Effect of Playing Surface on Knee and Hip Kinematics in Healthy Female Populations

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ABSTRACT

AMY L. FRALEY: Effect of Playing Surface on Knee and Hip Kinematics in Healthy Female Populations
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Previous research implicates specific hip and knee kinematics during functional tasks as increasing the risk of ACