomechanical difference between male and female athletes, but the difference in dynamic movements between female athletes participating in a variety of sports. By comparing movement patterns between high risk sports (soccer) and sports with lower

incidents of ACL injuries (gymnastics and lacrosse), research may identify the specific biomechanical risk factors leading to ACL injuries in females.

Statement of the Problem

The purpose of the study is to prospectively study the affect of movement strategies used by female collegiate soccer, gymnasts, and lacrosse athletes on trunk flexion, lower extremity joint kinematics, and ground reaction force data when performing a jump-landing, an unanticipated side-step cutting, and anticipated side-step cutting maneuver.

Null Hypotheses

1. There is no significant difference in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external rotation, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and peak vertical ground reaction forces when performing a jump-landing maneuver between female Division I soccer, gymnasts, and lacrosse athletes.

2. There is no significant difference in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and peak

vertical ground reaction forces, when performing an unanticipated side-step cutting maneuver between female Division I collegiate soccer, gymnasts, and lacrosse athletes.

3. There is no significant difference in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and peak vertical ground reaction forces, when performing an anticipated side-step cutting maneuver between female Division I collegiate soccer, gymnasts, and lacrosse athletes.

Research Hypotheses

1. A significant decrease in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external rotation, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and a decrease in peak vertical ground reaction forces, when performing a jump- landing task in female Division I soccer athletes when compared to collegiate gymnasts and lacrosse athletes.

2. A significant decrease in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external rotation, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and a decrease in peak vertical ground reaction forces, when performing a unanticipated side-step

cutting maneuver in female Division I collegiate soccer athletes when compared to collegiate gymnasts and lacrosse athletes.

3. A significant decrease in trunk flexion, lower extremity joint kinematics (hip flexion, hip abduction/adduction, hip internal/external rotation, knee flexion, knee valgus/varus), leg stiffness, anterior tibial shear, knee valgus moment, and a decrease in peak vertical ground reaction forces, when performing an anticipated side-step cutting maneuver in female Division I collegiate soccer athletes when compared to collegiate gymnasts and lacrosse athletes.

Operational Definitions

1. Athlete Exposure- the unit of risk, one athlete participating in one practice or game where he/she is exposed to the possibility of athletic injury.

2. Injury Rate- a ratio of the number of injuries in a particular category to the number of athlete exposures in that category. The value is expressed as injuries per 1,000 athlete exposures.

3. Vertical displacement (Center of Mass) - the total downward movement of the center of mass from initial ground contact to lowest point.

4. Lower extremity joint kinematics (stiffness)- relationship between the vertical force and the vertical displacement of the center of mass of the subject relative to the

surface from touch down to the lowest position of the subject's center of mass (Arampatzis, Stafilidis, Morey-Klapsing, & Bruggemann, 2004).

5. Side-step cutting maneuver will consist of a jump-and-cut of 35-55° off a 12-inch high platform. The front edge of the platform will be placed 75% the subject's height from the front edge of the force plate. The subject will plant the foot of the dominant leg and use the dominant leg to change the direction to the contralateral side.

6. Cross-over cutting maneuver will consist of a jump-and-cut of 35-55° off a 12-inch high platform. The front edge of the platform will be placed 75% the subject's height from the front edge of the force plate. The subject will plant the foot of the dominant leg and use the dominant leg to change the direction to the ipsilateral side.

7. Jump-landing maneuver will consist of dropping from a 12-inch high platform with a two-footed landing, the foot of the dominant leg on the force-plate and the foot of the non-dominant leg off the force plate with an immediate two-footed takeoff for maximum vertical height off the force plate. The subject will then land with their feet in the same position a second time on the force plate. The front edge of the take-off platform will be placed 50% of the subject's height from the edge of the force plate.

8. Knee valgus position- the angle formed between the tibial and femoral shafts, measured in the frontal plane during a jump-landing and side-cutting task at the time of peak vertical ground reaction force.

9. Initial ground contact- when vertical ground reaction force exceeds 5 N as the subject lands on the force-plate.

10. Landing phase- time period from initial ground contact until the first local minima of the vertical ground reaction force during the jump-landing maneuver.

Assumptions and Limitations

1. Test subjects will provide accurate background information regarding previous lower extremity injuries and level of play.

2. Subjects provide maximal effort performing the side-step cutting and jump-landing task.

Delimitations

1. Subjects are Division I female collegiate athletes (soccer, gymnastics, and lacrosse).

2. All subjects are females between the ages of 18-23 years of age.

3. All subjects are healthy and have no previous history of lower extremity injury, which limited activity in the previous month or have undergone lower extremity surgery within the past year and are currently enrolled in a formal rehabilitation program.

4. Kinematic data will be collected on the dominant leg for each subject.

Significance of the Study

Research over the years has consistently found clinically significant difference between lower extremity joint kinematics in males and females, in the general population as well as athletes. The effect of gender has on center of mass vertical displacement, lower extremity joint stiffness (kinematics), and vertical ground reaction forces has been well documented (Ferris & Farley, 1997; Granata, Padua et al., 2002; Granata, Wilson et al., 2002; Horita, Komi, Nicol, & Kyrolainen, 2002). Studies have focused on gender with regards to athletes of similar skill level and sport type. The gender related differences are believed to be directly associated with risk of lower extremity and ACL injuries. But, research has yet to compare injury rates and lower extremity kinematic differences between different female sports. Further researcher of this nature would remove gender differences in intrinsic factors and focus on biomechanical movements in high risk populations, such as women's soccer.

Biomechanical differences between female athletes in various sports including gymnastics, lacrosse, and soccer have yet to be as thoroughly studied. If a significant difference in trunk and lower extremity kinematics is observed between sport types in female

athletics, research may identify which dynamic movements may increase the risk of ACL injury in specific sports. By testing purely within the female athletic population, this could indicate a sport-specific effect that training may have on female athlete injury rates. For female sports with higher ACL injury rates, like soccer, incorporating training that includes modified landing and cutting techniques could potentially decrease the number of ACL injuries that occur each year.

CHAPTER II

REVIEW OF THE LITERATURE

Research has consistently found that female athletes are more likely to suffer a

serious knee injury, including ACL ruptures, than males participating in the same sports

(Arendt & Dick, 1995; Gray et al., 1985; Messina, Farney, & DeLee, 1999; Powell &

Barber-Foss, 2000). The most common mechanisms of injury has been identified as a

jumping and side-cutting non-contact maneuver, accounting for 70% of ACL injuries (Agel

et al., 2005). In jumping sports as much as 90% of all injuries occur in the lower extremity

(Arendt & Dick, 1995; Dufek & Bates, 1991; Powell & Schootman, 1992). Sports involving

jumping has come to include everything from volleyball, gymnastics, basketball, running,

and even soccer as players jump to head a ball (Dufek & Bates, 1991). These activities all

involve a jump in which the athlete is airborne for a period of time and then returns to the

ground. This body of research indicates athletes who are both female and involved in

jumping sports assume a greater risk. Similar findings have been found in sports involving

side-cutting maneuvers, a prime example being women's soccer. In a 13-year review of ACL

injury data from the NCAA found female soccer athletes had an injury rate of 0.33 per 1000

exposures and males a rate of 0.11 per 1000 exposures, the difference was found to be

statistically significant (Agel et al., 2005).

Injury rate variation between genders is seen in both the ankle and knee (Gomez, DeLee, & Farney, 1996; Messina et al., 1999; Powell & Barber-Foss, 2000). But, some studies indicate that the most significant difference in injuries occur at the knee joint (Arendt & Dick, 1995; Messina et al., 1999; Powell & Barber-Foss, 2000; Rozzi, Lephart, Gear, & Fu, 1999). A study of female high school-aged lacrosse athletes found that compared to their male counterparts, females sustained a 6% greater frequency of knee injuries (Hinton et al., 2005). Powell & Barber-Foss (2000) observed that in high school girl's basketball and soccer athletes were 2-3% more likely to suffer a major knee injury than males.

Epidemiology of Female Athletics

This increased risk of injury for female athletes is not isolated to the high school setting. Arendt and Dick (1995) revealed a significantly higher incidence of ACL injuries in collegiate female basketball and soccer players. This study demonstrated that female collegiate soccer athletes suffer twice as many knee injuries as their male counterparts. Non-contact mechanism for serious knee injury in women was three times more prevalent than in men (Gray et al., 1985; Griffin et al., 2000; Zelisko et al., 1982). A 13-year retrospective study that examined ACL injuries in collegiate men's and women's basketball and soccer once again found a significant difference in non-contact ACL injury between genders (Agel et al., 2005). Female soccer players included in the study sustained a total of 161 non-contact ACL injuries compared to 68 injuries for male soccer players.

A study involving the 12 teams of the German National League surveyed injury rate of female soccer players during the 2003-2004 season, which included 165 athletes (Faude et al., 2005). During the season, the female athletes sustained eleven ACL ruptures and 7 were attributed to a sudden change in direction. The ACL incidence rate of 2.2 ACL ruptures per 1000 match hours was observed and approximately 6% of all players sustained an ACL rupture. The incidence of an ACL rupture was seven times greater that previously reported with 0.31 vs. 2.2 per 1000 match hours (Hutchinson & Ireland, 1995). Also, the study reported that 58% of all severe injuries in which athletes missed more than 30 days occurred at the knee.

Women's Lacrosse is a one of the fastest growing sport in the country. Between 1995 and 2001, approximately 70 new collegiate women's teams have been established. As the sport has grown, researchers have found specific injury trends at both the collegiate and high school levels. The average rate of injury at the collegiate level per 1000 athletic exposures for men and women was 10.8 and 3.8, respectively (Matz & Nibbelink, 2004). The higher injury rate in men's lacrosse can in part be attributed to being a full contact sport, where women's lacrosse limits contact between players. Over 2 seasons, a total of 104 injuries occurred at 5 Division I and 14 Division III colleges (Matz & Nibbelink, 2004). Of these injuries, 47.7% of all injuries occurred to the head and face and 13% at the knee. The study reports that only 2 ACL reconstructions were performed during the 2 seasons, but it does not specifically indicate if any other ACL sprains occurred.

A 3-year prospective study examined lacrosse injuries in high school-aged (14 to 18 years of age) girls and boys participating in both interscholastic and summer camps in Virginia and Maryland (Hinton et al., 2005). The injury rate at the high school-aged level per

1000 athletic exposures for boys and girls was 2.89 and 2.54, respectively. The most common injury site for males and females was the ankle accounting for 16.1-18.1% in males and 10.4-25.4% in females. The knee was the second most frequently injured body part followed by the head and face. Females participating in the study received at total of 477 injuries, 110 of which occurred at the knee. The study identified 27 injuries as knee sprains with approximately 62% occurring as a result of indirect force, but it did not indicate the number of ACL injuries. The researchers noted that the primary injury scenarios for adolescent boys and girls involve the ankle and knee ligament sprains, reflecting the high speed and quick direction change inherent in the game. The study found that female players were significantly more likely to be injured, while defending a shot or catching a pass than males. During the same time period as the study, the injury rates in high school-level lacrosse were approximately one third of those seen at the collegiate level reported by the NCAA ISS. Studies have failed to note significantly higher ACL injury rates in female lacrosse athletes (Hinton et al., 2005; Matz & Nibbelink, 2004). This lower injury rate in the literature may signify some specific training differences between lacrosse and soccer, both of which are field sports that involve running and cutting maneuvers.

Unlike women's soccer, gymnastics has not display significantly different ACL injuries rates when compared to males competing in the sport (Dixon & Fricker, 1993). The lack of significantly higher ACL injury rates in women's gymnastics provides interesting information about the how important the mechanism of injury plays. In gymnastics, during a single-leg takeoff for an aerial somersault has shown peak ground reaction forces of 3.3 times body weight (Kinolik, Garhammer, & Gregor, 1980). During other maneuvers, even higher ground reaction forces can occur and translate into tremendous forces which gymnasts

must safely disperse throughout the lower extremity in a short period of time. Another unique

characteristic of gymnastics is that ACL injuries are commonly associated with a twist at

landing or hyperextension in elite gymnasts (Dixon & Fricker, 1993). Although gymnasts

sustain high impact loads, it is not the knee but the foot and ankle where most injuries are

seen. In a study that followed 64 female gymnasts during an 18 month period observed that

the most common site of injury was the foot and ankle (Kolt & Kirkby, 1999). The ankle

accounted for 31.2% of total injuries, followed by the lower back (14.9%), and then the knee

with 13.5% of injuries. The ankle and foot incurring the most injuries was consistent with

previous reports (Dixon & Fricker, 1993; Lindner & Caine, 1990). Gymnastics, unlike soccer

and lacrosse, involves mostly anticipated movement patterns. The body's response to

anticipated versus unanticipated movements may explain why fewer injuries are seen in

gymnastics.

Injury Risk Factors

Risk factors for ACL injury have been placed into four categories; anatomical,

hormonal, environmental, and biomechanical factors (Griffin et al., 2000; Hutchinson &

Ireland, 1995; Powell & Schootman, 1992). Anatomical factors include individual physical

characteristics like gender, height, weight, age, Q-angle, and medical history. In females,

hormonal factors may be an important aspect of ACL injuries due to the effect of hormone

levels on the ligamentous tissue. In addition, research has examined the clinically

significance of biomechanical movements as potential risk factors. All of these factors during

dynamic tasks, such as jump-landing and side-cutting may influence the forces applied to the

lower extremity and can potentially increase the risk of injury.

Anatomical Variations

Gender specific anatomical variations of the lower extremity (i.e. Q-angle) may indicate the increase in injury rates of female athletes. The Q-angle is the angle between the line connecting the anterior superior iliac spine and the midpoint of the patella, and the line connecting the tibial tubercle with the same reference point to the patella (Hutchinson & Ireland, 1995). The increased Q-angle in female athletes may increase valgus alignment at the knee and places increase strain on the ACL, MCL, and medial joint capsule(Hutchinson & Ireland, 1995). Hutchinson and Ireland also concluded that because women tend to have an increase in quadriceps angle, this can often lead to patellar tracking abnormalities. The increased quadriceps angle is due to a wider set pelvis and shorter femoral length in females (Woodland & Francis, 1992). Clinically abnormal quadriceps femoris angles are greater than 15° for men and 20° for women (Hutchinson & Ireland, 1995). Differences in lower extremity alignment had a strong correlation to increases in injury rates in recreational basketball players (Shambaugh, Klein, & Herbert, 1991). The study found that the average Q-angles of athletes sustaining knee injuries were significantly larger than the angles of players who were not injured.

Other anatomical factors that may influence an individual's risk of serious lower extremity injury are an increased joint laxity, and a decreased femoral notch width (Griffin et al., 2000; Hutchinson & Ireland, 1995; Rozzi et al., 1999). (Rozzi et al., 1999) found that healthy women possessed significantly greater knee joint laxity when compared to males. Healthy female athletes appear to adopt compensatory mechanisms to achieve functional joint stabilization. Women had a significantly higher anterior tibial translation when a 30 lbs.

anterior displacement force was placed on the knee. This joint laxity appears to be a factor in diminished joint proprioception. During six randomized trials degrees of angular motion and EMG where measured between men and women, the women took significantly longer to sense joint motion during knee extension. Significant gender differences in tibial lengths have also been observed, females having a decrease in the length of bone (Granata, Wilson et al., 2002). The difference in tibial length can lead to possible gender differences in muscle-length tension relationships and force production in the lower leg.

A narrow femoral intercondylar notch may be a factor in ACL injuries. Shelbourne et al. (1998) compared the intercondylar width of men and women with intact anterior cruciate ligaments, unilateral ACL tears, and bilateral ACL tears. The study found that femoral intercondylar notch width was wider in men than women. Also, notch width in both men and women was narrower in participants who sustained an ACL tear when compare to the control group.

Hormonal Differences

Previously, the structural and biomechanical differences between genders have been explored as a factor in knee injury. Hormonal differences may also play a role in injury rates. Throughout the menstrual cycle the hormones estrogen, progesterone, and relaxin levels fluctuate. These hormones are theorized to increase ligamentous laxity and decrease neuromuscular control in females (Griffin et al., 2000; Hewett, 2000). One study concluded that anterior cruciate ligament cells contained receptor sites for estrogen and progesterone. This finding suggests that female hormones can potentially have a direct influence on the laxity of the ACL (Liu et al., 1996).

Research has yet to develop conclusive evidence that a relationship exists between the menstrual cycle and serious knee injury. One study examined the phase in the menstrual cycle when injuries to the ACL were most likely to occur (Wojtys, Huston, Lindenfeld, Hewett, & Greenfield, 1998). The study concluded females were more likely to experience an ACL injury during the ovulatory phase of the menstrual cycle. Arendt et al. (1999) established that the ovulatory phase was the least likely phase for an injury to occur, contradicting the earlier study. Further research is needed to determine a relationship between hormone levels at the time of injury before any preventative measure concerning hormone levels can be considered.

Environmental Factors

Sports surfaces can influence an athlete in several ways. The effects a sports surface has on the body depend on the stiffness of a given surface. Research has found changes in lower extremity stiffness, muscle activity, and vertical ground reaction forces with various surface stiffness (Arampatzis et al., 2004; Farley, Houdijk, Van Strien, & Louie, 1998; Nigg, 1985). As a surface stiffness decreases the body will respond by increasing leg stiffness during a hopping activity (Farley et al., 1998). The same reaction has been observed during a drop jump. Arampatzis et al. (2004) found that there was an increase in leg stiffness when jumping on a "softer" surface due to the mechanical energy that can be stored within the surface. Also, this stored energy was attributed to an increase in average jump height.

In jumping activities understanding what occurs during the jump-landing sequence is the key to discovering the mechanisms of injury. The body's response to a landing task under various conditions can be examined by measurement of vertical ground reaction force, lower

extremity stiffness, and muscle activity. When these measures are combined with both the intrinsic and extrinsic factors involved in athletic injury, a multivariate analysis may allow researchers to clearly define methods that reduce injury rates.

Epidemiological studies have examined observed injury rates on sports surfaces like natural grass and Astroturf, the two most commonly used in football (Meyers & Barnhill, 2004; Powell & Schootman, 1992). Powell and Schootman (1992) observed significantly more ACL injuries on Astroturf. Meyers and Barnhill had similar findings in their study, concluding more severe injuries occur on an artificial playing surface, as compared to natural grass. These studies have allowed inferences about surface effect on injury rates to be made. However the research lacks biomechanical and EMG analysis on sports surfaces directly, allowing for a more accurate sports specific situation. The biomechanical aspects of a playing surface to date have used an apparatus called 'Artificial Athlete Stuttgart' to perform vertical load assessment of elastic surfaces (Nigg & Yeadon, 1987). The artificial Athlete Stuttgart was a mechanical device created to impersonate the lower extremity of a human subject. It is nearly impossible to generate an accurate human model that will mimic the body's lower extremity response to different surfaces because of the multiple factors that affect lower extremity stiffness. A retrospective study of injury rates in the Australian Football League found during a 12 year period that it was safer to play on rye grass and higher ACL injuries rates were associated with games played on Bermuda grass (Orchard, Chivers, Aldous, Bennell, & Seward, 2005). Researchers attributed the decrease in injury rates on rye grass to reduced "trapping" of the cleats in the ground, thus better release on the foot with changes in direction.

Biomechanical Differences

Biomechanical differences between males and females include landing kinematics and kinetics, landing vertical ground reaction forces, and mechanical power. Gender differences in movement patterns are yet another possible cause for increased rate of ACL injuries in female athletes. Yet, the significant increases in ACL injuries in the literature are confined primarily to women's basketball and soccer (Agel et al., 2005; Arendt & Dick, 1995; Gray et al., 1985). Both sports utilize side-step cutting maneuvers and jump-landings, which have already been established as non-contact mechanisms of injury. Many other female sports also employ these movements including gymnastics, lacrosse, and volleyball, but current literature has failed to note any significant increases in ACL injury in these sports. Also, research has neglected to compare sports like women's basketball and soccer to other female sports and to determine if significant injury rates exist between female sports. If a significant difference is observed, it is important to determine what factors within women's basketball and soccer predispose them to greater risk of injury.

Neuromuscular control and Muscular Strength

Neuromuscular control differences between genders include proprioception, muscular strength, muscular reaction time, and muscular recruitment (Hewett, 2000; Huston & Wojtys, 1996; Rozzi et al., 1999). When normalizing strength for body weight, both female athletes and non-athletic subjects demonstrated significantly less quadriceps and hamstring strength than male subjects (Huston & Wojtys, 1996).

When examining the neuromuscular differences of the lower extremity between genders, women are often identified as being quadriceps dominant (Huston & Wojtys, 1996).

Quadriceps dominance is defined as the quadriceps being the first muscle to activate in response to stress placed on the knee during and selective athletic maneuvers. This condition can result in excessive stress being placed on the anterior cruciate ligament because of its function in opposing anterior tibial translation due to a quadriceps contraction. (Rozzi et al., 1999) found female soccer and basketball athletes to have reduced proprioception and in theory may allow excessive joint motion before dynamic stabilizers, including both the quadriceps and hamstrings, can effectively protect the joint. Maturation of females has little to no affect on quadriceps peak torque, when compared to males (Hewett, Myer, & Ford, 2004). Males at every stage of development from prepubertal to postpubertal stage have a significantly greater quadriceps peak torque after normalizing for body weight. Therefore, no effect of age is seen on the forces placed on the ACL at different stages of development.

Gender differences have been discussed in muscle activation timing and peak torque generation of quadriceps, hamstrings, and gastrocnemius muscles (Hewett, 2000). This study concluded that females exhibit a slower peak torque generation of hamstrings and an earlier peak torque generation of quadriceps. Also, a significant increase in time to peak torque in the hamstrings of female subjects was found during an evaluation of knee function (Huston & Wojtys, 1996). These studies indicate that females tend to recruit the quadriceps and gastrocnemius muscle groups before the hamstring muscle group in reaction to anterior tibial translation. This reaction may actually increase the anterior translation force and potentially increase the risk of knee injury.

Other studies involving EMG data collection during jumping tasks found no significant changes in pre-activation time with changes in leg stiffness (Arampatzis, Bruggemann, & Klapsing, 2001; Arampatzis, Schade, Walsh, & Bruggemann, 2001; Horita

24

et al., 2002). But, examination of the entire preactivation phase has revealed differences indicating a potential level of activation may cause changes in leg stiffness (Arampatzis, Schade et al., 2001). In a study involving a distraction force applied to the knee, active muscle co-contraction was observed to reduce the resulting anterior tibia translation by 473% in men and only 217% in women (Wojtys, 1998). These findings indicated that males had larger muscular stabilization at the knee joint than women. When nine males were subjected to a series of drop jumps, it revealed a significant increase in EMG activity of the lateral gastrocnemius and vastus lateralis 50ms before landing (Horita et al., 2002). This activity was associated to observed knee joint flexion; while the ankle joint angle remained unchanged. In a similar study of 10 female gymnasts performing drop jumps at heights of 20 cm, differences in EMG preactivation were also seen (Arampatzis, Bruggemann et al., 2001). Significant increases in muscle activity were observed again in the vastus lateralis, lateral gastrocnemius, as well as the medial gastrocnemius.

Studies investigating muscular force and stabilization at the knee joint have revealed significant differences between men and women. Women have larger anterior tibial shear force placing the ACL under greater stress. This increased stress can in part be attributed to the quadriceps dominance seen in many female athletes and the lag time before the hamstrings fire in opposition of the quadriceps force. During the preactivation phase, females have been observed to have different muscle preactivation patterns which may affect their performance on select athletic tasks. These differences in females may be disadvantageous to the knee and lead to increased risk of injury.

Joint Kinematics and Kinetics

Research up to this point has focused on conducting comparisons during functional testing between genders with individuals being match by sport, level of activity, and age (Chappell et al., 2002; Dufek & Bates, 1991; Fagenbaum & Darling, 2003; Ford, Myer, & Hewett, 2003; Rozzi et al., 1999). Studies have observed that females present with decreased knee, hip, and trunk flexion during jump-landing and cutting tasks at landing. Female recreational athletes performing cutting and running tasks exhibited less knee flexion and more knee valgus movement than males (Lephart, Abt, & Ferris, 2002; Malinzak et al., 2001). Also, valgus knee motion and maximum valgus knee angle has been found to be significantly greater in female athletes (Ford et al., 2003). These studies clearly identify gender specific movements in female athletes that may be directly related to ACL injury rates in female athletes.

Currently, studies have begun to investigate the role of trunk flexion along with the lower extremity kinematics (Houck, Duncan, & Haven, 2005). Initial data has revealed that females tend to land with significantly less trunk flexion than men during side-step cutting maneuvers (DiStefano et al., unpublished 2004). It has been hypothesized that changes in trunk position may cause translation of the center of mass over the knee joint placing an increased load on the ACL (MacKinnon & Winter, 1993). These differences in women suggest possible changes in joint forces during select athletic tasks. Further investigation is needed with regards to trunk flexion angles to determine the influence on the displacement of center of mass, lower extremity joint kinematics and kinetics.

Throughout the kinetic chain, hip flexion and abduction have been examined during a side-step cutting maneuver (McLean, Lipfert, & van den Bogert, 2004). Female subjects

exhibited less hip flexion and abduction than males at peak stance phase. For other athletic

tasks, women have been found to exhibit greater hip flexion at initial contact for a

sidestepping task (McLean et al., 2005). Also, women did not present with significant

differences in hip flexion during a study examining kinematic differences during landing

(Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003). It has been observed that joint

angle patterns may vary according to the athletic task. During a unanticipated cutting

maneuver, no difference in hip flexion were observed between men and women at peak joint

angles and during the stance phase (Pollard, Davis, & Hamill, 2004).

Lower extremity movement patterns in females include decreased joint angulations at

landing during jumping and running maneuvers compared to males (Arendt & Dick, 1995;

Lephart, Abt et al., 2002; Malinzak et al., 2001; Zelisko et al., 1982). In the musculoskeletal

system, leg geometry can influence joint stiffness because of its' affects on the muscle-

tendon length and the level of activation required to apply a given force to the ground

(Weiss, Hunter, & Kearney, 1988). Lephart et al. (2002) studied collegiate female athletes

and recreational male athletes performing a single-leg landing and forward hopping tasks.

During the single-leg landing females had significantly greater hip internal rotation, less

lower-leg internal rotation, less lower-leg internal rotation maximal angular displacement,

less knee flexion, and less time to maximal angular displacement of knee flexion. The

forward hopping task created the same motions and displacement as the single-leg landing,

except there was an increase in time to maximal angular displacement for hip internal

rotation compared to males. Female recreational athletes performing cutting and running

tasks exhibited less knee flexion and more knee valgus movement than males (Malinzak et

al., 2001). These studies clearly identify gender specific movements in female athletes that may be directly related to injury rates.

During maturation of male and female athletes similarities have been seen in medial knee motion (valgus) in prepuberty (Hewett et al., 2004). When the female subjects were compared with their male counter parts, postpubertal females displayed a significantly greater knee valgus motion at both initial contact and at maximum knee flexion angle during landing from a drop jump. This study identifies that at approximately age 11, females will begin to show a divergence in neuromuscular performance. This developmental difference may lead to increases in lower extremity injury at this age.

During selected athletic tasks, females have presented with decreased knee flexion and increased knee valgus than their male counterparts (Ford et al., 2003; Ford, Myer, Toms, & Hewett, 2005; Lephart, Ferris, Riemann et al., 2002; B. Yu et al., 2005) . A study involving female jumping athletes, observed the effects of jump-training on landing mechanics and lower extremity strength (Hewett, Stroupe, Nance, & Noyes, 1996). During the jump-training program, most significant predictor of peak VGRF was found to be knee valgus/varus moments. The results signify that knee valgus/varus motion may have a greater influence on lower extremity kinetics than previously thought. Ford et al. (2003) also concluded that a significant increase in valgus knee motion can be found on the dominant leg in females only. The imbalance between the dominant and non-dominant leg may be a predisposing factor in noncontact ACL injuries. (Malinzak et al., 2001) compared male and female athletes performing selected athletic maneuvers and found women performed the activities with greater knee valgus. During a stop-jump task, women were again found to have significantly greater valgus knee movements (Chappell et al., 2002). Yu et al. (2005)

observed during a stop-jump task that female recreational soccer players presented with significantly less knee flexion at initial contact and during landing than males of the same age. For a side-cutting and cross-cutting task, women again presented with a significant decrease in knee flexion and increased valgus angles (Malinzak et al., 2001). Ford et al. (2003) and (2005) found observed that for both a jump-landing and an unanticipated cutting task young female athletes exhibited significantly greater maximum knee valgus angle than males. These altered knee motion patterns may increase the load placed on the ACL during athletic tasks, possible contributing to the increase in non-contact ACL injury rates among women.

Several studies have found that females display greater knee extension moments in comparison to males, as well as quadriceps activity (Chappell et al., 2002; Decker et al., 2003; Huston & Wojtys, 1996; Lephart, Ferris, Riemann et al., 2002; Malinzak et al., 2001). Chappell et al. (2002) examined the kinetic data between males and females during a stop-jump task and found that females displayed greater knee extension moments, anterior tibial shear, and knee valgus moment. During a study, researchers examined the kinetics of healthy, recreational athletes during an unanticipated cutting task (Houck et al., 2005). They observed that healthy individuals displayed a significantly smaller knee abduction moment during the loading phase of a side-step cut, indicating greater valgus moment. Other kinetic data of interest has been anterior tibial shear force and the differences found males and females during landing tasks (Chappell et al., 2002; Decker et al., 2003). Female recreational athletes consistently exhibited greater anterior tibial shear forces than males during the landing phase of a forward jump, a vertical jump, and a backward jump(Chappell et al., 2002; Decker et al., 2003). During the study a significant effect of task was also found

between the 3 jumping tasks. Results from previous studies have not only indicated the effect of task on lower extremity moments, but the potential effect of gender as well. Results have indicated that females may have altered movement strategies that result in disadvantageous position of the knee and greater ACL loads.

Overall, females have displayed significant difference in joint kinematics and kinetics than their male counterparts. It has been found that women in general present with decreased trunk, hip, and knee flexion during select athletic tasks. The smaller joint angles have been proposed to create greater stress on the knee joint, as well as the ACL. Other additional ACL stress in females has been observed due to increased knee valgus. Researchers believe that these different joint angles attribute in large part to the increased risk of knee injury in females.

Joint Stiffness

True joint stiffness of the human body is the sum of all the individual stiffness values supplied by muscles, tendons, ligaments, cartilage, and bones (Butler, Crowell, & Davis, 2003). Of these components of joint stiffness, muscle stiffness has been heavily researched in various activities, as well as differences between genders (Dufek, Bates, Davis, & Malone, 1991; Farley et al., 1998; Granata, Padua et al., 2002; Granata, Wilson et al., 2002; Horita et al., 2002; Lephart, Ferris, Riemann et al., 2002). During athletic activities the forces on the joint go further than the stabilizing ability of the joint capsule and ligaments, compelling the muscles to assist in stabilize the joint. This intense study of muscle stiffness can also be attributed to the ease at which muscular morphology and neuromuscular behavior can be modified with training, unlike the ligaments and bones which remain relatively unchanged

with training. The importance of active muscle stiffness was found in not only joint stiffness, but as part of the biomechanical stability of a joint (Granata, Padua et al., 2002).

Leg stiffness can change under various conditions. During jumping landing activity, 15 male decathletes were instructed to jump "a little faster that your previous jump". They exhibited a significant increase in leg stiffness with short periods of ground contact (Arampatzis, Schade et al., 2001). It was concluded that leg stiffness directly influenced the vertical take off velocity and mechanical power during the push-off phase of drop jumps. A similar study involving 10 female gymnasts also found an increase in leg stiffness with short ground contact time when performing jump landing on a spring loaded surface (Arampatzis, Bruggemann et al., 2001).

Gender and joint load can significantly influence effective stiffness for both the quadriceps and hamstrings. During isometric knee flexion and extension tests, females exhibited 56-73% of the effective stiffness of male subjects (Granata, Wilson et al., 2002). Leg stiffness in females during a hopping task was 77% of their male counterparts at three different hopping frequencies (Granata, Padua et al., 2002). Research has found that males have larger amounts of muscular stiffness to aid in joint stabilization. Therefore, females must focus on muscular strengthening and control in order to see increase muscular stiffness and stabilization at the knee joint.

Mechanisms of ACL Injury

Research has identified two predominant mechanisms of ACL injury, non-contact cutting and jumping. Studies have approximated that 70% of all ACL injuries in women's basketball and soccer occur by these two mechanisms (Arendt & Dick, 1995; Griffin et al., 2000). Agel et al. (2005), also observed that injuries in female athletes occurred predominantly by a non-contact mechanism when compared to males.

The non-contact cutting maneuver is an important offensive strategy utilized in many sports like soccer, lacrosse, and basketball. During athletic competition, the maneuver is commonly associated with a sudden deceleration phase on impact, accompanied by a rapid speed and/or directional change to evade an oncoming defensive opponent (McLean et al., 1999) The maneuver has been shown to cause an significant increased peak knee valgus moment in women, placing greater force on the ACL (McLean et al., 2005). Due to the spontaneous nature of the movement, studies have been limited because the task is often performed in a controlled laboratory setting.

The other type of non-contact mechanisms commonly associated to ACL injury is landing from a jump. Gerberich et al. (1987) found that the jump-landing sequence during typical game play of volleyball players was associated with 63% of all reported injuries, including 61% of knee injuries. In a survey of injuries for female collegiate gymnasts one of the three main mechanisms for knee injuries was landing from a jump with the knee hyper-extended (Dixon & Fricker, 1993). The most frequently occurring problem for runners is knee joint pain and has been attributed to the repetitive impacts that occur during landing (James, Bates, & Osternig, 1978; McKenzie, Clement, & Taunton, 1985).

Cross-gender biomechanical analysis research has been used to examine the difference between males and females during cutting and jumping maneuvers. Researchers are becoming more educated about the potential gender-specific factors that put female athletes at greater risk for injury by identifying biomechanical differences. Gender bias of injuries in female athletes has lead to the challenge of determining specific movement patterns during ACL injury mechanisms that increase the risk of lower extremity injury in females. When comparing genders, the role of joint angles and muscle stiffness during a side-cutting maneuver and a jump-landing task may be an important factor to understanding the risk of injury and needs to be closely examined in future research.

Biomechanics during Side-Cutting Maneuver

Side-cutting maneuver are often seen in sports that require evading players of the opposing team. Soccer, lacrosse, and basketball players employ side-cutting maneuvers to avoid contact with other players and to offensively move the ball. Recent research has examined kinematic differences between genders at the knee joint during a side-cutting maneuvers (Malinzak et al., 2001). Female recreational athletes exhibited decreased knee flexion, increased knee valgus angles, greater quadriceps activation, and lower hamstring activation in comparison to males during the stance phases when performing side-cutting, cross-cutting, and running maneuvers. However, the study did not investigate differences in hip kinematics and hip or knee moments. Hip kinematics have been found to effect knee kinematics during running in females (Ferber, Davis, & Williams, 2003). Research has noted that increases in hip adduction contribute to increased knee adduction, which places greater force on the ACL during movement. Also, in vitro studies have identified a high-risk loading

33

pattern on the ACL, which consisted of an internal rotation torque and valgus moment placed on the knee flexed between 0° and 40° (Markolf, Bargar, Shoemaker, & Amstutz, 1981; Markolf et al., 1995). Ferber et al. (2003) also found that women exhibited greater hip internal rotation angles and greater hip external rotation velocity than male recreational runners. These biomechanical differences noted between males and females during a jump-landing task have been thought to increase stresses on the ACL and place the ligament at higher risk for injury in women.

Anticipated vs. Unanticipated Side-cutting Maneuver

Often, athletes are required to make spontaneous, unplanned movements to evade other players. When sports movements are anticipated by the athlete postural adjustments and reflex responses have been observed (Besier et al., 2003). These compensatory responses lead to better body position during movement. (Besier et al., 2001) compared males performing both an anticipated and unanticipated cutting maneuver. The study observed unanticipated knee moments that were twice the magnitude of the anticipated condition. A follow-up study examined a cutting maneuver in males at two different cutting angles under a preplanned and an unanticipated condition. As in the previous study, differences in kinematics and knee moments were observed in the test subjects. Besier and others believe that analysis of unanticipated cutting maneuvers closely simulate the motion and torque in the lower extremity during sports activities. Therefore, it is important to include unanticipated side-cutting maneuvers during laboratory testing to mimic conditions seen during activity.

Biomechanics during Jump-Landing

Most sports involve jump-landing maneuvers. Gymnasts perform a split leap on the floor and soccer players going up for a header are both examples of jump-landings. A large amount of biomechanical research has been conducted on the forces acting on the body during a jump-landing (Arampatzis, Schade et al., 2001; Arampatzis et al., 2004; Devita & Skelly, 1992; Lephart, Ferris, Riemann et al., 2002; McNair & Prapavessis, 1999). Also, the effect of gender on biomechanics during a jump-landing has been studied (Chappell et al., 2002; Lephart, Ferris, Riemann et al., 2002; McNair & Prapavessis, 1999). When performing a biomechanical analysis of a jump-landing, a researcher must consider what occurs in the different phases of the jump-landing and the ground reaction forces produced.

Phases of a Jump-landing

During a biomechanical analysis of jumping the ground contact or landing phase is the first to be described. Although it is not the first phase of jumping, it is one of the most important in understanding the forces that act on the lower extremity. Prior to a jump, an athlete must prepare to jump by stopping the current activity (i.e. running). The athlete then will produce biomechanical changes in the lower extremity including hip flexion, knee flexion, and foot dorsiflexion. This leads to the pre-loading flight phase, which is defined as a length of time immediately prior to initial ground contact during a jump-landing. Next the initial airborne phase occurs during which the body is no longer in contact with the ground. Subsequently, the body returns to the ground and the initial landing phase or the loading stance phase occurs. The loading stance phase is termed the stop-jump aspect of the jump-landing activity. This loading stance phase is the time period including initial ground contact

to airborne pre-landing flight phase during a jump-landing. The second flight or pre-landing flight phase is the airborne phase most often scrutinized. This phase is the most similar to actual jumping activities during an athletic event. The pre-landing flight phase is described as the period of time in the airborne phase following initial ground contact prior to the later landing stance phase secondary ground contact. The landing stance phase is the final phase in a jump-landing. It is the time period from secondary ground contact until post-contact and the dissipation of downward momentum.

Ground Reaction Forces Associated with Jump-Landing

The ground reaction forces denote the intensity and duration of stress that the human body is subjected to during ground contact when performing a jump-landing task (Devita & Skelly, 1992; McNair & Prapavessis, 1999). Researchers identify aspects of an individual's biomechanics that create differences in peak vertical ground reaction forces. Often studies will modify parameters of the jumping task in order to increase or decrease ground reaction forces to determine if an optimal jumping condition exists (Arampatzis, Schade et al., 2001; Horita et al., 2002). This optimal jumping condition is assumed from changes observed in lower extremity stiffness.

During the stance phase of a jump-landing, the person contacts the ground and the ground in return applies an equal and opposite force on the subject. This force is termed the ground reaction force and is examined in three different forms: vertical, medial/lateral, and anterior/posterior. Jump-landing studies are most often concerned with vertical ground reaction forces (VGRF). The intensity and rate of VGRF have been identified as mechanisms that increase the risk of injury (Dufek & Bates, 1991; Lephart, Ferris, & Fu, 2002).

36

Non-sports specific tasks (i.e., drop-jumps) are repeatedly used during jump-landing tasks for the investigation of ground reaction forces (Arampatzis, Bruggemann et al., 2001; Arampatzis, Schade et al., 2001; Horita et al., 2002). While drop-jumps do not occur during an athletic event, important information can be generalized about the way in which the body responds to forces. The most imperative response involves the body's innate ability to decrease peak ground reaction force and in turn, decrease the risk of lower extremity injury. When the body is unable to make proper adjustments to the ground reaction forces, tissue overload and increased joint motion can lead to injury (Butler et al., 2003). Tissue overload and excessive joint motion increase the risk of both chronic (i.e., osteoarthritis, stress fractures) and acute (i.e., anterior cruciate ligament ruptures) lower extremity injuries (Butler, 2003).

When landing the quadriceps play a critical role in the dissipation and transmission of VGRF up the kinetic chain in females (Lephart, Ferris, Riemann et al., 2002). In jump landing tasks no significant difference in VGRF is often seen between subjects of different genders, if the surface remains unchanged (Horita et al., 2002; Lephart, Ferris, Riemann et al., 2002). The lack of significant force difference has been attributed to possible changes in ankle kinematics or muscle activity level (Gross & Nelson, 1988; Horita et al., 2002; Weiss et al., 1988). Studies to date have adequately tested for these variables. The foot is the primary point of contact of the body when landing. This identifies the ankle as the first major joint to receive the VGRF.

When genders have been compared in both a jump-landing and side cutting maneuvers, research has failed to note any significant differences in vertical ground reaction forces between genders (Decker et al., 2003; Ford et al., 2003; McLean et al., 2004). These

studies utilized recreational athletes as subjects for the biomechanical analysis. These findings would allow future researchers to assume that when normalized to body weight, no significant increase in the amount of vertical ground reaction forces that must be dissipated by the body will be observed between genders in recreational athletes. Although at the collegiate level, athletes have been found to have significant differences in vertical ground reaction between genders (Salci, Kentel, Heycan, Akin, & Korkusuz, 2004). Salci et al. (2004) observed that during four different jump-landing maneuvers, collegiate female volleyball athletes landed with significantly more force than their male counterparts. Therefore, when examining collegiate athletes during a jump-landing task it is important to consider that differences in VGRF may exist that have an effect on lower extremity movement.

Summary

In jumping and side-step activities understanding what occurs during the dynamic movements is key to discovering the mechanisms of injury. The body's response to a landing task and side-step cutting maneuver under various conditions can be examined by measurement of vertical ground reaction force, lower extremity stiffness, and muscle activity. Variations have been found between genders in both lower extremity stiffness and muscle activity indicating their role in gender biasing of injury rates. Differences in the kinematics and kinetics between males and females have shown increased stress being placed on the knee in female subjects. This stress places structures, like the ACL, in a particularly vulnerable position for injury. When the lower extremity stiffness and joint moments are combined with the intrinsic factors involved in athletic injury, an analysis may allow

researchers to clearly define methods that will reduce injury rates. In order to isolate the kinematic and kinetic variables, it is necessary to remove intrinsic variables in initial analyses. Hence, the comparison of female athletes with similar intrinsic factors allows the best isolation of the desired extrinsic variables.

When there is a decrease in knee flexion and increase in hip internal rotation it makes female athletes more vulnerable to abnormal loading of the ACL. This situation occurs in most female athletes who perform a type of jumping task in sports. Skilled, well-trained female athletes, like gymnasts, have been reported to have increased ankle plantar flexion, knee flexion, and lower vertical ground reaction forces when landing (Lephart, Ferris, Riemann et al., 2002). These training adaptations allow for increase in time in which impact forces can be distributed throughout the kinetic chain, not just the ACL. So, jumping and side cutting training may allow female athletes in particular to develop preprogram muscle pattern to coordinate increased joint flexion, muscular stiffness, and overall control of the lower extremity. If female athletes incorporate proper movement techniques a significant decline in lower extremity injuries may be observed.

CHAPTER III

METHODS

Subjects

Subjects consisted of 38 Division I female collegiate athletes [age= 19.97yrs (1.668), height= 165.32cm (8.18), weight= 64.86kg (8.17)] for a total of 38 participants. The groups were composed of 11 gymnasts, 15 lacrosse, and 12 soccer athletes. An apriori power analysis (minimum of 0.80) was performed for all study variables. All subjects filled out a pre-participation questionnaire for demographics and to determine any history of lower extremity or back injury. Subjects were excluded if they had suffered a lower extremity injury in the past 3 months that limited activity for more than three days. Also, subjects with a previous history of lower extremity surgery were excluded if the surgery was within the past year and they were participating in a formal rehabilitation program. Prior to testing, all subjects were required to read and sign an informed consent form, which was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill's Medical School.

Instrumentation

Force Plate

To measure peak ground reaction forces (GRF), subjects performed a jump-landing, and an anticipated and unanticipated cutting maneuver on a force platform (Bertec 4060-10, Chicago, IL), sampling at 1440 Hz.

Kinematic Analysis: Flock of Birds

The Motion Monitor electromagnetic motion analysis system (Flock of Birds) was used to collect three dimensional lower extremity kinematic and kinetic data at a sampling rate of 144Hz. The system employs a DC transmitter with three orthogonal coils to generate a magnetic field. Also, the system incorporates four sensor receivers that record the electromagnetic flux in the field generated by the transmitter and conveys the signals to a computer via hard wiring. The electromagnetic tracking system was calibrated prior to data collection. The transmitter was affixed to a stationary stand, .914 meters in height, to establish the global reference system. An embedded right-hand Cartesian coordinate system will be defined for the shank, thigh, hip, and trunk to describe the three-dimensional position and orientation of these segments. Eular angles were used to calculate the knee joint angle between the shank and thigh and the hip joint angle between the thigh and pelvis in an order of rotations of (1) flexion-extension about the Y-axis, (2) valgus-varus (knee) or abduction-adduction (hip) about the X-axis, and (3) internal and external rotation about the Z-axis. Kinematic data was filtered using a 4th order zero phase lag Butterworth low-pass filter at 14.5 Hz (Bing Yu, Gabriel, Noble, & An, 1999).

Procedures

The study involved a prospective comparison of female gymnastic, lacrosse, and soccer athletes regarding various biomechanical factors. Subjects participating in this study reported to the Sports Medicine Research Laboratory at the University of North Carolina at Chapel Hill for one testing session lasting approximately one hour. Each subject was instructed to wear running shoes, athletic shorts or spandex, and a t-shirt during the testing session. When the subjects arrived at the laboratory, the testing procedures were explained and an informed consent form was then signed. A questionnaire was completed to insure compliance with the inclusion criteria. The subject's anthropomorphic data was collected including age (years), height (cm), mass (kg), and leg dominance. Kinematic and kinetic testing was performed on the subject's dominant leg, defined as the leg they would select to kick a soccer ball for maximal distance.

Subjects performed a five-minute warm up on a stationary bike at 50% perceived maximal exertion and a standardized lower extremity stretching routine that includes stretches for the gluteal, hamstring, quadriceps, and gastroc-soleus muscle groups. Computerized random selection was used to determine if subjects would perform the side-cutting first or the jump-landing maneuver. During the side-step cutting tasks, each subject performed the unanticipated cutting before the anticipated cutting. The unanticipated side-cuts were also randomized, using a cross-over cut as the alternative task. Data was collected for the cross-over cut, but it was not analyzed for this study. The subjects performed 2-3 practice trials of both the anticipated and unanticipated side-step cutting and jump-landing maneuver before testing.

Electromagnetic tracking sensors were placed on each subject over the spinous process of the T1 vertebrae, the apex of the sacrum, midpoint of the lateral thigh, and shank of the tibia. Sensors of the thigh and tibia were placed in areas consisting of the least amount of muscle mass to minimize potential artifact induced by muscle contraction. The sensors were affixed to the body by double-sided tape and an elastic wrap. Prior to sensor application, the skin was dried and an alcohol swab was used to remove any dead skin cells.

Once the electromagnetic sensors were attached, the subjects were asked to stand in a neutral posture with their arms relaxed at their sides. The following bony landmarks were then digitized, in the following order, using a mobile electromagnetic sensor attached to a stylus: xiphoid process, spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, lateral malleolus, left anterior superior iliac spine, and right anterior superior iliac spine. Digitization of bony landmarks served to define the segment end-points and joint centers of the lower extremity segments. The ankle joint center is located at the midpoint between the medial and lateral malleoli. Knee joint center is located at the midpoint between the medial and lateral femoral condyles. The hip joint center will be determined by the Bell method (Bell, Pedersen, & Brand, 1990). This method consists of estimating the hip joint center using the left and right anterior superior iliac spine as landmarks to mathematically estimate the hip joint center. Once the subject was digitized, they were instructed to stand relaxed with their arms at their side allowing the computer to calibrate the subject's neutral position. A standing trial was recorded for data comparison. Kinematic and kinetic data was collected as the subject performed a standardized anticipated and unanticipated side-step cutting and a jump-landing maneuver.

Side-Step Cutting

The side-step cutting maneuver involved a jump-and-cut off a 12-inch high platform. The take-off platform was set at a horizontal distance equal to 75% of the subject's body height from the front of the force-plate. The direction of the cutting maneuver was randomized and cued by a laser light system. The light was cued when subjects broke the laser beam, placed 40% of the distance from the front of the box to the force plate (Sell et al., 2006). Two lights placed on a board indicated whether the subjects performed a side-step cutting or a cross-over cutting maneuver. Through randomization, we hoped to create a true unanticipated response by the subject, allowing for a more "game-like" situation and movement patterns. During the cutting maneuvers, the subjects were instructed to plant the foot of their dominant leg on the force plate and cut 35-55° toward either their contralateral or the ipsilateral side, depending upon the light direction. The subjects were instructed to point the foot of the planted (dominant) leg forward before making a cut. For example, an athlete is right leg dominant and the light system indicated a cut to the left; the athlete planted the right foot on the force plate and cut to the left (contralateral) side. If the light system indicated a cut to the right, the athlete planted with the right (dominant) foot on the plate and perform a cross-over cut to the right (ipsilateral). To insure that the cuts are made within the appropriate angle range, tape was placed on the ground to indicate 35-55° from the center of the force plate. These values were chosen to reflect the angles at which side-step cutting is typically performed during game play (McLean et al., 1999).

Subjects performed twenty-four trials of the anticipated and unanticipated cutting maneuvers, eight trials of each maneuver (anticipated side-step cut, unanticipated side-step cut, and cross-over cut). Subjects were given 30 seconds of rest between each trial to

minimize the risk of fatigue. Kinematic data was only collected on the dominant leg during the side-step and cross-over cutting maneuvers. The three most consistent trials were averaged and used during data analysis. The trials used in data reduction were determined by successful initial foot contact following the cutting action falling within the prescribed range.

Jump-landing

The jump-landing maneuver consisted of jumping off a 12-inch high platform onto a force plate with the dominant foot, while the non-dominant foot was off the force-plate. The take-off platform was set at a horizontal distance equal to 50% of the subject's body height from the front edge of a force-plate. Each subject was instructed to jump straight forward off the 12-inch platform and minimize vertical motion. After landing the subjects were instructed to perform a vertical jump for maximum height, limiting horizontal motion and landing with the dominant foot on the force-plate and the non-dominant foot off of the force-plate. Prior to testing subjects were allowed to perform 2-3 practice trails to familiarize themselves with the jump-landing maneuver. During testing the subjects performed 8 trials with 30 seconds of rest time between trials, to minimize the risk of fatigue. Trials in which the subject failed to land with the foot of the dominant leg on the force plate and the foot of the non-dominant foot off the force plate were removed and a new trial was performed. The 3 most consistent trials were used for data analysis.

Data Reduction

The kinematic data from three trials of the side-cutting and jump-landing maneuver were averaged together for each of the lower extremity variables. The lower extremity variables include knee flexion, knee valgus/varus, hip flexion, hip abduction/ adduction, and trunk flexion angles at initial contact and at peak ground reaction force. Three-dimensional trunk, hip, and knee angles were determined at initial ground contact of the side-step cutting and jump-landing maneuver. Initial ground contact (IC) was defined as the time when vertical ground reaction force exceeded 5 N as the subject landed on the force-plate from the 12-inch high platform. During the side-step cutting maneuver, the kinematic variables were also examined at maximum knee valgus angle for the side-step cutting maneuvers. Kinetic variables included knee extension moment, knee valgus moment, hip flexion-extension moment, and anterior tibial shear force. Vertical ground reaction force was taken for both side-step cutting and jump-landing maneuvers.

During the jump-landing maneuver, kinematic variables were measured at initial contact and peak ground reaction force. To estimate the net joint reaction forces and moments during side-step cutting and jump-landing maneuvers, the dominant leg was modeled as a three-dimensional system of four rigid segments that include the shank, thigh, pelvis, and trunk. Knee joint moments and reaction forces were reported in the coordinate system of the shank relative to the knee joint. Also, the kinetic variables included peak anterior tibial shear forces, knee valgus moment, knee extension moment, and hip flexion-extension moment. These variables were reduced for the landing phase of the jump-landing. The vertical ground reaction force associated with the impact between the subject and the force-plate as they land from the 12-inch high platform was used to characterize the landing

phase. The landing phase was defined as the time period from initial ground contact until the first local minima of the vertical ground reaction force during the jump-landing maneuver. Peak VGRF and the magnitude of the knee joint moments were normalized to the subject's body weight (N) and height (m). Raw data collected from the electromagnetic tracking system was converted to rotations with respect to the anatomical coordinate axes, as defined previously. The data was processed using the Motion Monitor software. Kinematic and force plate data was put through a Butterworth low pass digital-filter at a frequency of 14.5 Hz. Once again, the average across the three separate trials was used to calculate each of the kinematic and kinetic variables associated with the side-step cutting and jump-landing maneuver. Data was imported into Matlab software version 7.0.4.365 for data reduction and analysis.

Data Analysis

Kinematic and kinetic data that was collected during the anticipated and unanticipated side-step cutting and jump-landing maneuvers was analyzed using multiple one-way analysis of variance (MANOVA) with sport type as the between subject factor. A mixed-model ANOVA was used to analyze differences within the unanticipated vs. anticipated trials and between the subject groups. Statistical significance was set with the alpha level at $\alpha < 0.05$. Tukey post-hoc was performed for all statistically significant findings. Statistical analyses were used to analyze data with SPSS software version 13.0.

CHAPTER IV

RESULTS

Subject Descriptive Characteristics

There was a significant group main effect of weight which using a one-way ANOVA [F $_{(2, 35)}$ =14.94, P<0.001] analysis.   A group main effect of height was also found utilizing a one-way ANOVA [F $_{(2, 35)}$ =8.834, P =0.001]. Post hoc analyses revealed that gymnast were significantly smaller in height than both lacrosse (P=0.001) and soccer (P<0.001) athletes. Gymnasts also had significantly less body mass than lacrosse (P=0.001) and soccer (P<0.001) athletes. No significant differences were found between groups regarding age. Means and standard deviations for subject descriptive statistics can be found in Table 1.

Jump-landing Maneuver

Initial Ground Contact: Means and standard deviations for kinematic data during the jump-landing task are present in Table 2. There was a significant group main effect for the MANOVA [F $_{(16, 58)}$ =2.25, P=0.013]. One-way ANOVA results indicated that there were significant differences between groups for knee flexion [F $_{(2, 35)}$ =18.41, P <0.001] and hip flexion [F $_{(2, 35)}$ =5.09, P= 0.011] at initial contact. Post hoc analyses of the significant group differences for knee flexion at initial contact revealed that gymnasts demonstrated significantly less knee flexion than both lacrosse (P<0.001) and soccer (P<0.001). Gymnasts

also displayed significantly less hip flexion than lacrosse ($P=0.016$) and soccer ($P=0.031$). There were no significant differences in knee valgus, hip adduction, and trunk flexion between groups ($P>.0.05$).

Landing Phase: During the landing phase there was no significant group main effect observed for the MANOVA [$F_{(2, 35)}=1.27$, $P=0.236$]. One-way ANOVA revealed no significant difference between groups for knee flexion, knee valgus, hip flexion, and hip adduction. Also, no differences were found for trunk flexion during the landing phase. Table 3 contains the means and standard deviations for the kinematic data during the landing phase.

Kinetic Data: Table 4 illustrates the mean and standard deviation for the joint moments, anterior tibial shear force, and vertical ground reaction force during the landing phase. Results of the MANOVA indicated a significant group main effect [$F_{(12, 62)} =2.20$, $P=0.022$]. The one-way ANOVA findings demonstrated significant differences between groups for knee extension moment [$F_{(2, 35)} =8.97$, $P=0.001$], knee valgus moment [$F_{(2, 35)} =6.43$, $P=0.004$], and hip flexion moment [$F_{(2, 35)} =7.36$, $P=0.002$] during the landing phase. Also, there were significant difference found for the anterior tibial shear force [$F_{(2, 35)} =3.99$, $P=0.027$] and vertical ground reaction force [$F_{(2, 35)} = 10.22$, $P=0.001$].

Post hoc analysis of the significant group differences for knee extension moment revealed that gymnasts exhibit a significantly greater knee extension moment than soccer athletes ($P=0.001$). Lacrosse athletes also displayed a significantly larger knee extension moment than soccer ($P=0.011$), but did not significantly differ from gymnasts. The gymnasts displayed significantly larger knee valgus moment than both lacrosse ($P=0.046$) and soccer

(P=0.003). Hip flexion moment was found to be significantly larger in gymnasts when compared to soccer (P=0.002). Peak anterior tibial shear force in gymnasts was also shown to be significantly larger than in soccer athletes (P=0.003). Vertical ground reaction force were also significantly larger for gymnasts in comparison to both lacrosse (P=0.001) and soccer (P=0.002) athletes.

Summary

For the jump-landing maneuver, gymnasts exhibit significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast had significantly larger knee extension moment and anterior tibial shear force than soccer athletes. Lacrosse had a significantly larger knee extension moment than soccer, but not gymnastics. No significant differences were found for the following variables at initial contact: knee valgus, hip adduction, and trunk flexion angles. The landing phase showed no significant values for any of the test joint angles. Also, for hip extension moment there were no significant findings. Tables 2 and 3 summarize initial ground contact angles and landing phase joint angles for all the tested joint motions during the jump-landing tasks. Table 4 illustrates the means and standard deviations for the joint moments, anterior tibial shear force, and vertical ground reaction force during the landing phase.

Anticipated Side-step Cutting Maneuver

Initial Ground Contact: During initial ground contact, there was a significant group main effect for the MANOVA [F $(_{16, 58})$ =1.936, P=0.035]. ANOVA results from the one-way ANOVA indicated that there were significant differences between groups for knee flexion [F $(_{2, 35})$ =7.86, P=0.002] and hip flexion [F $(_{2, 35})$ =6.64, P=0.004] at initial ground contact. Post hoc analyses of the significant group differences for knee flexion displayed that gymnasts had significantly less knee flexion than lacrosse (P=0.003) and soccer (P=0.004) athletes at initial ground contact. Also, gymnasts exhibited significantly less hip flexion than both lacrosse (P=0.041) and soccer (P=0.003) athletes. There were no significant differences in knee valgus, hip adduction, and trunk flexion angle between groups (P>0.05). Table 5 summarizes initial ground contact angles during the anticipated side-step cutting task.

Landing Phase: There was no significant group main effect for the MANOVA [F $(_{24, 50}}$ =1.23, P=0.264, 1-β=0.778]. The one-way ANOVA results indicated that there were no significant differences between groups for knee flexion, knee valgus, hip flexion, hip adduction, or trunk flexion. Table 6 displays the landing phase contact angles during the anticipated side-step cutting task.

Kinetic Data: A summary of means and standard deviations for the kinetic data can be found in Table 7. A significant group main effect was seen during the landing phase for the joint moment data using the MANOVA [F $(_{16, 58})$ =2.70, P=0.003]. Using a one-way ANOVA, the results indicated that there were significant differences between groups for knee extension moment (P=0.001) and knee valgus moment (P=0.031). There were also

51

significant differences in hip flexion (P=0.050) and extension (P=0.044) moments. Post hoc analyses of the significant group differences at knee extension moment revealed that gymnasts have a significantly larger knee extension moment during the landing phase than both lacrosse (P=0.003) and soccer (P=0.000) athletes. Also, gymnasts displayed significantly greater knee valgus moment than lacrosse (P=0.024) athletes. For hip flexion moment during landing phase, gymnasts exhibited a greater moment than lacrosse (P=0.039) athletes. Gymnast displayed a greater hip extension moment than soccer (P=0.037) athletes during the anticipated side-step cutting task. A significant group difference for hip adduction with post hoc analyses revealed that lacrosse displayed a significantly greater hip adduction moment than soccer (P=0.034) athletes.

A significant group main effect for the MANOVA [F $_{(8, 66)}$ =2.12, P=0.046] was observed for anterior tibial shear force and vertical ground reaction force during the landing phase. A one-way ANOVA analysis revealed that there were significant differences between group for both anterior tibial shear [F $_{(2, 35)}$ =6.54, P=0.004] and vertical ground reaction [F $_{(2, 35)}$ =3.34, P=0.047] forces. Post hoc analyses of significant group differences for anterior tibial shear forces during the landing phase indicated that gymnasts exhibited significantly more anterior tibial shear force than soccer (P=0.003) athletes. Also, gymnasts displayed significantly more vertical ground reaction force than soccer (P=0.040) athletes during the landing phase.

Summary

During the anticipated side-step cutting maneuver, gymnasts exhibited significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast demonstrated significantly larger knee extension moments than lacrosse and soccer athletes. Also, gymnast had significantly larger hip extension moments, anterior tibial shear forces, and vertical ground reaction forces than soccer athletes. Lacrosse had significantly smaller knee valgus and hip flexion moments than gymnasts. No significant differences were found for the following variables at initial contact: knee valgus, hip adduction, and trunk flexion angles. The landing phase showed no significant values for any of the test joint angles. Table 5 and table 6 summarize joint angels at initial ground contact and the landing phase during the anticipated side-step cutting task. A summary of means and standard deviations for the kinetic data can be found in Table 7.

Unanticipated Side-step Cutting Maneuver

Initial Ground Contact: There was a significant group main effect for the MANOVA [F $_{(16, 58)}$ =2.31, P=0.010]. One-way AVONA analysis of the variables between groups indicated significant differences at knee flexion [F $_{(2, 35)}$ =8.85, P=0.001] and trunk flexion [F $_{(2, 35)}$ =5.98, P=0.006] with reference to the world axis during the initial ground contact. After a post hoc analysis, gymnasts demonstrated significantly less knee flexion than both lacrosse (P=0.002) and soccer (P=0.004) at initial contact. Also, gymnast had significantly less trunk flexion that soccer athletes (P=0.004). Table 8 includes the mean and standard deviation for the kinematic variable at initial contact for the anticipated side-step cutting maneuver.

Landing Phase: The MANOVA [F $_{(24, 50)}$ =1.33, P=0.195, 1-β=0.82] discovered no significant group main effect for the kinematic variables. However, the one-way ANOVA results indicated a significant difference in trunk flexion (P=0.001) during the landing phase. Post hoc analysis found that gymnasts exhibit significantly less trunk flexion during the landing phase than soccer athletes (P=0.001). Lacrosse also displayed significantly less trunk flexion than soccer (P=0.026), but no significant difference was found between lacrosse and gymnastics. Table 9 displays the kinematic variables for the unanticipated side-step cutting maneuver during the landing phase.

Kinetic Data: There was no significant group main effect for the MANOVA F $_{(24, 50)}$ =1.64, P=0.070, 1-β=0.910]. Yet, the one-way ANOVA revealed a significant difference in knee extension moment (P=0.001), hip flexion moment (P=0.010), and hip extension moment (P=0.008). The post hoc analyses of the significant group differences for knee extension moment revealed gymnastic displayed a significantly larger moment than soccer (P=0.001). Also, lacrosse demonstrated larger knee extension moments than soccer (P=0.028) athletes. For hip flexion moment, gymnasts displayed significantly greater difference than lacrosse (P=0.023) and soccer (P=0.15). Gymnasts exhibited a significantly greater hip extension moment than soccer (P=0.006), but not lacrosse.

There was a significant group main effect for the MANOVA F $_{(8, 66)}$ =3.38, P=0.003]. One-way ANOVA for anterior tibial shear force F $_{(2, 35)}$ =11.18, P<0.001] and vertical ground reaction force [F $_{(2, 35)}$ =5.176, P=0.011] during the landing phase revealed significant group difference for both variables. Post hoc analyses identified that gymnasts have a significantly greater anterior tibial shear force than soccer (P<0.001). Lacrosse also had a

significantly larger anterior tibial shear force than soccer (P=0.011) athletes. Furthermore, gymnasts have significantly larger vertical ground reaction forces than both lacrosse (P=0.029) and soccer (P=0.015).

Summary

During the unanticipated side-step cutting maneuver, gymnasts exhibit significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast had significantly less trunk flexion than soccer athletes. The landing phase showed significantly less trunk flexion in gymnast compared to soccer athletes. Lacrosse athletes also had significantly less trunk flexion during the landing phase compared to soccer. Gymnasts had a larger knee extension moment than lacrosse and soccer athletes. Also, they displayed significantly larger hip flexion moments and vertical ground reaction forces compared to lacrosse and soccer athletes. Also, gymnast had significantly larger hip extension moments, hip extension, and anterior tibial shear forces than soccer athletes. Lacrosse athletes had a significantly smaller knee valgus and hip flexion moment than gymnasts. No significant differences were found for the following variables at initial contact: knee valgus, hip flexion, and hip adduction. Knee valgus moment was not significantly different between groups. Tables 8 and 9 display the kinematic data at initial contact and the landing phase for the anticipated side-step cutting maneuver. Table 10 summarizes the means and standard deviations for the kinetic data and ground reaction forces during the unanticipated side-step cutting maneuver.

Table 1:

Descriptive Statistics for Subject Characteristics

	Gymnastics (N=11)		Lacrosse (N=15)		Soccer (N=12)	
Age (yrs)	20.09	(1.04)	19.53	(.990)	20.42	(2.57)
Height (cm)	157 [a,b]	(4.69)	167.27	(6.34)	170.5	(7.09)
Weight (kg)	57.67 [a,b]	(4.42)	66.88	(5.98)	68.93	(9.26)

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Table 2:

Jump Landing Kinematic Data at Initial Contact

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	1.39 [a,b] (6.13)	-12.91 (7.04)	-17.72 (9.93)	0.000	1.00
Valgus	-1.99 (5.20)	-1.13 (5.62)	0.86 (4.07)	0.387	0.143
Hip					
Flexion	17.10 [a,b] (6.61)	25.34 (7.67)	26.66 (8.90)	0.011	0.787
Adduction	-4.27 (7.17)	-7.38 (5.26)	-6.97 (4.05)	0.343	0.228
Trunk					
Flexion (sacrum)	-10.31 (25.55)	-9.04 (10.36)	-0.95 (9.61)	0.313	0.245
Flexion (world)	-2.74 (27.75)	0.14 (10.09)	5.77 (6.33)	0.457	0.176

Measured in degrees
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Table 3:

Jump Landing Kinematic Data during Landing Phase

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	-51.71 (14.43)	-54.56 (8.37)	-54.67 (7.03)	0.730	0.097
Valgus	-8.61 (9.04)	-6.57 (7.51)	-3.12 (6.54)	0.235	0.300
Hip					
Flexion	42.23 (12.11)	43.94 (13.91)	43.89 (8.13)	0.923	0.061
Adduction	-2.25 (6.37)	-3.62 (5.09)	-3.05 (4.32)	0.81	0.080
Trunk					
Flexion (sacrum)	-8.89 (25.23)	-6.20 (10.18)	2.57 (8.77)	0.193	0.337
Flexion (world)	1.01 (26.90)	2.15 (8.57)	8.27 (6.09)	0.485	0.165

Measured in degrees

Table 4:

Jump Landing Kinetic Data

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Extension Moment	-0.23 [b] (0.091)	-0.19 [c] (0.064)	-0.10 (0.078)	0.001	0.96
Valgus Moment	-0.124 [a,b] (0.069)	-0.076 (0.044)	-0.052 (0.032)	0.004	0.88
Hip					
Flexion Moment	-0.71 [b] (0.21)	-0.58 (0.17)	-0.41 (0.20)	0.002	0.92
Extension Moment	0.53 (0.21)	0.49 (0.19)	0.31 (0.17)	0.108	0.45
Landing Phase					
Anterior tibial shear force	0.97 [b] (0.46)	0.89 (0.37)	0.55 (0.32)	0.027	0.68
Vertical ground reaction force	3.47 [a,b] (0.83)	2.55 (0.60)	2.59 (0.72)	0	0.98

Joint moment normalized to body weight (N)* height (m)
VGRF normalized to body weight (N)
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Table 5:

Anticipated Side-step Cut at Initial Contact

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	3.43 [a,b] (7.03)	-6.64 (7.09)	-6.84 (7.38)	0.002	0.935
Valgus	-1.06 (5.08)	-1.03 (4.83)	-2.63 (3.50)	0.606	0.127
Hip					
Flexion	16.63 [a,b] (6.07)	24.25 (9.73)	27.94 (5.34)	0.004	0.888
Adduction	-15.39 (8.91)	-18.25 (4.69)	-13.77 (6.20)	0.215	0.317
Trunk					
Flexion (sacrum)	-7.41 (35.44)	-24.57 (9.86)	-18.43 (10.31)	0.128	0.415
Flexion (world)	1.23 (36.83)	-11.24 (10.18)	-3.04 (11.09)	0.334	0.233

Measured in degrees
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Table 6:

Anticipated Side-step Cut Kinematic Data during Landing Phase

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	-31.63 (8.52)	-28.57 (8.82)	-31.93 (8.45)	0.535	0.148
Valgus	-5.82 (8.26)	-4.99 (5.71)	-6.04 (5.87)	0.909	0.063
Hip					
Flexion	25.22 (9.73)	30.46 (11.30)	33.22 (5.28)	0.129	0.414
Adduction	-10.38 (7.72)	-10.46 (5.07)	-6.86 (4.72)	0.233	0.301
Trunk					
Flexion (sacrum)	-4.55 (35.18)	-21.69 (10.26)	-13.34 (11.79)	0.134	0.408
Flexion (world)	5.08 (36.69)	-8.22 (9.78)	1.94 (12.25)	0.267	0.276

Measured in degrees

Table 7:

Anticipated Side-step cut Kinetic Data

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Extension Moment	-0.22 [a,b] (0.06)	-0.16 (0.04)	-0.13 (0.06)	0.001	0.96
Valgus Moment	-0.09 [a] (0.04)	-0.05 (0.03)	-0.06 (0.42)	0.031	0.66
Hip					
Flexion Moment	-0.47[a] (0.11)	-0.34 (0.14)	-0.39 (0.12)	0.05	0.585
Extension Moment	0.42 [b] (0.16)	0.33 (0.14)	0.28 (0.11)	0.044	0.606
Landing Phase					
Anterior tibial shear force	0.85 [b] (0.30)	0.69 (0.35)	0.42 (0.19)	0.004	0.88
Vertical ground reaction force	4.92 [b] (1.46)	4.20 (0.64)	3.84 (0.91)	0.47	0.59

Joint moment normalized to body weight (N)* height (m)
VGRF normalized to body weight (N)
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Table 8:

Unanticipated Side-step Cut at Initial Contact

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	3.61 [a,b] (6.56)	-7.14 (8.35)	-6.91 (6.07)	0.001	0.953
Valgus	-2.65 (5.54)	-1.03 (4.82)	-1.63 (4.62)	0.716	0.100
Hip					
Flexion	18.15 (5.54)	22.80 (14.01)	23.15 (7.51)	0.43	0.187
Adduction	-18.44 (8.59)	-22.31 (5.00)	-20.65 (4.46)	0.294	0.257
Trunk					
Flexion (sacrum)	-29.54 (13.93)	-26.05 (12.40)	-17.91 (10.72)	0.079	0.505
Flexion (world)	-21.15 [b] (8.84)	-15.16 (9.00)	-7.77 (10.08)	0.006	0.851

Measured in degrees
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Table 9:

Unanticipated Side-step Cut Kinematic Data during Landing Phase

| Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Flexion	-27.83 (4.65)	-30.82 (8.93)	-31.79 (7.60)	0.427	0.188
Valgus	-8.32 (8.02)	-7.01 (5.89)	-6.10 (5.65)	0.714	0.100
Hip					
Flexion	27.19 (7.25)	30.42 (13.86)	30.71 (8.18)	0.679	0.108
Adduction	-12.44 (7.99)	-13.83 (5.46)	-13.84 (4.88)	0.818	0.079
Trunk					
Flexion (sacrum)	-27.16 [b] (12.72)	-24.35 [c] (12.01)	-12.45 (11.62)	0.013	0.777
Flexion (world)	-16.83 [b] (9.14)	-11.63 [c] (8.83)	-1.827 (9.91)	0.001	0.936

Measured in degrees
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Table 10:

Unanticipated Side-step cut Kinetic Data

Motion	Gymnastics	Lacrosse	Soccer	P-value	Power
Knee					
Extension Moment	-0.21 [b] (0.09)	-0.16 (0.04)	-0.10 (0.05)	>0.001	0.984
Valgus Moment	-0.06 (0.04)	-0.03 (0.04)	-0.04 (0.03)	0.098	0.466
Hip					
Flexion Moment	-0.43 [a,b] (0.12)	-0.32 (0.10)	-0.31 (0.07)	0.01	0.806
Extension Moment	0.38 [b] (0.10)	0.30 (0.11)	0.25 (0.07)	0.008	0.826
Landing Phase					
Anterior tibial shear force	0.86 [b] (0.33)	0.65 [c] (0.28)	0.33 (0.19)	>0.001	0.987
Vertical ground reaction force	5.16 [a,b] (1.24)	4.18 (0.74)	4.03 (0.76)	0.011	0.794

Joint moment normalized to body weight (N)* height (m)
VGRF normalized to body weight (N)
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Figure 1:

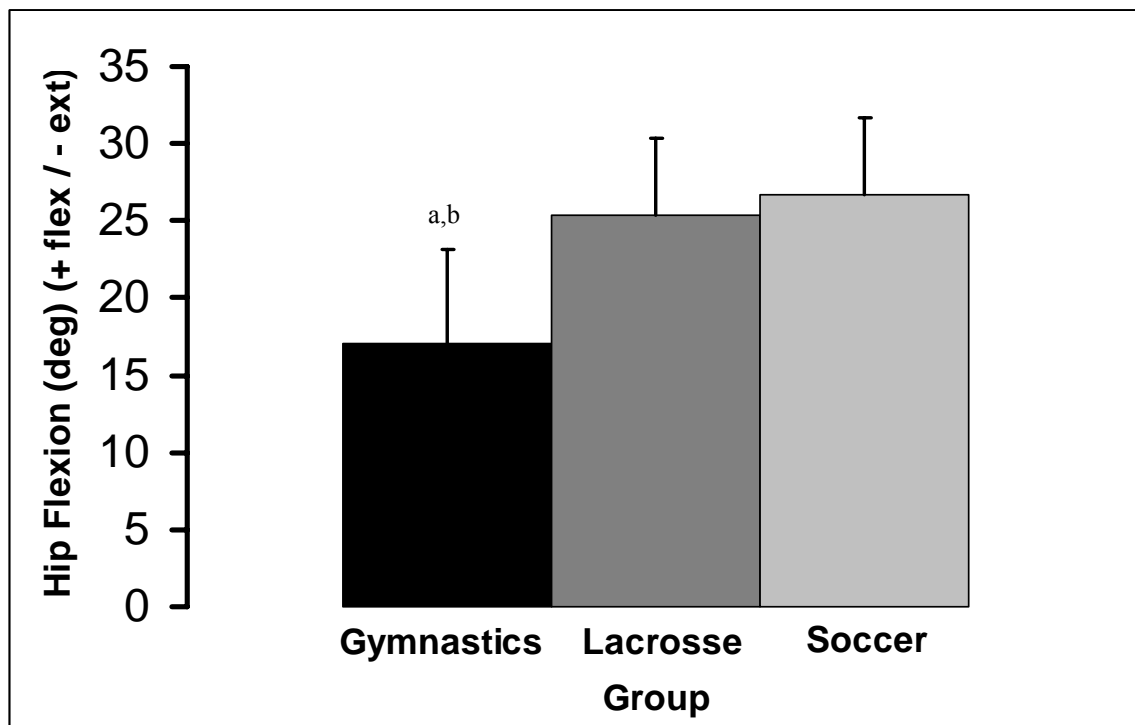Jump-landing Maneuver: Knee Flexion at Initial Contact
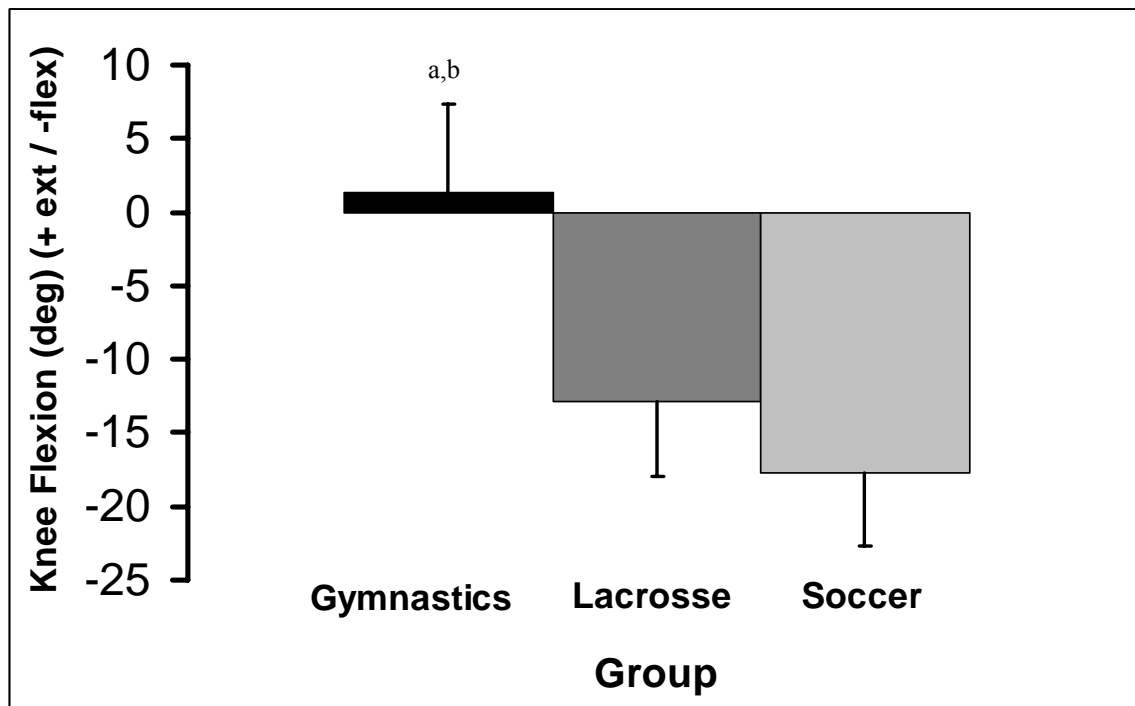
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 2:

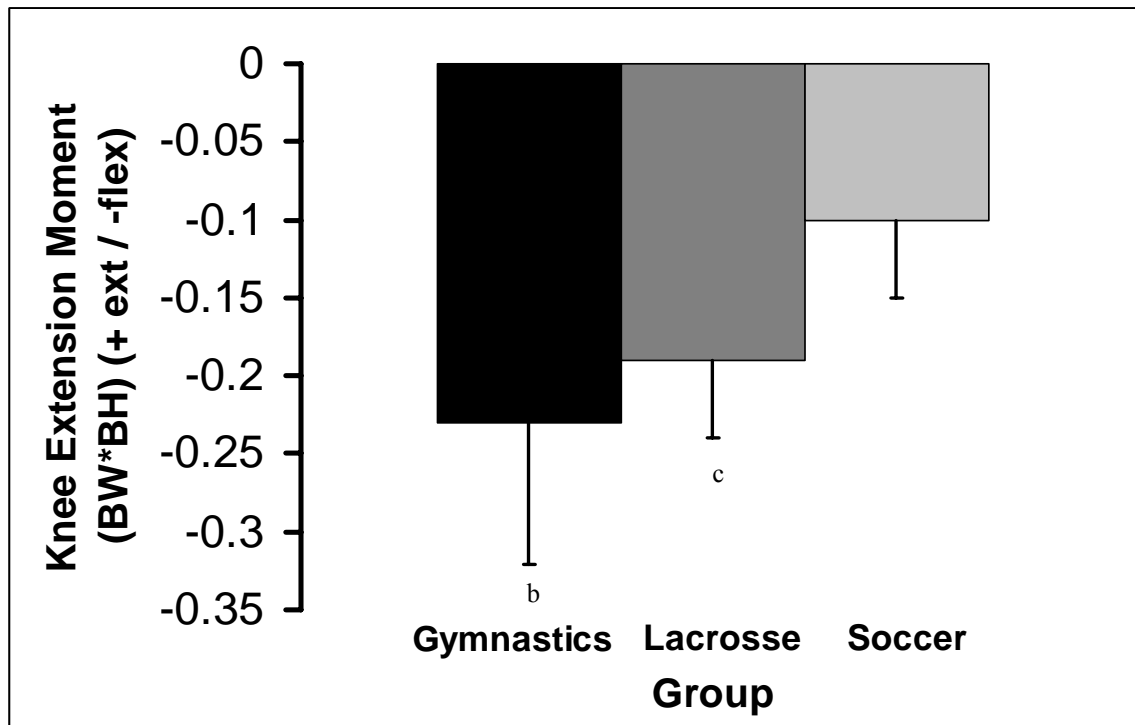Jump-landing Maneuver: Hip Flexion at Initial Contact

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 3:

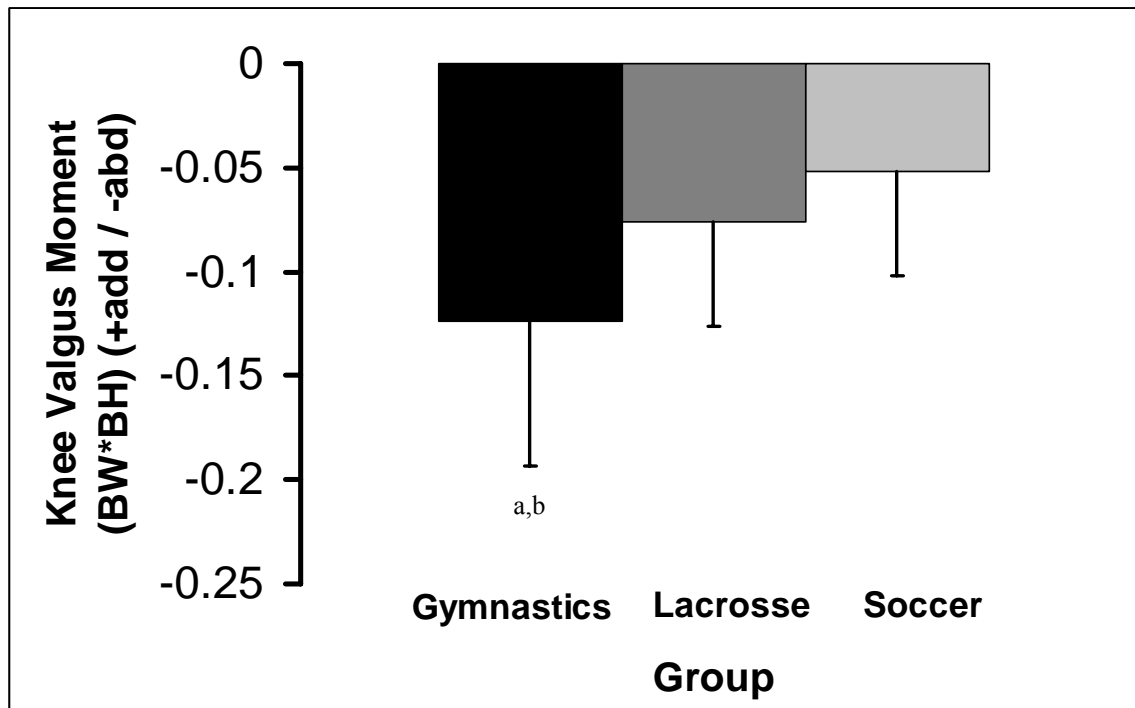Jump-landing Maneuver: Knee Extension Moment

b Significantly different between Gymnastics and Soccer
c Significantly different between Lacrosse and Soccer

Figure 4:

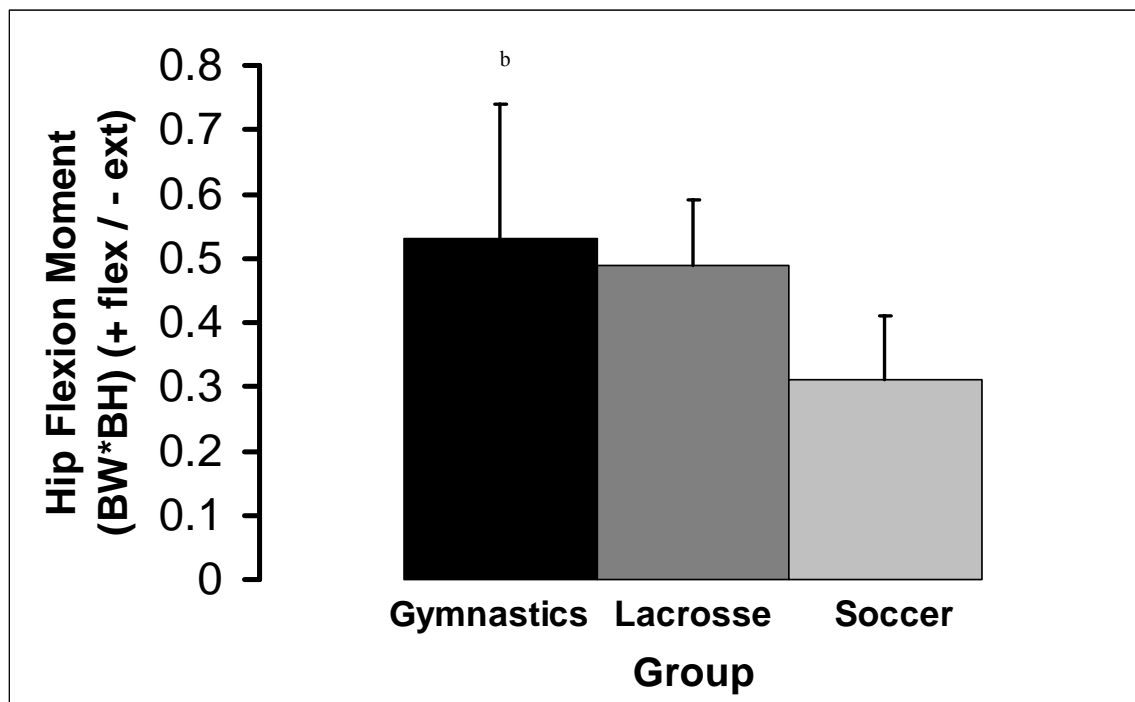Jump-landing Maneuver: Knee Valgus Moment

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 5:
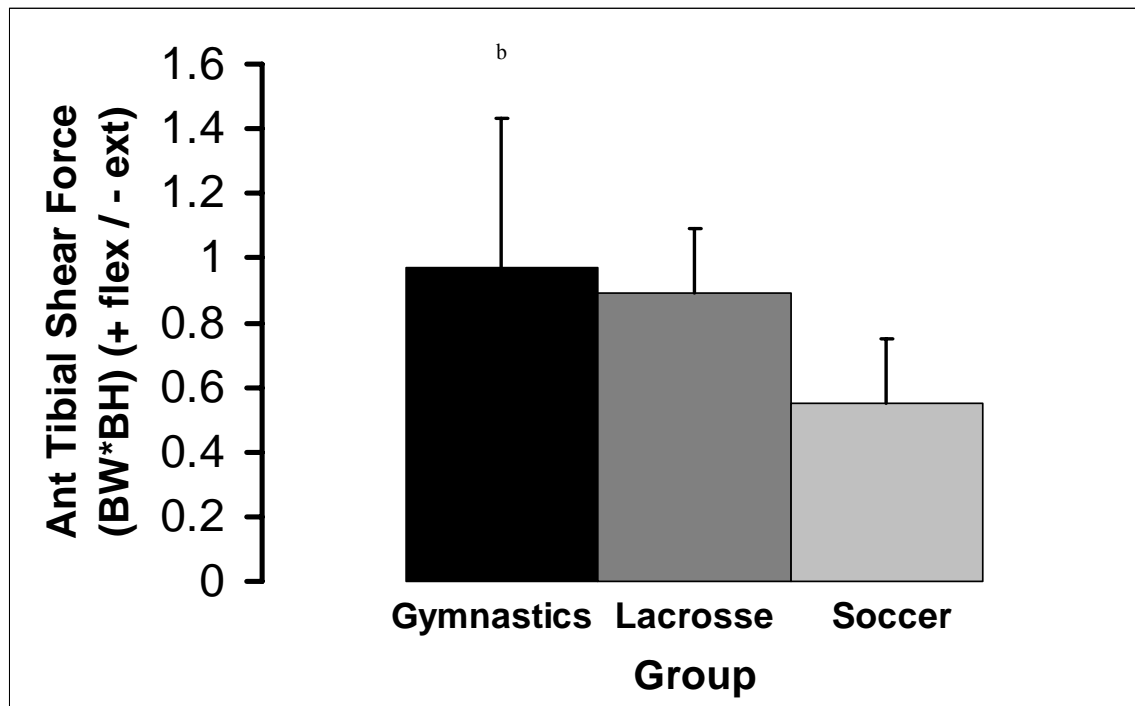
Jump-landing Maneuver: Hip Flexion Moment

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

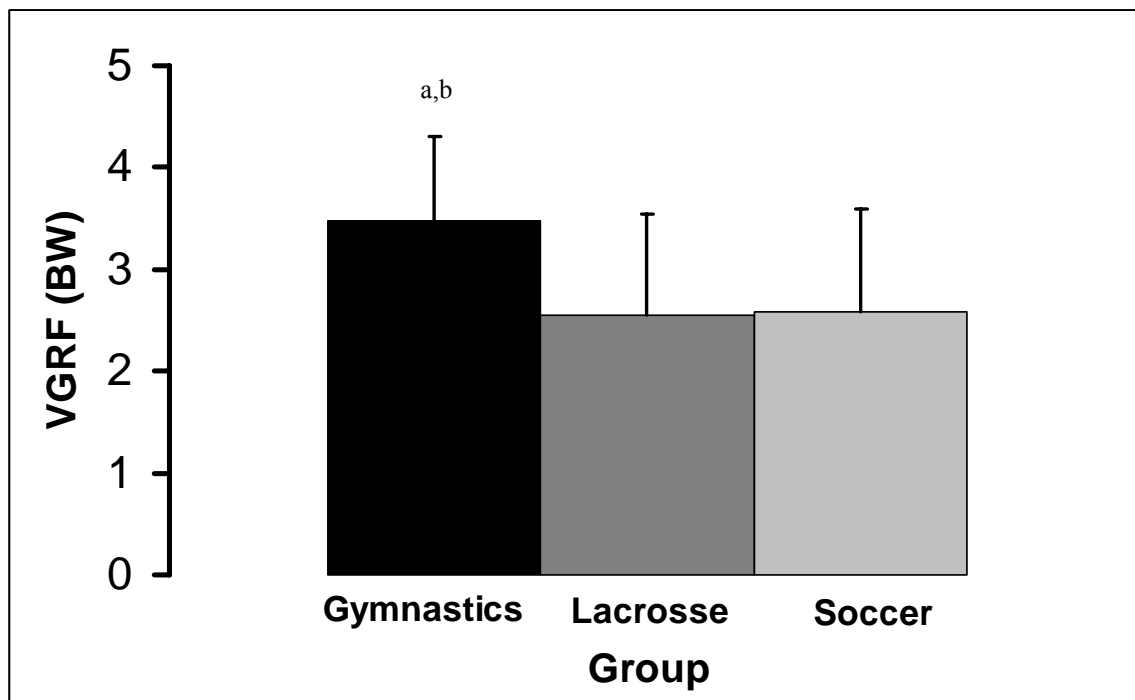Figure 6:

Jump-landing Maneuver: Anterior Tibial Shear Force

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Figure 7:

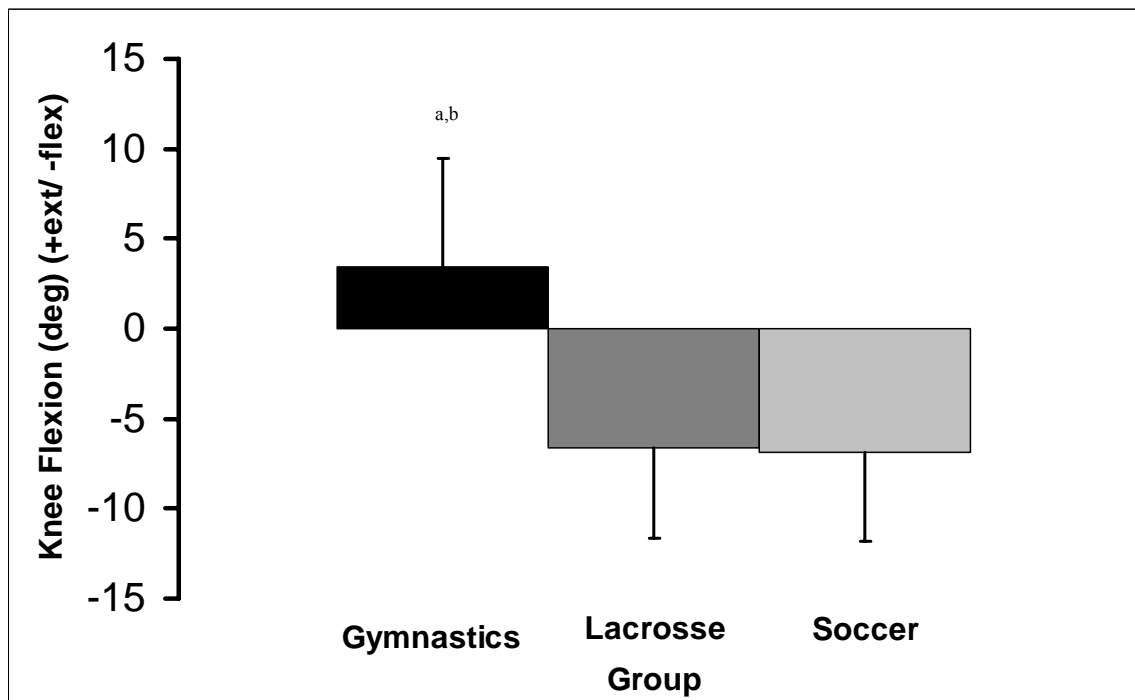Jump-landing Maneuver: Vertical Ground Reaction Force

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 8:

Anticipated Side-step Cutting Maneuver: Knee Flexion at Initial Contact

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 9:

Anticipated Side-step Cutting Maneuver: Hip Flexion at Initial Contact
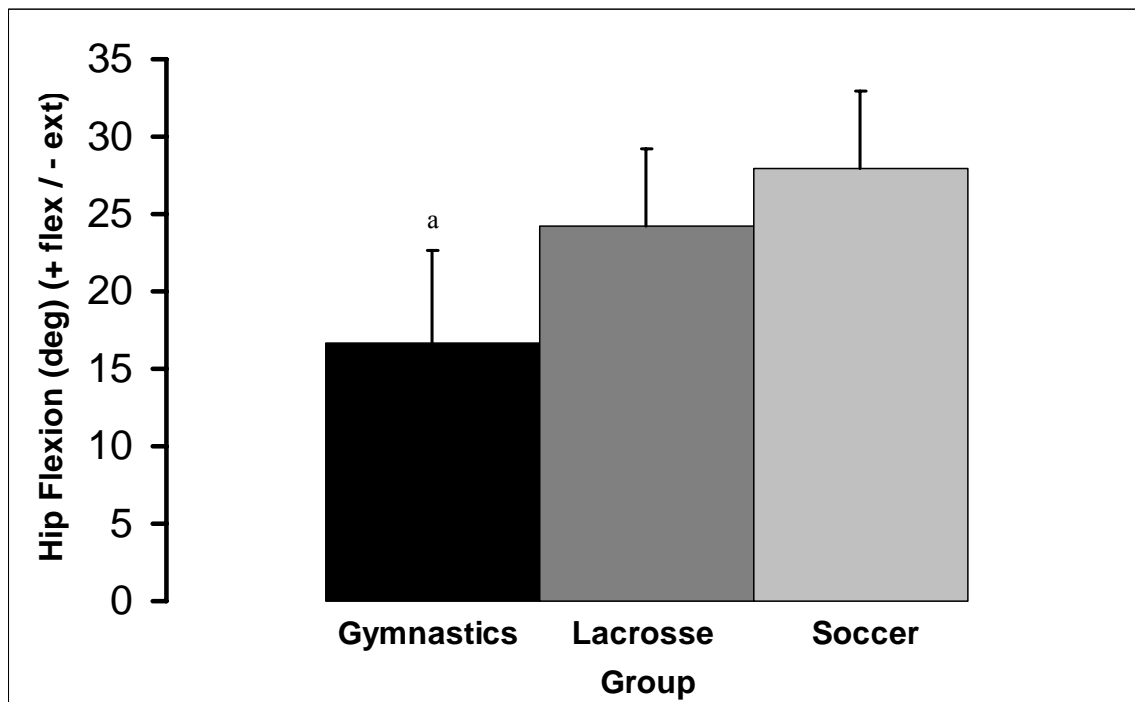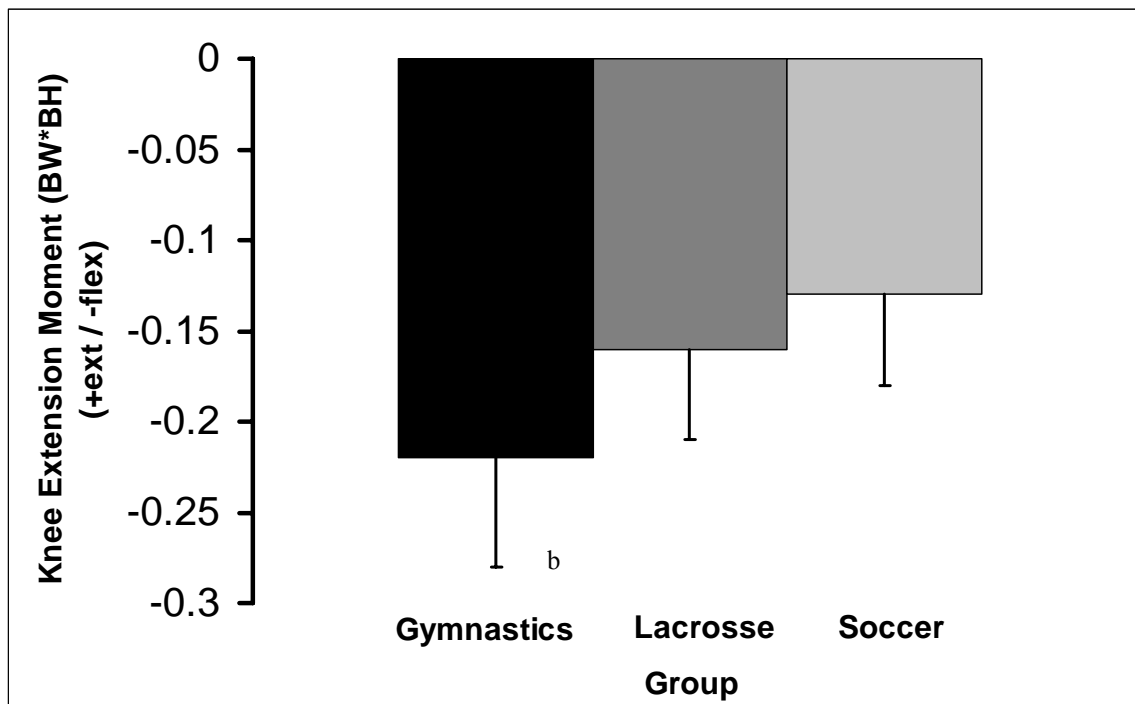

[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

Figure 10:

Anticipated Side-step Cutting Maneuver: Knee Extension Moment

b Significantly different between Gymnastics and Soccer

Figure 11:

Anticipated Side-step Cutting Maneuver: Knee Valgus Moment

[a] Significantly different between Gymnastics and Lacrosse

Figure 12:

Anticipated Side-step Cutting Maneuver: Hip Flexion Moment

[a] Significantly different between Gymnastics and Lacrosse

Figure 13:

Anticipated Side-step Cutting Maneuver: Hip Extension Moment

[b] Significantly different between Gymnastics and Soccer

Figure 14:

Anticipated Side-step Cutting Maneuver: Anterior Tibial Shear Force

[b] Significantly different between Gymnastics and Soccer

Figure 15:

Unanticipated Side-step Cutting Maneuver: Knee Flexion at Initial Contact

a Significantly different between Gymnastics and Lacrosse
b Significantly different between Gymnastics and Soccer
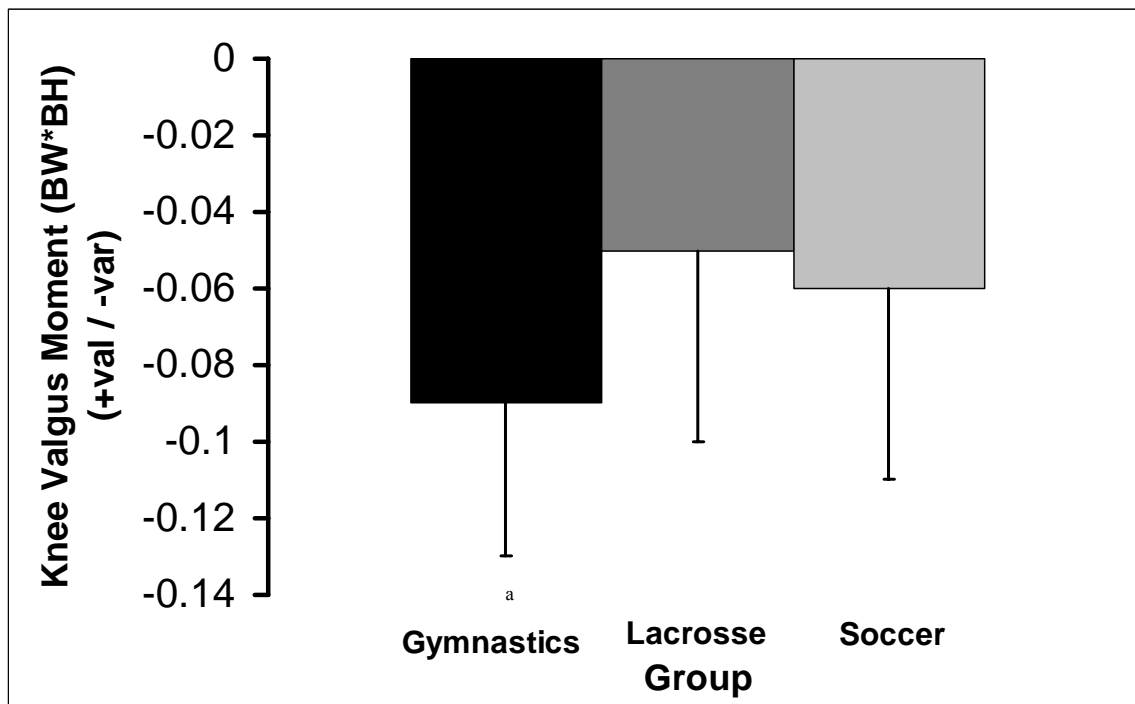
Figure 16:

Unanticipated Side-step Cutting Maneuver: Trunk Flexion during the Landing Phase

b Significantly different between Gymnastics and Soccer

Figure 17:

Unanticipated Side-step Cutting Maneuver: Knee Extension Moment
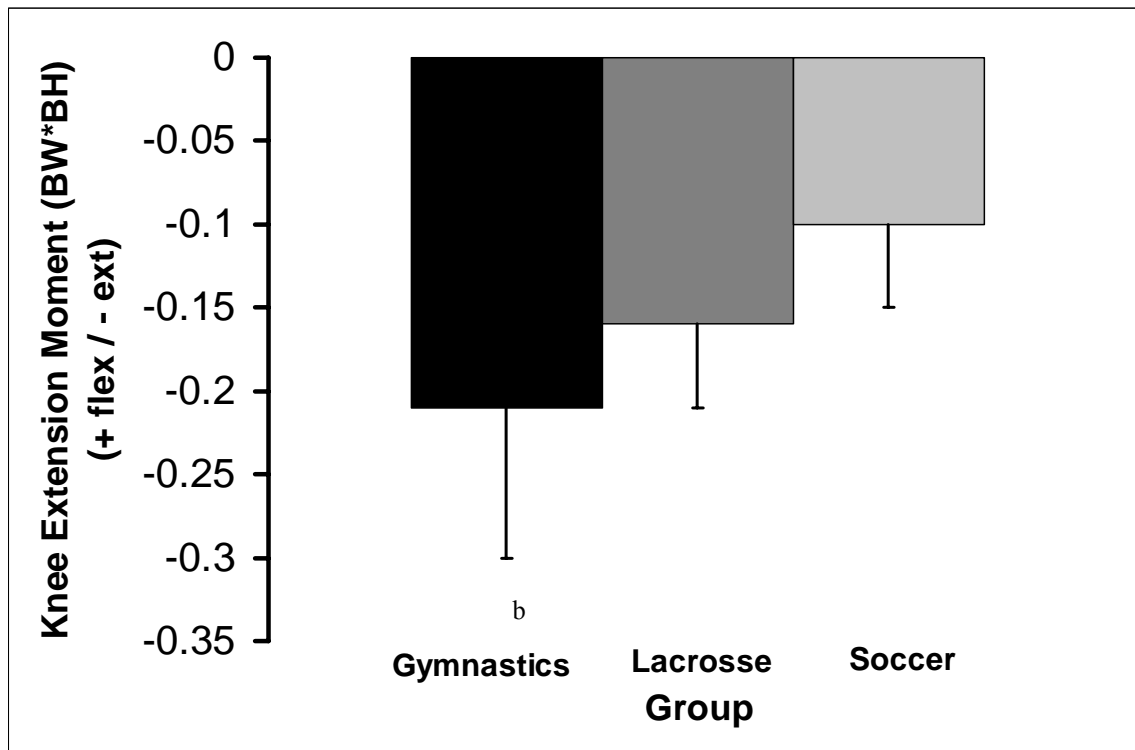
[b] Significantly different between Gymnastics and Soccer
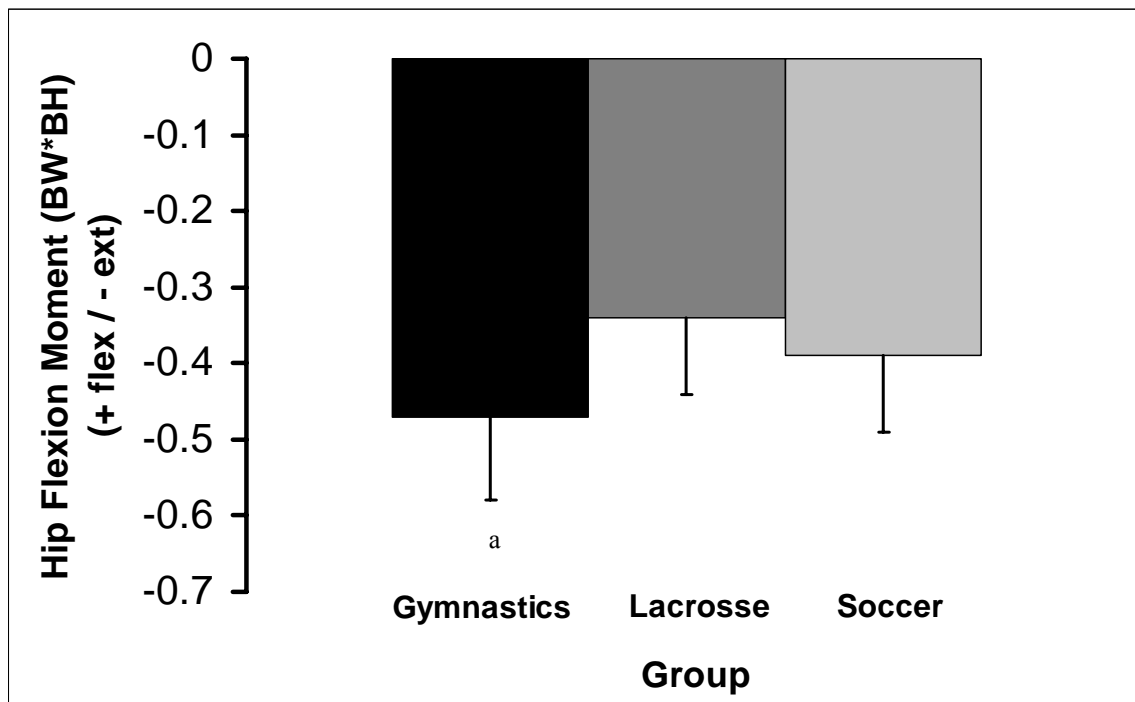
Figure 18:

Unanticipated Side-step Cutting Maneuver: Hip Flexion Moment
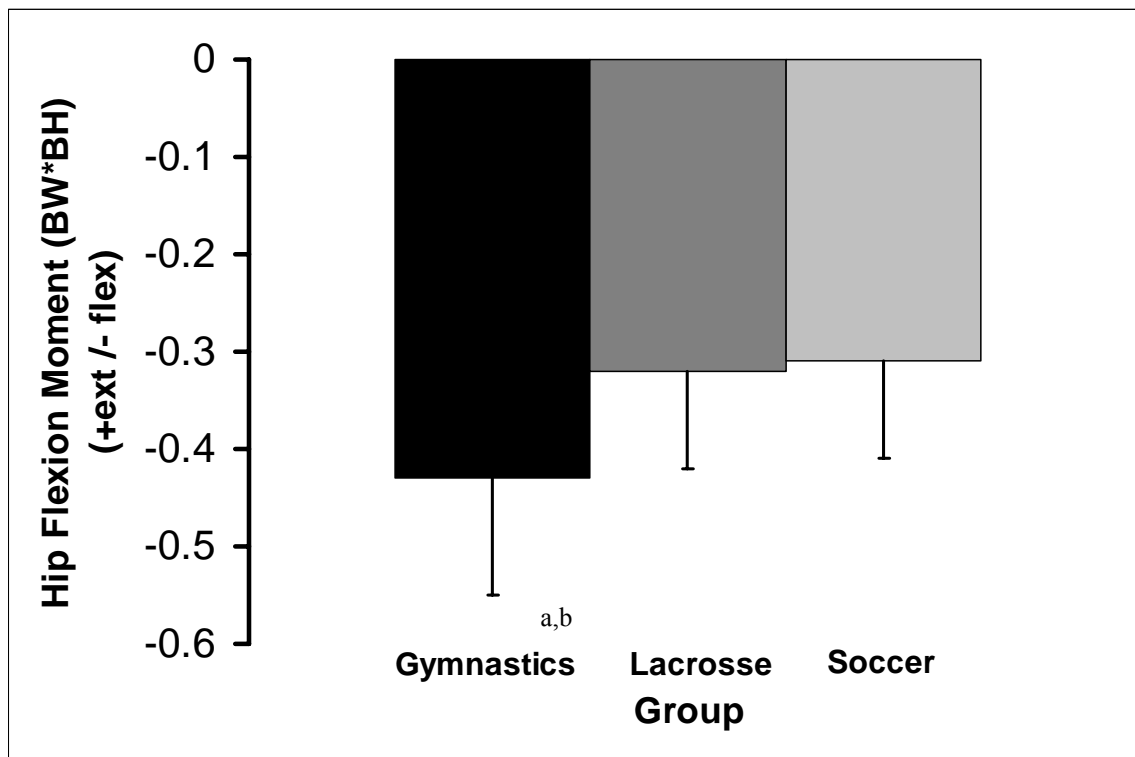
ª Significantly different between Gymnastics and Lacrosse
ᵇ Significantly different between Gymnastics and Soccer
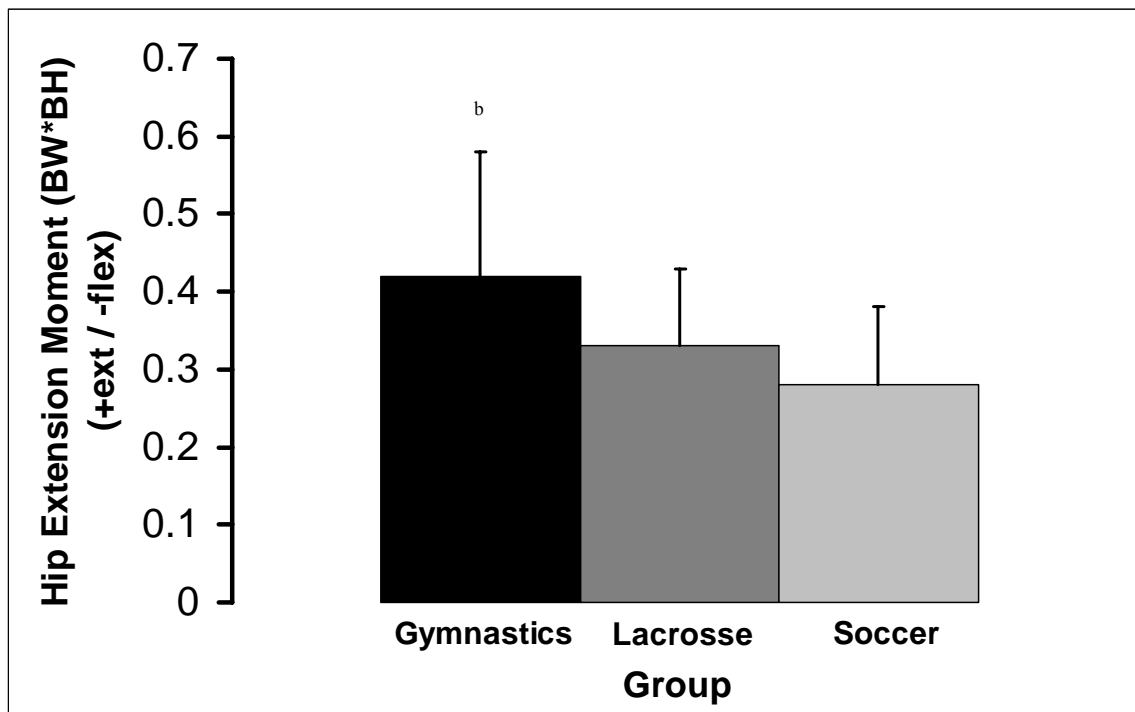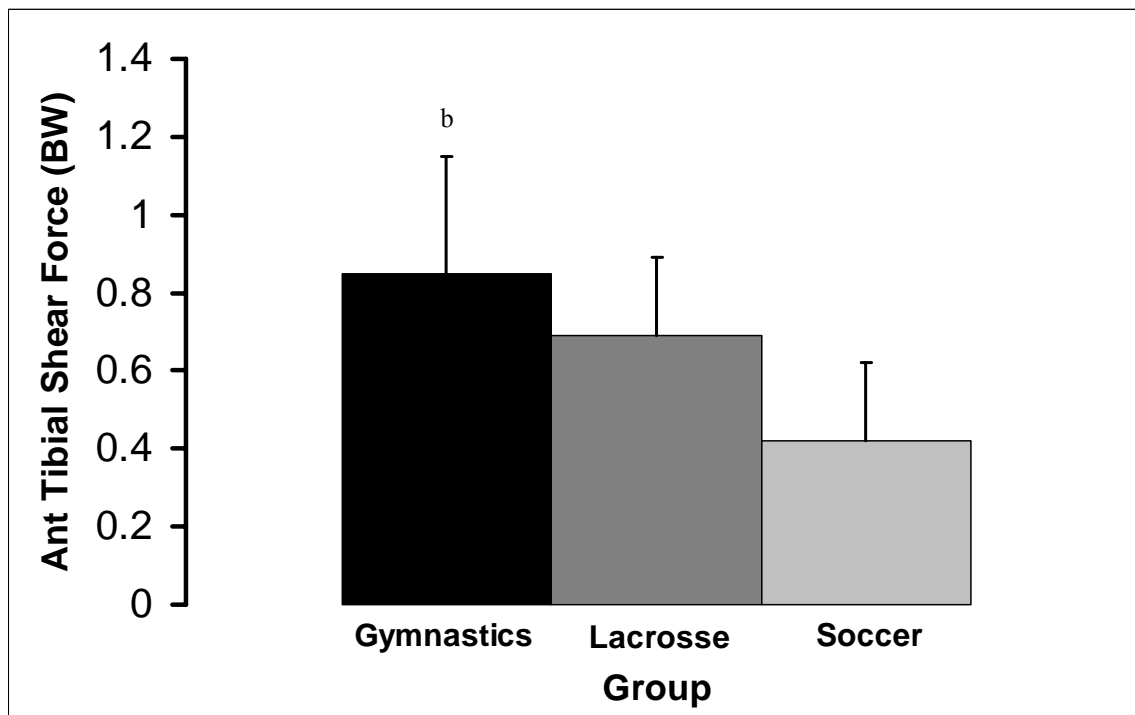
Figure 19:

Unanticipated Side-step Cutting Maneuver: Hip Extension Moment

[b] Significantly different between Gymnastics and Soccer

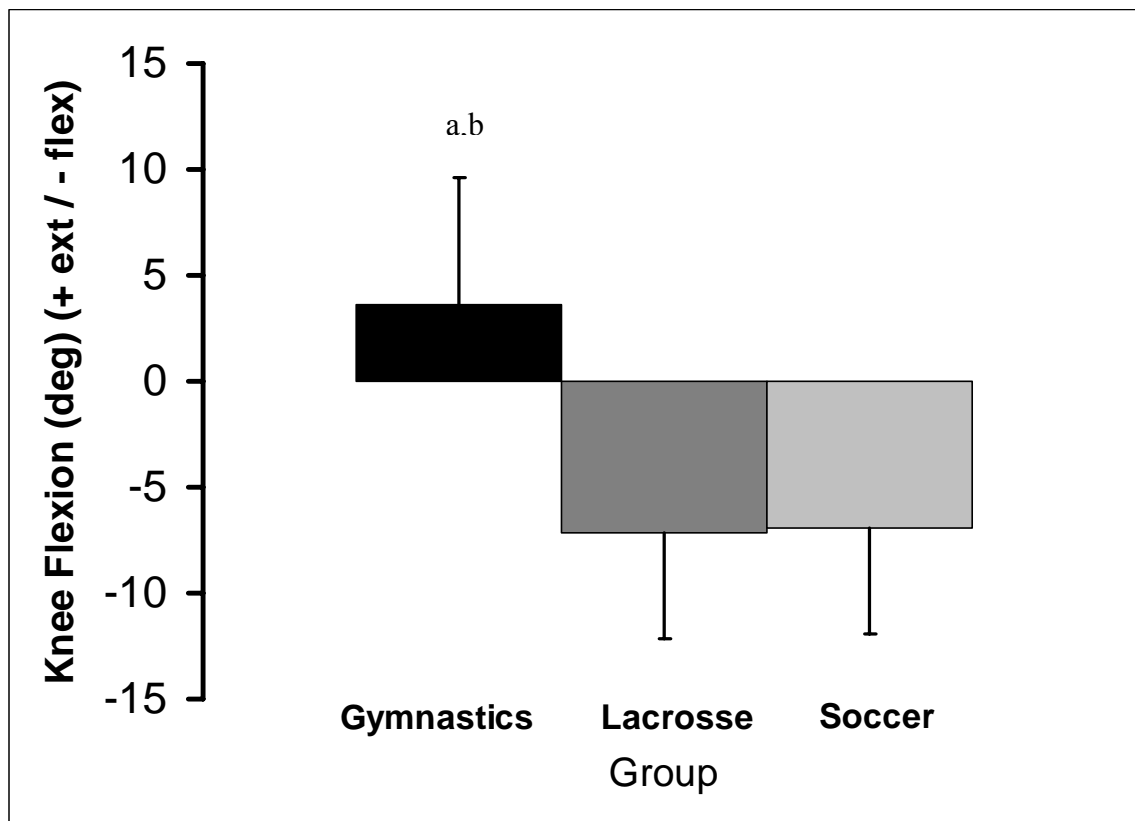Figure 20:

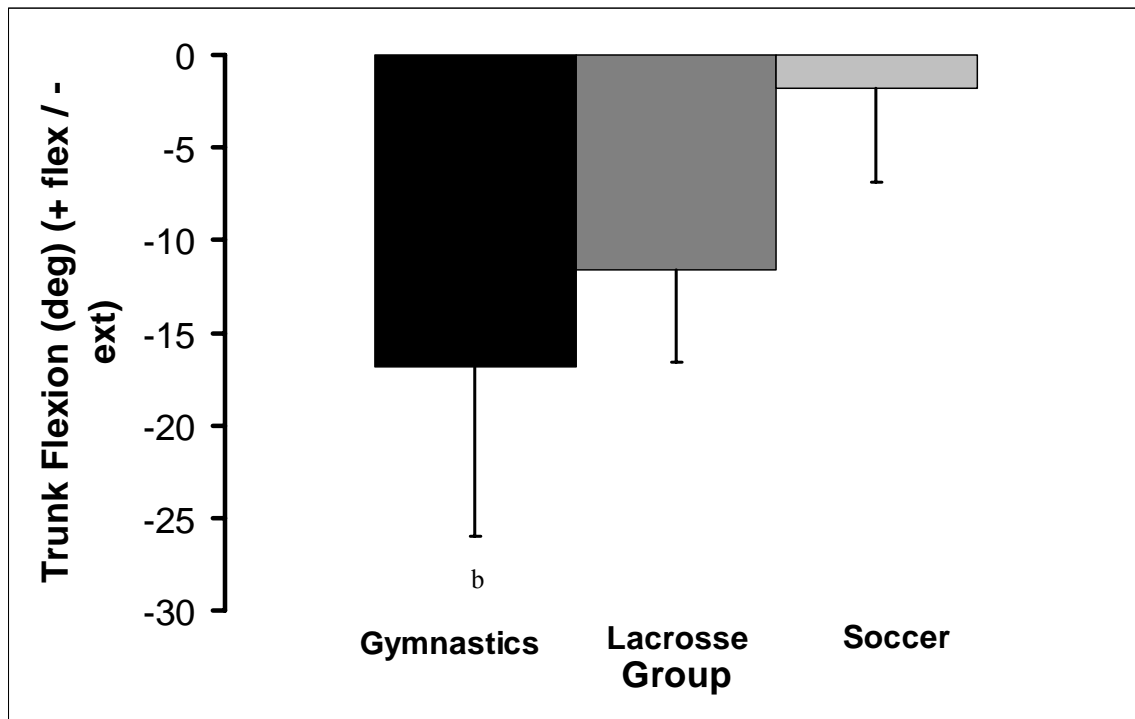Unanticipated Side-step Cutting Maneuver: Anterior Tibial Shear Force
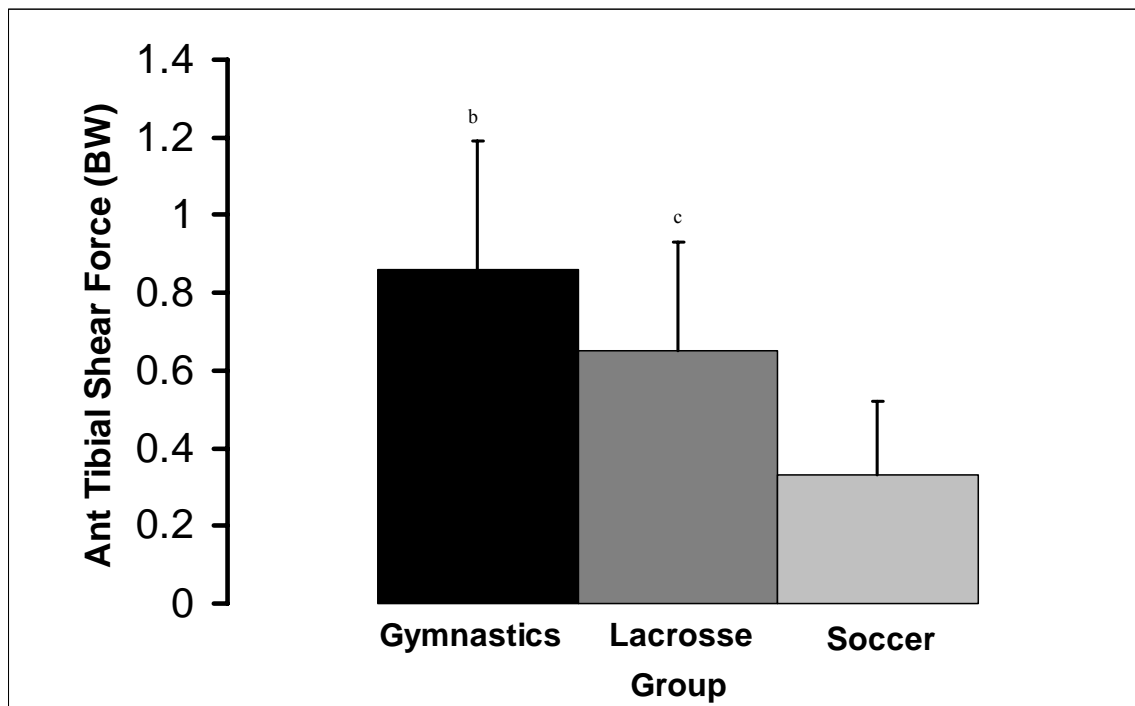
[b] Significantly different between Gymnastics and Soccer
[c] Significantly different between Lacrosse and Soccer

Figure 21:

Unanticipated Side-step Cutting Maneuver: Vertical Ground Reaction Force
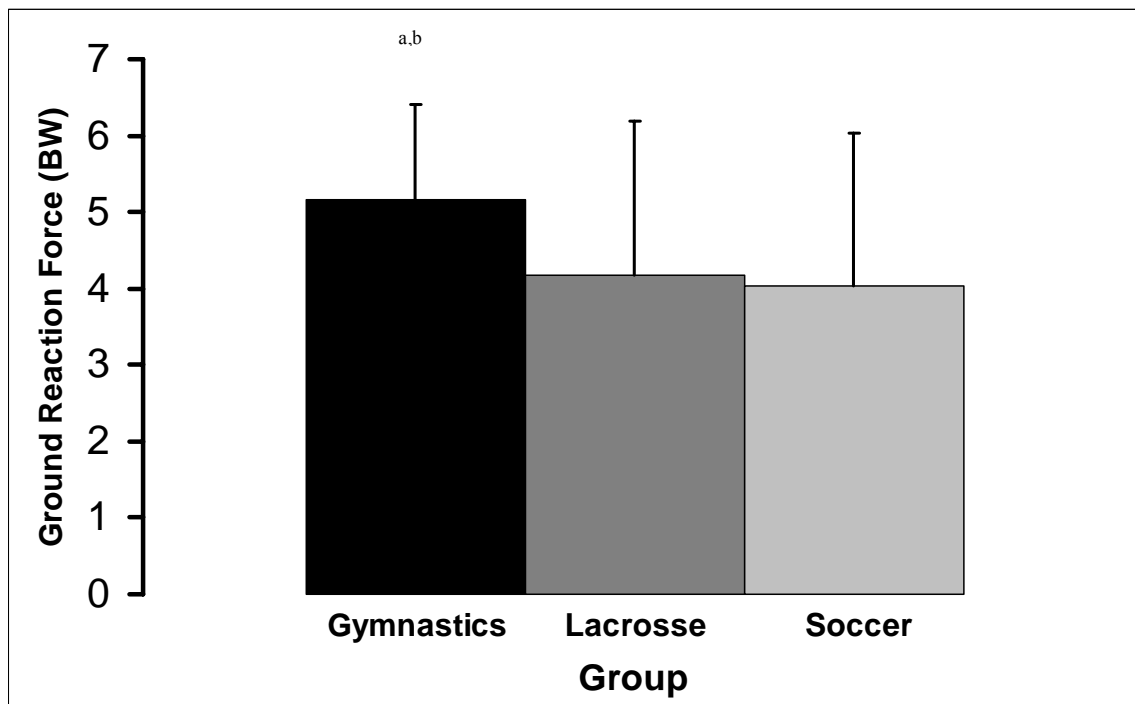
[a] Significantly different between Gymnastics and Lacrosse
[b] Significantly different between Gymnastics and Soccer

CHAPTER V

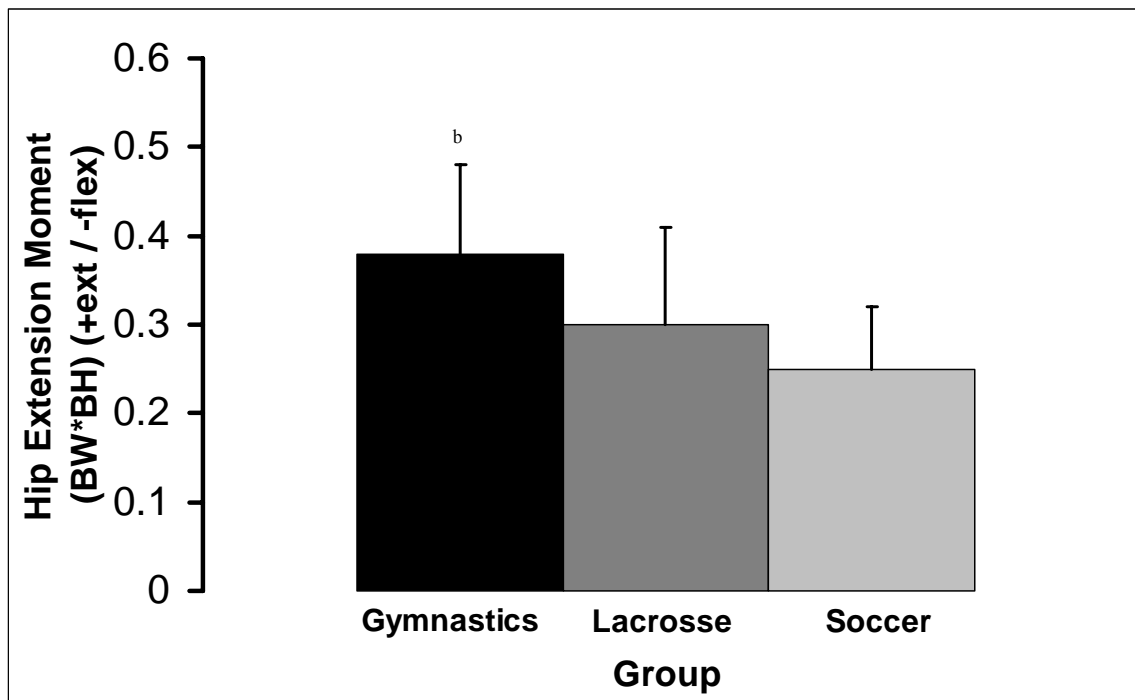DISCUSSION

The results of this study have been found to support the hypothesis that significant differences in kinematic, kinetic, and ground reaction force variables exist between Division I female athletes during a jump-landing, an anticipated side-step cut, and an unanticipated side-step cut maneuvers. With our current findings it was concluded that significant differences in movement patterns can be seen between different female athletes, not just between gender and sport matched athletes. Also, the outcome of the study indicates that sport-related differences occur at the knee, hip, and trunk during movement in collegiate female athletes. The observed differences in kinematic, kinetic, and ground reaction force data between female athletes may present new insight into the sports-related risk of non-contact ACL injury on different high-level female athletes.

Our study observed significant differences between groups in the unanticipated side-step cutting task only. Female gymnasts were found to have significantly less trunk flexion at initial contact than soccer athletes. Also, lacrosse exhibited significantly less trunk flexion during the landing phase when compared to soccer athletes. This more erect posture could be due to sports specific needs in each sport. Gymnasts land in an erect position in order to receive higher scores for what is considered proper body position at landing. During a lacrosse game, athletes have been observed to run in a more upright posture in order to keep

control of the ball in the net while looking for a teammate to pass the ball to. The lack of difference between groups for the jump-landing and anticipated side-step cutting task was more than likely due to preplanned movement strategies by the athletes. It has been found that when sports movements are anticipated by the athlete postural adjustments and reflex responses have been observed (Besier et al., 2003). These adjustments can lead to better body position during movement. Besier et al. (2001) compared males performing both an anticipated and unanticipated cutting maneuver and observed those unanticipated knees moments that were twice the magnitude of the anticipated condition.

Among the other kinematic variables, hip flexion was determined to be significantly less for gymnasts when compared to lacrosse and soccer athletes for both the anticipated side-step cutting and jump-landing maneuvers. During both the jump-landing and side-step cutting maneuvers, significantly less hip flexion at initial contact was observed in gymnasts when compared to the other two groups. But during the landing phases of all three tasks, the groups of female athletes presented with no difference in hip kinematics. The current data may indicate that hip flexion and adduction at initial contact is the area to investigate in order to identify hip kinetics as a significant factor in the prediction of risk for ACL injury. No differences were seen between groups regarding hip adduction during the three athletic maneuvers. Hip internal rotation was not examined in this study due to a low power calculation, but has been discussed as another possible risk factor predictor (Malinzak et al., 2001).

At the knee, our results illustrated similar differences in knee kinematics between Division I female athletes. Gymnasts consistently displayed significantly less knee flexion angle compared to lacrosse and soccer at initial contact. The difference in knee flexion angles

at initial contact were observed for all three athletic tasks. Although, no knee valgus angle differences were found between groups at initial contact or during the landing phase. With regard to the literature, the findings of this study may validate that greater knee valgus is inherent to all female athletes. Knee valgus may increase the risk in female athletes, but significant differences in knee flexion may identify potential higher risk groups. According to this theory, female gymnasts may be particularly susceptible to non-contact ACL injury due to significantly smaller knee flexion angles. However, gymnasts often land with on two feet which disperses the force at landing and most movements are anticipates or planned. This may explain why epidemiological studies have failed to note any significant differences in non-contact ACL injury in gymnastics. Further investigation is required into non-contact ACL injury rates and lower extremity movement patterns to fully understand the risk of injury associated with women's gymnastics.

Kinetic differences in this study existed between groups for each of the 3 tasks. During the jump-landing and unanticipated side-step cutting tasks, both female gymnasts and lacrosse athletes displayed significantly larger knee extension moments during the landing phase than soccer athletes. Gymnasts for the anticipated cutting tasks had a larger knee extension moment than both lacrosse and soccer. In regards to knee valgus moment, gymnasts displayed greater moments than both lacrosse and soccer during the jump-landing. Female gymnasts also had significantly larger knee valgus moments than lacrosse for the anticipated cutting task during the landing phase. During the unanticipated cutting task, no differences were found for knee valgus moment between groups. These results indicated that during unplanned movements female athletes tend to undergo the same increase in moments regardless of sport. But female lacrosse and soccer athletes may have more advantageous

pre-planned movement patterns during the jump-landing and anticipated cutting than gymnast. These movement patterns may also identify a greater risk for gymnasts than previously thought.

Significant differences have been observed in the anterior tibial shear force between groups. Throughout the three tasks of this study, gymnasts have exhibited significantly larger anterior tibial shear forces than female soccer athletes. No significant difference was discovered between lacrosse and gymnastic or lacrosse and soccer. Gymnasts during the landing phase displayed an anterior tibial shear force of almost a full body weight in the 3 tasks, indicating extremely larger forces acting on the knee in these athletes. Lacrosse athletes landed with an anterior tibial shear force of almost 90% body weight during the jump-landing maneuver. Further investigation of the landing phases and the moments that occur in this phase may provide additional insight into the potentially damaging forces acting on the ACL during athletic tasks.

During this study, gymnasts exhibited VGRF that were significantly higher in all three maneuvers. Gymnasts landed with an average of 4-5 times body weight for the maneuvers. Also, it should be noted that during jump-landing ground reaction force data was taken for only one (dominant) foot and that the true VGRF may be even larger. The jump-landing and unanticipated side-step cutting task displayed that gymnasts had significantly larger VGRF than both lacrosse and soccer. Gymnast also had a larger VGRF than soccer athletes during the anticipated side-step cutting. It has been discussed that gymnasts through their training may utilize these higher ground reaction forces in order to perform the necessary tumbling skills involved in the sport. Further comparison is needed between other

female collegiate sports to accurately state whether or not VGRF differ between athletic groups for select athletic tasks.

Clinical Significance

According to the findings of this study, female Division I gymnasts appear to be at the greatest risk for non-contact ACL injury. While current biomechanical and epidemiological research has stated that female soccer athletes are at the greatest risk, this may not be true. During the athletic task, female gymnast displayed significantly less knee flexion, hip flexion, and trunk flexion angles indicating a more erect posture at initial contact and during the landing phase. This more erect posture has been used by other researchers as a possible explanation of the increased risk of non-contact ACL injury in women. Gymnasts have also been observed in this study to have significantly greater knee extension moment, anterior tibial shear force, and vertical ground reaction force. These increased forces at the knee have been supported by many studies as potentially harmful to the ACL. When gymnasts performed both of the side-step cutting maneuvers, their ground reaction forces were approximately 5 times body weight as measure by the dominant foot on the force plate. The gymnasts not only land in a more erect posture, but with significantly more ground reaction forces to dissipate throughout the lower extremity. Further analysis of the muscular contribution in dissipating force is needed in gymnastics to understand the reason that non-contact ACL injuries are not currently known to be more prevalent in the sport.

During the unanticipated cutting maneuver, female lacrosse athletes demonstrated significantly less knee flexion and greater anterior tibial shear force in the landing phase compared to soccer athletes. Women's lacrosse has grown in popularity over the past decade

91

in the United States. As more females choose to participate in the sport, it is important for epidemiological studies to be employed by researchers. The results indicate that female lacrosse players are also landing in a more erect posture and with significantly greater anterior tibial shear force occurring at the knee in relation to soccer athletes. Once again, these finding indicate that other sports may have a potentially higher risk of non-contact ACL injury than soccer.

Throughout research we have observed significant difference in kinematic, kinetics, and ground reaction forces between male and females. Previous literature has discussed the movements and forces that have been proposed to be more harmful and therefore leading to greater risk of non-contact ACL injury in females. Epidemiological studies have also been used to determine the relative risk of a sport by exposure for different female athletes. Until now women's soccer has been viewed as a high-risk sport for non-contact ACL injury, with significantly greater injury rate than other females sports (Agel et al., 2005). Nonetheless, this study indicated that in a laboratory setting other female athletes (gymnastics and lacrosse) performing tasks known to cause non-contact ACL injury display movement patterns that are believed to place greater forces on the knee joint and ACL.

The differences observed in the study signal that further research needs to be conducted in the area of biomechanical analysis between different types of female athletes. In addition, there is a call for further epidemiological studies in sports other than just soccer and basketball, to understand the full scope of non-contact ACL injury risk in female athletes. In regards to potential ACL injury prevention training programs, this study has noted that not all sports display the same movement patterns. Further research is needed for each sport in order to determine the specific training needs of the sport.

Limitations

Some limitations of this study include the inability to recruit larger numbers of healthy athletes. The small group numbers were due in part to gymnastics and lacrosse athletes being excluded due to acute injury or previous history of an ACL repair on their dominant leg. Also, it is difficult to match skill level between sports due to the variation in the sport specific demands of each activity and quality of athletes recruited among the different teams. Our study only examined healthy subjects with no previous history of ACL injury to the dominant limb. Additionally, the healthy subjects that reach the collegiate level of competition without injury may have already developed movement patterns to reduce the chances of injury. No data was collected for the non-dominant limb, therefore variance between dominant and non-dominant limbs for the three maneuvers is unknown.

Conclusions

Previous literature has documented gender difference in kinematic, kinetics, and vertical ground reaction force. Gender specific intrinsic factors including joint laxity, muscular stabilization forces, and quadriceps angle have been discussed as some of the possible causes of variation in movement patterns between males and females. Females have displayed movement patterns believed to place them at greater risk for a non-contact ACL injury in sports like soccer. Our study attempted to remove the intrinsic variations between groups and focus on the effect different sports may have on female athletes. We found that according to previous findings in the literature, female gymnastic and lacrosse athletes' exhibit during testing movement patterns that may place them at a greater risk than female soccer athletes. Currently, additional epidemiological studies are required in order to

determine if higher non-contact ACL injury rates can be found in sports like gymnastics and

lacrosse when compared to female soccer athletes. Also, further research is needed to

validate the findings of this study among other female athletic groups (i.e. basketball) in

order to identify if other difference exist in other female sports.

Comparison of Lower Extremity Biomechanics in Division I Female Collegiate Gymnastics, Lacrosse, and Soccer Athletes

Christin Chamberlain, MA, ATC, Darin Padua, PhD, ATC, William Prentice, PhD, ATC, PT, Alexander Creighton, MD, ATC, Melanie McGrath, MS

From the Sports Medicine Research Laboratory at The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

Background: Studies have shown that females are more likely to tear their anterior cruciate ligament than males, in particular female soccer players. Currently, there are no biomechanical studies comparing female Division I athletes (gymnasts, lacrosse, and soccer) from different sports during jump-landing and side-step cutting maneuvers.
Hypothesis: Female soccer athletes will exhibit less trunk, hip, and knee flexion angles; than gymnastic and lacrosse athletes during the jump-landing, anticipated side-step cutting and unanticipated side-step cutting maneuvers. Also, female soccer athletes will display a greater knee extension moment, knee valgus moment, hip flexion-extension moment, anterior tibial shear, and vertical ground reaction force for the three maneuvers.
Study Design: Controlled laboratory study.
Methods: Eleven gymnastics, fifteen lacrosse, and twelve soccer collegiate athletes with no history of lower extremity injuries in the past month and no previous anterior cruciate ligament injury performed a jump-landing, and two types (anticipated and unanticipated) of side-step cutting maneuvers. Trunk, hip, and knee kinematics were collected on their dominant leg. Kinetic and vertical ground reaction forces were also recorded and analyzed.
Results: Females gymnasts demonstrated significantly less knee and hip flexion, and greater knee extension moment, hip flexion, moment, anterior tibial shear force, and vertical ground reaction forces.
Conclusion: The collegiate gymnast in this study performed the jump-landing and cutting maneuvers in such a way that predispose them to anterior cruciate ligament injury.
Clinical Relevance: No other study has compared different female collegiate athletes during jump-landing and side-step cutting maneuvers. Our results suggest that female soccer athletes may not be at the greater risk for a non-contact anterior cruciate ligament injury, when compared to other female athletes.

Cross gender studies have been utilized for a number of years in order to determine the factors associated with an increased risk of anterior cruciate ligament (ACL) injury. When compared to males participating in the same sports, female athletes are approximately 6 times more likely to experience an ACL injury (Arendt & Dick, 1995; Gray et al., 1985; Hutchinson & Ireland, 1995; Powell & Barber-Foss, 2000). A recent epidemiological study of the NCAA examined anterior cruciate ligament injuries in men's and women's basketball and soccer. The study utilized information gathered by the Injury Surveillance System (ISS) between the years of 1990 to 2002 (Agel, Arendt, & Bershadsky, 2005). During this time 682 ACL injuries occurred in basketball (514 women and 168 men) and 586 injuries in soccer (394 women and 192 men). For both sports, females sustained significantly more ACL injuries than males; more specifically female soccer players had the highest rate of ACL injuries. The research findings indicate that gender differences in ACL injury rates are sport dependent. Women's soccer athletes seem to be susceptible to ACL injuries, due in part to the unanticipated cutting maneuvers required in the sport.

Non-contact mechanisms for serious knee injury in women is three times more prevalent than in men (Gray et al., 1985; Griffin et al., 2000; Zelisko, Noble, & Porter, 1982). Studies have approximated that 70% of all ACL injuries in women's basketball and soccer occur during non-contact cutting and jumping activities (Arendt & Dick, 1995; Griffin et al., 2000). According to the current literature females participating in sports involving jump-landing and cutting maneuvers (i.e. soccer, basketball, gymnastics, and lacrosse) may be at greatest risk of sustaining an ACL injury.

Recent studies have supported the idea that female soccer athletes are at the highest risk of ACL injury. In a study by Agel et al. (2005), female soccer players sustained a total of

161 non-contact ACL injuries compared to 68 injuries for male soccer players. Also, the study found that female soccer athletes exhibited a significantly higher contact ACL injury rate compared to male soccer players and female basketball players. This recent epidemiological study has reinforced previous findings that women's soccer is the sport with the greatest risk of ACL injury (Agel et al., 2005; Arendt & Dick, 1995; Faude, Junge, Kindermann, & Dvorak, 2005; Hutchinson & Ireland, 1995; Powell & Barber-Foss, 2000).

Unlike soccer and basketball, in gymnastics the ACL injuries rates between male and female gymnasts have not significantly differed (Dixon & Fricker, 1993). The lack of a gender bias in ACL injury rates in female gymnasts may suggest interesting information about how important the mechanism of injury is in relation to sport type in female athletes. Anterior cruciate ligament injuries are commonly associated with a twist at landing or hyperextension in elite gymnasts, which differs from the mechanisms of injury in most non-contact ACL injuries (Dixon & Fricker, 1993). The ankle and foot incurring the most injuries was consistent with previous reports for women's gymnastics (Dixon & Fricker, 1993; Lindner & Caine, 1990). These studies have failed to note any significant ACL injury rates in women's gymnastics.

Women's Lacrosse is one of the fastest growing sports in the country; over 70 collegiate teams were added between 1995 and 2001. In a study involving 19 collegiate female lacrosse teams over two seasons, a total of 104 injuries occurred and of these injuries 47.7% of all injuries occurred to the head and face and only 13% at the knee (Matz & Nibbelink, 2004). During the study, only 2 ACL reconstructions were performed during the 2 seasons. Once again, studies have failed to note significantly higher ACL injury rates in female lacrosse athletes (Hinton, Lincoln, Almquist, Douoguih, & Sharma, 2005; Matz &

Nibbelink, 2004). This lower injury rate in the literature may signify some specific movement strategies or training differences between gymnastics, lacrosse, and soccer, sports that involve jump-landing and side-step cutting maneuvers.

Epidemiological studies have lead to other research into the identification of risk factors that are responsible for higher ACL injury rates in female athletes (Dufek & Bates, 1991; Hewett, 2000; Kolt & Kirkby, 1999; Lephart, Ferris, & Fu, 2002; McLean, Huang, & van den Bogert, 2005; McLean, Neal, Myers, & Walters, 1999; Shelbourne, Davis, & Klootwyk, 1998). Many studies have examined the contribution of both intrinsic and extrinsic factors. Intrinsic factors consist of anatomical or hormonal differences that may influence the risk of knee injury. Extrinsic factors include biomechanical and neurological factors (Griffin et al., 2000; Hewett, 2000; Hutchinson & Ireland, 1995). Numerous differences in intrinsic and extrinsic factors have been observed when comparing males and females. For example, female athletes have been found to have an increased Q-angle, which may be associated to an increase valgus alignment at the knee (Hutchinson & Ireland, 1995). The greater valgus alignment may increase strain on the ACL, MCL, and medial joint capsule. Also, a study that compared the intercondylar notch width of men and women with intact anterior cruciate ligaments, unilateral ACL tears, and bilateral ACL tears (Shelbourne et al., 1998). Researchers found that femoral intercondylar notch width was wider in men than women and that a narrower notch width was observed in participants who sustained an ACL tear when compared to the control group.

These intrinsic differences between genders may partially explain the increase in ACL injuries of female athletes. But, these factors cannot adequately explain the reason for higher rates of non-contact ACL injury in female basketball and soccer (Agel et al., 2005;

Arendt & Dick, 1995). While intrinsic factors may predispose athletes to injury, research has not overlooked the role of dynamic movement strategies. Studies have focused on the functional effect of extrinsic factors through biomechanical analysis of the lower extremity, in particular the knee. These research projects examine the influence of the gender on biomechanics of the lower extremity (Arendt & Dick, 1995; Dufek & Bates, 1991; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Powell & Barber-Foss, 2000; Zelisko et al., 1982)). Cross-gender biomechanical analysis research has investigated the biomechanical difference between males and females during cutting and jumping maneuvers to better understand the observed gender differences in ACL injury rates. Previous research focused on biomechanical factors such as leg stiffness, joint kinematics and kinetics, ground reaction forces, and muscle activity. Leg stiffness during side-cutting and jump-landing tasks has been found to be significantly larger in male athletes (Chappell, Yu, Kirkendall, & Garrett, 2002; Granata, Padua, & Wilson, 2002; Granata, Wilson, & Padua, 2002; Lephart, Ferris, Riemann et al., 2002). Also, males were found to have a greater degree of knee flexion at the time of landing. Vertical ground reaction forces were similar between genders once normalized for body mass and it has been theorized that adjustments in stiffness are made at different joints to normalize these forces. By identifying biomechanical differences, researchers are becoming more educated and aware of the potential gender-specific factors that may put female athletes at greater risk for injury in sports like soccer.

Another important part of biomechanical analysis is to create "game-like" situations to increase the validity of findings to sports participation. Athletes are often required to make spontaneous, unplanned movements to elude opposing players. When sports movements are

anticipated by the athlete postural adjustments and reflex responses have been observed, leading to better body position (Besier, Lloyd, & Ackland, 2003). Besier et al. (2001) compared males performing both an anticipated and unanticipated cutting maneuver. The study observed unanticipated knee moments that were twice the magnitude of the anticipated condition. Besier and others believe that analysis of unanticipated cutting maneuvers closely simulates the motion and torque in the lower extremity during sports activities. The findings reinforce the use of unanticipated side-cutting maneuvers during laboratory testing to mimic conditions seen during activity.

Researchers are now charged with the task of determining if differences may also exist in the sports-specific movement strategies and type of training that female athletes undergo during athletic participation in various sports. These movement strategies may be an important factor in ACL injury rates. Hence, it is important for research to not only examine the biomechanical difference between male and female athletes, but the difference in dynamic movements between female athletes participating in a variety of sports. By comparing movement patterns between high risk sports (soccer) and sports with lower incidents of ACL injuries (gymnastics and lacrosse), research may identify the specific biomechanical risk factors leading to ACL injuries in females.

The purpose of the study is to prospectively study the affect of movement strategies used by female collegiate soccer, gymnasts, and lacrosse athletes on trunk flexion, lower extremity joint kinematics, and ground reaction force data when performing a jump-landing, an unanticipated side-step cutting, and anticipated side-step cutting maneuver.

100

MATERIALS AND METHODS

Subjects

Subjects consisted of 38 Division I female collegiate athletes [age= 19.97yrs (1.668), height= 165.32cm (8.18), weight= 64.86kg (8.17)] for a total of 38 participants. The groups were composed of 11 gymnasts, 15 lacrosse, and 12 soccer athletes. An apriori power analysis (minimum of 0.80) was performed for all study variables. All subjects filled out a pre-participation questionnaire for demographics and to determine any history of lower extremity or back injury. Subjects were excluded if they had suffered a lower extremity injury in the past 3 months that limited activity for more than three days. Also, subjects with a previous history of lower extremity surgery were excluded if the surgery was within the past year and they are participating in a formal rehabilitation program. Prior to testing, all subjects were required to read and sign an informed consent form, which was be approved by the Institutional Review Board of the University of North Carolina at Chapel Hill's Medical School.

Procedures

Subjects participating in this study reported to the Sports Medicine Research Laboratory at the University of North Carolina at Chapel Hill for one testing session lasting approximately one hour. Each subject was instructed to wear running shoes, athletic shorts or spandex, and a t-shirt during the testing session. When the subjects arrived at the laboratory, the testing procedures were explained and informed consent form was then signed. A questionnaire was completed to insure compliance with the inclusion criteria. The subject's anthropomorphic data was collected including age (years), height (cm), mass (kg), and leg

dominance. Kinematic and kinetic testing was performed on the subject's dominant leg, defined as the leg they would select to kick a soccer ball for maximal distance.

Subjects performed a five-minute warm up on a stationary bike at 50% perceived maximal exertion and a standardized lower extremity stretching routine that includes stretches for the gluteal, hamstring, quadriceps, and gastroc-soleus muscle groups. Computerized random selection was used to determine if subjects would perform the side-cutting first or the jump-landing maneuver. During the side-step cutting tasks, each subject performed the unanticipated cutting before the anticipated cutting. The unanticipated side-cuts were also randomized, using a cross-over cut as the alternative task. Data was collected for the cross-over cut, but it was not analyzed for this study. The subjects performed 2-3 practice trials of both the anticipated and unanticipated side-step cutting and jump-landing maneuver before testing.

Side-Step Cutting

The side-step cutting maneuver involved a jump-and-cut off a 12-inch high platform. The take-off platform was set at a horizontal distance equal to 75% of the subject's body height from the front of the force-plate. The direction of the cutting maneuver was randomized and cued by a laser light system. The light was cued when subjects broke the laser beam, placed 40% the distance from the front of the box to the force plate (Sell et al., 2005). Two lights placed on a board indicated whether the subjects performed a side-step cutting or a cross-over cutting maneuver. With the use of randomization, we hoped to create a true unanticipated response by the subject, allowing for a more "game-like" situation and movement patterns. During the cutting maneuvers, the subjects were instructed to plant the

foot of their dominant leg on the force plate and cut 35-55° toward either their contralateral

or the ipsilateral side, depending upon the light direction. The subjects were instructed to

point the foot of the planted (dominant) leg forward before making a cut. For example, an

athlete is right leg dominant and the light system indicated a cut to the left; the athlete

planted the right foot on the force plate and cut to the left (contralateral) side. If the light

system indicated a cut to the right, the athlete planted with the right (dominant) foot on the

plate and perform a cross-over cut to the right (ipsilateral). To insure that the cuts are made

within the appropriate angle range, tape was placed on the ground to indicate 35-55° from the

center of the force plate. These values were chosen to reflect the angles at which side-step

cutting is typically performed during game play (McLean et al., 1999).

Subjects performed twenty-four trials of the anticipated and unanticipated cutting

maneuvers, eight trials of each maneuver (anticipated side-step cut, unanticipated side-step

cut, and cross-over cut). Subjects were given 30 seconds of rest between each trial to

minimize the risk of fatigue. Kinematic data was only collected on the dominant leg during

the side-step and cross-over cutting maneuvers. The three most consistent trials were

averaged and used during data analysis. The trials used in data reduction were determined by

successful initial foot contact following the cutting action falling within the prescribed range.

Jump-landing

The jump-landing maneuver consisted of jumping off a 12-inch high platform onto a

force plate with dominant foot and the non-dominant foot off the force-plate. The take-off

platform was set at a horizontal distance equal to 50% of the subject's body height from the

front edge of a force-plate. Each subject was instructed to jump straight forward off the 12-

inch platform and minimize vertical motion. The subjects were then asked to land with the

foot of the dominant leg on the force-plate and the foot of the non-dominant leg off of the

force-plate. After landing the subjects were instructed perform a vertical jump for maximum

height, limiting horizontal motion and landing with the dominant foot on the force-plate and

the non-dominant foot off of the force-plate. Prior to testing subjects were allowed to

perform 2-3 practice trails to familiarize themselves with the jump-landing maneuver. During

testing the subjects performed 8 trials with 30 seconds of rest time between trials, to

minimize the risk of fatigue. Trials in which the subject fails to land with the foot of the

dominant leg on the force plate and the foot of the non-dominant foot off the force plate were

removed and a new trial was performed. The 3 most consistent trials were used for data

analysis.

Data Collection

A Flock of Birds® (Ascension Technologies, Inc., Burlington, VT) electromagnetic

motion analysis system controlled by Motion Monitor® (Innovative Sports Training, Inc.

Chicago, IL) data acquisition computer software was used to process trunk, hip, and knee

kinematics at a sampling rate of 144 Hz. The system employs a DC transmitter with three

orthogonal coils to generate a magnetic field. Also, the system incorporates four sensor

receivers that record the electromagnetic flux in the field generated by the transmitter and

conveys the signals to a computer via hard wiring. The transmitter was affixed to a stationary

stand, .914 meters in height, to establish the global reference system. Kinematic data was

filtered using a 4th order zero phase lag Butterworth low-pass filter at 14.5 Hz (Bing Yu,

Gabriel, Noble, & An, 1999). Four sensors recorded the electromagnetic changes in the field

generated by the transmitter and transferred the signals to a recording computer via hard wiring. Sensor data were used for the calculation of position and orientation of the trunk, thigh, and shank. The electromagnetic tracking system was calibrated prior to data collection.

Electromagnetic tracking sensors were placed on each subject over the spinous process of the T1 vertebrae, the apex of the sacrum, midpoint of the lateral thigh, and shank of the tibia. After the electromagnetic sensors were attached, the subjects stood in a neutral posture with their arms relaxed by their side. Once the electromagnetic sensors were attached, the subjects were asked to stand in a neutral posture with their arms relaxed at their sides. The following bony landmarks were then digitized, in the following order, using a mobile electromagnetic sensor attached to a stylus: xiphoid process, spinous process of T12, medial femoral condyle, lateral femoral condyle, medial malleolus, lateral malleolus, left anterior superior iliac spine, and right anterior superior iliac spine. Digitization of bony landmarks served to define the segment end-points and joint centers of the lower extremity segments. The ankle joint center is located at the midpoint between the medial and lateral malleoli. Knee joint center is located at the midpoint between the medial and lateral femoral condyles. The hip joint center will be determined by the Bell method (Bell, Pedersen, & Brand, 1990). This method consists of estimating the hip joint center using the left and right anterior superior iliac spine as landmarks to mathematically estimate the hip joint center. Once the subject was digitized, they were instructed to stand relaxed with their arms at their side allowing the computer to calibrate the subject's neutral position. A standing trial was recorded for data comparison. The local coordinate systems were aligned with the global

coordinate system. Kinematic and kinetic data was collected as the subject performed a standardized anticipated and unanticipated side-step cutting and a jump-landing maneuver.

To measure peak ground reaction forces (GRF), subjects performed a jump-landing, and an anticipated and unanticipated cutting maneuver on a force platform (Bertec 4060-10, Chicago, IL), sampling at 1440 Hz.

Data Reduction

The kinematic data from three trials of the side-cutting and jump-landing maneuver were averaged together for each of the lower extremity variables. The lower extremity variables include knee flexion, knee valgus/varus, hip flexion, hip abduction/ adduction, and trunk flexion angles at initial contact and at peak ground reaction force. Three-dimensional trunk, hip, and knee angles were determined at initial ground contact and the landing phase of the side-step cutting and jump-landing maneuvers. Initial ground contact (IC) will be defined as the time when vertical ground reaction force exceeds 5 N as the subject lands on the force-plate from the 12-inch high platform. During the side-step cutting maneuver, the kinematic variables were also examined at maximum knee valgus angle for the side-step cutting maneuvers. Kinetic variables included knee extension moment, knee valgus moment, hip flexion-extension moment, and anterior tibial shear force. Vertical ground reaction force was taken for both side-step cutting and jump-landing maneuvers.

During the three maneuvers, kinematic variables were measured at initial contact and landing phase. To estimate the net joint reaction forces and moments during side-step cutting and jump-landing maneuvers, the dominant leg was modeled as a three-dimensional system of four rigid segments that include the shank, thigh, pelvis, and trunk. Knee joint moments

and reaction forces were reported in the coordinate system of the shank relative to the knee joint. Also, the kinetic variables included peak anterior tibial shear forces, knee valgus moment, knee extension moment, and hip flexion-extension moment. These variables were reduced for the landing phase of the jump-landing. The vertical ground reaction force associated with the impact between the subject and the force-plate as they land from the 12-inch high platform was used to characterize the landing phase. The landing phase was defined as the time period from initial ground contact until the first local minima of the vertical ground reaction force during the jump-landing maneuver. Peak VGRF and the magnitude of the knee joint moments were normalized to the subject's body weight (N) and height (m). Raw data collected from the electromagnetic tracking system was converted to rotations with respect to the anatomical coordinate axes, as defined previously. The average across the three separate trials was used to calculate each of the kinematic and kinetic variables associated with the side-step cutting and jump-landing maneuver. Data was imported into Matlab software version 7.0.4.365 for data reduction and analysis.

Data Analysis

Kinematic and kinetic data that was collected during the anticipated and unanticipated side-step cutting and jump-landing maneuvers was analyzed using separate one-way analysis of variance (ANOVA) with sport type as the between subject factor. A mixed-model ANOVA was used to analyze differences within the unanticipated vs. anticipated trials and between the subject groups. Statistical significance was set with the alpha level at $\alpha < 0.05$. Tukey post-hoc was performed for all statistically significant findings. Statistical analyses were used to analyze data with SPSS software version 13.0.

RESULTS

Thirty-eight healthy varsity collegiate athletes (11 gymnastics, 15 lacrosse, and 12 soccer) with no history of anterior cruciate ligament injury or lower extremity injury volunteered to participate in this study. Each subject had knee, hip, and trunk kinematic data collected while completing a jump-landing task and two (anticipated and unanticipated) side-step cutting maneuvers as described in chapter 3. Subject characteristics are listed in Table 1. Data analyses revealed that gymnast were significantly smaller in height than both lacrosse (P=0.001) and soccer (P<0.001) athletes. Gymnasts also had significantly less body mass than lacrosse (P=0.001) and soccer (P<0.001) athletes.

Jump-landing Maneuver

Initial Ground Contact: There was a significant group main effect for the MANOVA [F $(_{16, 58})$ =2.25, P=0.013]. One-way ANOVA results indicated that there were significant differences between groups for knee flexion [F $(_{2, 35})$ =18.41, P <0.001] and hip flexion [F $(_{2, 35})$ =5.09, P= 0.011] at initial contact. Post hoc analyses of the significant group differences for knee flexion at initial contact revealed that gymnasts demonstrated significantly less knee flexion than both lacrosse (P<0.001) and soccer (P<0.001). Gymnasts also displayed significantly less hip flexion than lacrosse (P=0.016) and soccer (P=0.031). There were no significant differences in knee valgus, hip adduction, and trunk flexion between groups (P>.0.05).

Landing Phase: During the landing phase there was no significant group main effect observed for the MANOVA [F $(_{2, 35})$=1.27, P=0.236]. One-way ANOVA revealed no significant difference between groups for knee flexion, knee valgus, hip flexion, and hip adduction. Also, no differences were found for trunk flexion during the landing phase.

Kinetic Data: Results of the MANOVA indicated a significant group main effect [$F_{(12, 62)}$ =2.20, P=0.022]. The one-way ANOVA findings demonstrated significant differences between groups for knee extension moment [$F_{(2, 35)}$ =8.97, P=0.001], knee valgus moment [$F_{(2, 35)}$ =6.43, P=0.004], and hip flexion moment [$F_{(2, 35)}$ =7.36, P=0.002] during the landing phase. Also, there were significant difference found for the anterior tibial shear force [$F_{(2, 35)}$ =3.99, P=0.027] and vertical ground reaction force [$F_{(2, 35)}$ = 10.22, P=0.001].

Post hoc analysis of the significant group differences for knee extension moment revealed that gymnasts exhibit a significantly greater knee extension moment than soccer athletes (P=0.001). Lacrosse athletes also displayed a significantly larger knee extension moment than soccer (P=0.011), but did not significantly differ from gymnasts. The gymnasts displayed significantly larger knee valgus moment than both lacrosse (P=0.046) and soccer (P=0.003). Hip flexion moment was found to be significantly larger in gymnasts when compared to soccer (P=0.002). Peak anterior tibial shear force in gymnasts was also shown to be significantly larger than in soccer athletes (P=0.003). Vertical ground reaction force was also significant larger for gymnasts in comparison to both lacrosse (P=0.001) and soccer (P=0.002) athletes.

Summary

For the jump-landing maneuver, gymnasts exhibit significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast had significantly larger knee extension moment and anterior tibial shear force than soccer athletes. Lacrosse had a significantly larger knee extension moment than soccer, but not gymnastics. No significant differences were found for the following variables at initial contact: knee valgus, hip adduction, and trunk flexion angles. The landing phase showed no significant values for any

of the test joint angles. Also, for hip extension moment there were no significant findings. Tables 2 and 3 summarize initial ground contact angles and landing phase joint angles for all the tested joint motions during the jump-landing tasks. Table 4 illustrates the mean and standard deviation for the joint moments, anterior tibial shear force, and vertical ground reaction force during the landing phase.

Anticipated Side-step Cutting Maneuver

Initial Ground Contact: During initial ground contact, there was a significant group main effect for the MANOVA [F $_{(16, 58)}$ =1.936, P=0.035]. ANOVA results from the one-way ANOVA indicated that there were significant differences between groups for knee flexion [F $_{(2, 35)}$ =7.86, P=0.002] and hip flexion [F $_{(2, 35)}$ =6.64, P=0.004] at initial ground contact. Post hoc analyses of the significant group differences for knee flexion displayed that gymnasts had significantly less knee flexion than lacrosse (P=0.003) and soccer (P=0.004) athletes at initial ground contact. Also, gymnasts exhibited significantly less hip flexion than both lacrosse (P=0.041) and soccer (P=0.003) athletes. There were no significant differences in knee valgus, hip adduction, and trunk flexion angle between groups (P>0.05).

Landing Phase: There was no significant group main effect for the MANOVA [F $_{(24, 50)}$ =1.23, P=0.264, 1-β=0.778]. The one-way ANOVA results indicated that there were no significant differences between groups for knee flexion, knee valgus, hip flexion, hip adduction, or trunk flexion.

Kinetic Data: A significant group main effect was seen during the landing phase for the joint moment data using the MANOVA [F $_{(16, 58)}$ =2.70, P=0.003]. Using a one-way ANOVA, the results indicated that there were significant differences between groups for

knee extension moment (P=0.001) and knee valgus moment (P=0.031). There were also significant differences in hip flexion (P=0.050) and extension (P=0.044) moments. Post hoc analyses of the significant group differences at knee extension moment revealed that gymnasts have a significantly larger knee extension moment during the landing phase than both lacrosse (P=0.003) and soccer (P=0.000) athletes. Also, gymnasts displayed significantly greater knee valgus moment than lacrosse (P=0.024) athletes. For hip flexion moment during landing phase, gymnasts exhibited a greater moment than lacrosse (P=0.039) athletes. Gymnast displayed a greater hip extension moment than soccer (P=0.037) athletes during the anticipated side-step cutting task. A significant group difference for hip adduction with post hoc analyses revealed that lacrosse displayed a significantly greater hip adduction moment than soccer (P=0.034) athletes.

A significant group main effect for the MANOVA [F $_{(8, 66)}$ =2.12, P=0.046] was observed for anterior tibial shear force and vertical ground reaction force during the landing phase. A one-way ANOVA analysis revealed that there were significant differences between group for both anterior tibial shear [F $_{(2, 35)}$ =6.54, P=0.004] and vertical ground reaction [F $_{(2, 35)}$ =3.34, P=0.047] forces. Post hoc analyses of significant group differences for anterior tibial shear forces during the landing phase indicated that gymnasts exhibited significantly more anterior tibial shear force than soccer (P=0.003) athletes. Also, gymnasts displayed significantly more vertical ground reaction force than soccer (P=0.040) athletes during the landing phase.

Summary

During the anticipated side-step cutting maneuver, gymnasts exhibit significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast had significantly larger

knee extension moment than lacrosse and soccer athletes. Also, gymnast had significantly

larger hip extension moments, anterior tibial shear forces, and vertical ground reaction forces

than soccer athletes. Lacrosse had a significantly smaller knee valgus and hip flexion

moment than gymnasts. No significant differences were found for the following variables at

initial contact: knee valgus, hip adduction, and trunk flexion angles. The landing phase

showed no significant values for any of the test joint angles. Table 5 and 6 summarizes joint

angels at initial ground contact and the landing phase during the anticipated side-step cutting

task. A summary of means and standard deviations for the kinetic data can be found in Table

7.

Unanticipated Side-step Cutting Maneuver

Initial Ground Contact: There was a significant group main effect for the MANOVA

[$F_{(16, 58)}$ =2.31, P=0.010]. One-way AVONA analysis of the variables between groups

indicated significant differences at knee flexion [$F_{(2, 35)}$ =8.85, P=0.001] and trunk flexion [$F_{(2, 35)}$ =5.98, P=0.006] with reference to the world axis during the initial ground contact. After

a post hoc analysis, gymnasts demonstrated significantly less knee flexion than both lacrosse

(P=0.002) and soccer (P=0.004) at initial contact. Also, gymnast had significantly less trunk

flexion that soccer athletes (P=0.004).

Landing Phase: The MANOVA [$F_{(24, 50)}$ =1.33, P=0.195, 1-β=0.82] discovered no

significant group main effect for the kinematic variables. However, the one-way ANOVA

results indicated a significant difference in trunk flexion (P=0.001) during the landing phase.

Post hoc analysis found that gymnasts exhibit significantly less trunk flexion during the

landing phase than soccer athletes (P=0.001). Lacrosse also displayed significantly less trunk

flexion than soccer (P=0.026), but no significant difference was found between lacrosse and gymnastics.

Kinetic Data: There was no significant group main effect for the MANOVA $F_{(24, 50)}$ =1.64, P=0.070, 1-β=0.910]. Yet, the one-way ANOVA revealed a significant difference in knee extension moment (P=0.001), hip flexion moment (P=0.010), and hip extension moment (P=0.008). The post hoc analyses of the significant group differences for knee extension moment revealed gymnastic displayed a significantly larger moment than soccer (P=0.001). Also, lacrosse demonstrated larger knee extension moments than soccer (P=0.028) athletes. For hip flexion moment, gymnasts displayed significantly greater difference than lacrosse (P=0.023) and soccer (P=0.15). Gymnasts exhibited a significantly greater hip extension moment than soccer (P=0.006), but not lacrosse.

There was a significant group main effect for the MANOVA F $_{(8, 66)}$ =3.38, P=0.003]. One-way ANOVA for anterior tibial shear force F $_{(2, 35)}$ =11.18, P<0.001] and vertical ground reaction force [F $_{(2, 35)}$ =5.176, P=0.011] during the landing phase revealed significant group difference for both variables. Post hoc analyses identified that gymnasts have a significantly greater anterior tibial shear force than soccer (P<0.001). Lacrosse also had a significantly larger anterior tibial shear force than soccer (P=0.011) athletes. Gymnasts furthermore have significantly larger vertical ground reaction forces than both lacrosse (P=0.029) and soccer (P=0.015).

Table 8 and 9 display the kinematic data at initial contact and the landing phase for the anticipated side-step cutting maneuver. Table 10 summarizes the means and standard deviations for the kinetic data and ground reaction forces during the unanticipated side-step cutting maneuver.

Summary

During the unanticipated side-step cutting maneuver, gymnasts exhibit significantly less knee and hip flexion than both lacrosse and soccer athletes. Gymnast had significantly less trunk flexion than soccer athletes. The landing phase showed significantly less trunk flexion in gymnast compared to soccer athletes. Lacrosse athletes also had significantly less trunk flexion during the landing phase compared to soccer. A larger knee extension moment than lacrosse and soccer athletes. Gymnasts displayed significantly larger hip flexion moments and vertical ground reaction forces compared to lacrosse and soccer athletes. Also, gymnast had significantly larger hip extension moments, hip extension, and anterior tibial shear forces than soccer athletes. Lacrosse had a significantly smaller knee valgus and hip flexion moment than gymnasts. No significant differences were found for the following variables at initial contact: knee valgus, hip flexion, and hip adduction. Knee valgus moment was not significant between groups.

DISSCUSION

The results of this study have been found to support the hypothesis that there are significant differences in kinematic, kinetic, and ground reaction force variables between Division I female athletes during a jump-landing, an anticipated side-step cut maneuver, and an unanticipated side-step cut maneuvers. With our current findings it was concluded that significant differences in movement patterns can be seen between different female athletes, not just between gender and sport matched athletes. Also, the outcome of the study indicates that sport-related differences occur at the knee, hip, and trunk during movement in collegiate female athletes. The observed differences in kinematic, kinetic, and ground reaction force

114

data between female athletes may present new insight into the sports-related risk of non-contact ACL injury on different high-level female athletes

Our study observed significant differences between groups in the unanticipated side-step cutting task only. Female gymnasts were found to have significantly less trunk flexion at initial contact than soccer athletes. Also, lacrosse exhibited significantly less trunk flexion during the landing phase when compared to soccer athletes. This more erect posture could be due to sports specific needs in each sport. Gymnasts attempt to land in an erect posture to receive higher scores for what is considered proper body position at landing. During a lacrosse game, athletes have been observed to run in a more upright posture in order to keep control of the ball in the net while looking for a teammate to pass the ball to. The lack of difference between groups for the jump-landing and anticipated side-step cutting task was more than likely due to preplanned movement strategies by the athletes. It has been found that when sports movements are anticipated by the athlete postural adjustments and reflex responses have been observed (Besier et al., 2003). These adjustments can lead to better body position during movement. Besier et al. (2001) compared males performing both an anticipated and unanticipated cutting maneuver and observed those unanticipated knees moments that were twice the magnitude of the anticipated condition.

Among the other kinematic variables hip flexion was determined to be significant less for gymnasts when compared to lacrosse and soccer athletes for both the anticipated side-step cutting and jump-landing maneuvers. During both the jump-landing and side-step cutting maneuvers, significantly less hip flexion at initial contact was observed in gymnasts when compared to the other two groups. But during the landing phases of all three tasks, the groups of female athletes presented with no difference in hip kinematics. The current data may

indicate that hip flexion and adduction at initial contact is the area to investigate in order to investigate hip kinetics as a significant factor in the prediction of risk for ACL injury. No differences were seen between groups regarding hip adduction during the three athletic maneuvers. Hip internal rotation was not examined in this study due to a low power calculation, but has been discussed as another possible risk factor predictor (Malinzak et al., 2001).

At the knee, our results illustrated that gymnasts consistently displayed significantly less knee flexion angle compared to lacrosse and soccer at initial contact. The difference in knee flexion angles at initial contact were observed for all three athletic tasks. Although, no knee valgus angle differences were found between groups at initial contact or during the landing phase. With regard to the literature, the findings of this study may validate that greater knee valgus is inherent to all female athletes. Knee valgus may increase the risk in female athletes, but significant differences in knee flexion may identify potential higher risk groups. According to this theory, female gymnasts may be particularly susceptible to non-contact ACL injury due to significantly smaller knee flexion angles. But, epidemiological studies have failed to note any significant differences in non-contact ACL injury in gymnastics. Further investigation is required into non-contact ACL injury rates and lower extremity movement patterns to full understand the risk of injury associated with women's gymnastics.

Kinetic differences in this study existed between groups for each of the 3 tasks. During the jump-landing and unanticipated side-step cutting tasks, both female gymnasts and lacrosse athletes displayed significantly larger knee extension moments during the landing phase than soccer athletes. Gymnasts for the anticipated cutting tasks had a larger knee

extension moment than both lacrosse and soccer. In regards to knee valgus moment, gymnasts displayed greater moments than both lacrosse and soccer during the jump-landing. Female gymnasts also had significantly larger knee valgus moments than lacrosse for the anticipated cutting task during the landing phase. During the unanticipated cutting task, no differences were found for knee valgus moment between groups. These results indicated that during unplanned movements female athletes tend to undergo the same increase moments regardless of sport. But female lacrosse and soccer athletes may have more advantageous pre-planned movement patterns during the jump-landing and anticipated cutting than gymnast. These movement patterns may also identify a greater risk for gymnasts than previously thought.

Significant differences have been observed in the anterior tibial shear force between groups. Throughout the three tasks of this study, gymnasts have exhibited significantly larger anterior tibial shear forces than female soccer athletes. No significant difference was discovered between lacrosse and gymnastic or lacrosse and soccer. Gymnasts during the landing phase displayed an anterior tibial shear force of almost a full body weight in the 3 tasks, indicating extremely larger forces acting on the knee in these athletes. Lacrosse athletes landed with an anterior tibial shear force of almost 90% body weight during the jump-landing maneuver. Further investigation of the landing phases and the moments that occur in this phase may provide additional insight into the potentially damaging forces acting on the ACL during athletic tasks.

During this study, gymnasts exhibited VGRF that were significantly higher in all three maneuvers. Gymnasts landed with an average of 4-5 times body weight for the maneuvers. Also, it should be noted that during jump-landing ground reaction force data was

taken for only one (dominant) foot and that the true VGRF may be even larger. The jump-landing and unanticipated side-step cutting task indicated that gymnasts had significantly larger VGRF than both lacrosse and soccer athletes. Gymnasts also had a larger VGRF than soccer athletes during the anticipated side-step cutting. It has been suggested discussed that gymnasts through their training may utilize these higher ground reaction forces to perform the necessary tumbling skills involved in the sport. Further comparison is needed between other female collegiate sports to accurately conclude whether or not VGRF differ between athletic groups for select athletic tasks.

Clinical Significance

According to the findings of this study, female Division I gymnast appear to be at the greatest risk for non-contact ACL injury. While current biomechanical and epidemiological research has stated that female soccer athletes are at the greatest risk, this may not be true. During the athletic task, female gymnast displayed significantly less knee flexion, hip flexion, and trunk flexion angles indicating a more erect posture at initial contact and during the landing phase. This more erect posture has been used by other researchers as a possible explanation of the increased risk of non-contact ACL injury in women. Gymnasts have also been observed in this study to have significantly greater knee extension moment, anterior tibial shear force, and vertical ground reaction force. These increased forces at the knee have been supported by many studies as potentially harmful to the ACL. When gymnasts performed the both side-step cutting maneuvers, their ground reaction forces were approximately 5 times body weight as measure by the dominant foot on the force plate. The gymnasts not only land in a more erect posture, but with significantly more ground reaction

forces to dissipate throughout the lower extremity. Further analysis of the muscular contribution in dissipating force is need in gymnastics to understand the reason that non-contact ACL injuries are not currently known to be more prevalent in the sport.

During the unanticipated cutting maneuver, female lacrosse athletes demonstrated significantly less knee flexion and greater anterior tibial shear force in the landing phase compared to soccer athletes. Women's lacrosse has grown in popularity over the past decade in the United States. As more females choose to participate in the sport, it is important for epidemiological studies to be employed by researchers. The results indicate that female lacrosse players are also landing in a more erect posture and with significantly greater anterior tibial shear force occurring at the knee in relation to soccer athletes. Once again, these finding indicate that other sports may have a potentially higher risk of non-contact ACL injury than soccer.

Throughout research we have observed significant difference in kinematic, kinetics, and ground reaction forces between male and females. Previous literature has discussed the movements and forces that have been proposed to be more harmful and therefore leading to greater risk of non-contact ACL injury in females. Epidemiological studies have also been used to determine the relative risk of a sport by exposure for different female athletes. Until now women's soccer has been viewed as a high-risk sport for non-contact ACL injury, with significantly greater injury rate that other females sports (Agel et al., 2005). Nonetheless, this study indicated that in a laboratory setting other female athletes (gymnastics and lacrosse) performing tasks known to cause non-contact ACL injury display movement patterns that are believe to place greater forces on the knee joint and ACL.

The differences observed in the study signal that further research needs to be conducted in the area of biomechanical analysis between different types of female athletes. In addition, there is a call for further epidemiological studies in sports other than just soccer and basketball, to understand the full scope of non-contact ACL injury risk in female athletes. In regards to potential ACL injury prevention training programs, this study has noted that not all sports display the same movement patterns. Further research is needed for each sport in order to determine the specific training needs of the sport.

IRB CONSENT FORM

University of North Carolina-Chapel Hill
Consent to Participate in a Research Study
Adult Subjects
Biomedical Form

_____

IRB Study #_____
Consent Form Version Date: _____

Title of Study: Comparison of Lower Extremity Biomechanics & ACL Injury Rates between Female Division I Gymnastic, Lacrosse, and Soccer Athletes

Principal Investigator: Christin Rose Chamberlain, BS, ATC
UNC-Chapel Hill Department: Exercise and Sports Science
UNC-Chapel Hill Phone number: (919) 962-5175
Email Address: Christinc1@aol.com
Co-Investigators: Alexander Creighton, M.D.
                    William Prentice, Ph.D.
                    Christopher Hirth, MS, PT
Faculty Advisor: Darin A. Padua, Ph.D.

Study Contact telephone number: 407-963-0132
Study Contact email: Christinc1@aol.com

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<u>What are some general things you should know about research studies?</u>
You are being asked to take part in a research study. To join the study is voluntary.
You may refuse to join, or you may withdraw your consent to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your relationship with the researcher, your health care provider, or the University of North Carolina-Chapel Hill. If you are a patient with an illness, you do not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study.

You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

What is the purpose of this study?

The purpose of this research study will be to investigate the effect of sport type on the way, in which the trunk and lower body move in female soccer, gymnastic, and lacrosse athletes. You are being asked to be in the study because you are currently a member of either the University of North Carolina-Chapel Hill varsity women's gymnastics, lacrosse, or soccer team.

Are there any reasons you should not be in this study?
You should not participate in this study if any of the following apply to you:

- You have a previous history of an anterior cruciate ligament (ACL) injury in either leg
- You have had surgery on your dominant leg
- You have had a lower extremity injury in the past month that required you to miss three or more consecutive days of physical activity

How many people will take part in this study?
If you decide to be in this study, you will be one of approximately 45 people in this research study.

How long will your part in this study last?
Your participation in this study will last for approximately 60-minutes.

What will happen if you take part in the study?
During the course of this study, the following will occur:

You will report to the Sports Medicine Research Laboratory for one testing session. You will be asked to wear athletic shorts, t-shirts, and your normal running shoes. To ensure that electrodes will be secured in place a small area will be shaved. You will have motion-tracking sensors placed on your lower leg, outer thigh, low back, and upper back that are designed to measure the movement patterns of the lower extremity and trunk. A female examiner (Christin Chamberlain) will perform all electrode and sensor placements.

Once the electrodes positioned, you will be asked to perform a series of landing and cutting maneuvers. Landing maneuvers involve jumping down from a box onto the ground. Cutting maneuvers involve jumping from a box and then planting your foot and cutting at 35 to 55-degree angle in the direction indicated by the light system. Before you perform the landing and cutting maneuvers you will be asked to ride a stationary bicycle at a self-selected pace for five-minutes, undergo a self-directed lower extremity stretching routine and perform several practice trials of the landing and cutting maneuvers to warm-up and become familiar with the testing procedures.

What are the possible benefits from being in this study?

Research is designed to benefit society by gaining new knowledge. There are no direct benefits to you for participation in this study. The researcher will discuss your performance on the jump-landing and cutting maneuvers with you if you wish. This information may help educate you on improving your landing and cutting technique.
The benefits to society include gaining information that researchers can analyze to understand how the body moves in different female athletes during a landing and cutting maneuver. Other benefits of this study include learning how these differences affect performance and injury risk to help develop exercise programs designed for injury prevention.

What are the possible risks or discomforts involved with being in this study?
This study involves side step cutting maneuvers that may involve the following risks and/or discomforts to you:

- Possibility of a ligament injury to the joints of your lower extremities
- Possibility of muscle strains/pulls/soreness in your lower extremities
- Possibility of skin irritation due to sensor placement
- There may be uncommon or previously unrecognized risks that might occur

In addition, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

If you choose not to be in the study, what other treatment options do you have?

There will be no penalty if you decide not to participate in this study.

What if we learn about new findings or information during the study?
You will be given any new information gained during the course of the study that might affect your willingness to continue your participation.

How will your privacy be protected?
No subjects will be identified in any report or publication about this study. All subjects will be identified as a number throughout data collection. All data storage and analysis will be on computers the sports medicine research lab where a password is necessary for access to the computers. Only members performing research have access to the lab and use of its computers. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, The University of North Carolina at Chapel Hill will take all steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

What will happen if you are injured by this research?
All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you do not give up any of your legal rights.

What if you want to stop before your part in the study is complete?
You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

Will you receive anything for being in this study?
You will not receive anything for taking part in this study.

Will it cost you anything to be in this study?
The only cost to you will be in your time and transportation to the University of North Carolina at Chapel Hill Sports Medicine Research Laboratory for your testing session.

What if you are a UNC student?
You may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration if you take part in this research.

Who is sponsoring this study?
This research project is not being funded by any companies or institutions.

What if you have questions about this study?
You have the right to ask, and have answered, any questions you may have about this research. If you have questions, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

What if you have questions about your rights as a research subject?
All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject you may contact, anonymously if you wish, the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

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<u>Subject's Agreement:</u>

I have read the information provided above. I have asked all the questions I have at this time.
I voluntarily agree to participate in this research study.

_____   _____
Signature of Research Subject   Date

_____
Printed Name of Research Subject

_____   _____
Signature of Person Obtaining Consent   Date

_____
Printed Name of Person Obtaining Consent

ACL Injury Study in Female Athletes

Are you a member of UNC women's gymnastic, lacrosse, and soccer teams?

You may be eligible to participate in a study investigating trunk and lower extremity movement patterns during select cutting and jump-landing maneuvers. This study is sponsored by the UNC Department of Exercise and Sports Science and conducted in the Sports Medicine Research Laboratory located in Room 06F Fetzer Gym.

Volunteers must be: (1) healthy, (2) age 18-23, (3) without a history of lower extremity injury in the past 3 months that limited activity for more than three days, and (4) if history of lower extremity surgery, volunteer must be cleared for full participation and not participating in a formal rehabilitation program

To receive more information, contact:

Christin Chamberlain, ATC, LAT
Chamby1@email.unc.edu
407-963-0132

UNC Sports Medicine Research Lab

SUBJECT QUESTIONNAIRE

University of North Carolina-Chapel Hill
Research Study Questionnaire
Adult Subjects

Medical IRB Study #

Title of Study: Comparison of Lower Extremity Biomechanics & ACL Injury Rates between Female Division I Gymnastic, Lacrosse, and Soccer Athletes
Principal Investigator: Christin Chamberlain, BS, ATC, LAT
UNC-CH Department: EXSS
Phone number: 407-963-0132

Sponsor: None

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1. Are you currently in good general health?

      YES / NO

2. Have you had a lower extremity injury in the past three months that required three consecutive days missed from physical activity?

      YES / NO

3. Do you have any current symptoms of injury?

      YES / NO

4. Have you ever had surgery on your dominant leg (the leg used to kick a ball)?

      YES / NO

5. If yes, when was the surgery and indicate if you are still currently participating in a rehabilitation program.

6. Have you ever had a back injury or chronic lower back pain? If yes, what was the injury or condition causing pain?

DATA COLLECTION SHEET

Date:_____

Subject #: _____   Name: _____

Sport:_____   Dominant Leg:_____

Start Time: _____   Finish Time:_____

Height: _____cm   Weight:_____kg

Stylus offset:_____m   RMS Error:_____ m

# of Jump-landing Trials: _____

# of Anticipated cuts:

# of Side-cutting Maneuvers: _____

# of Cross-over Cutting Maneuvers: _____

Order of Cutting Maneuvers: _____

Problems:

Notes:

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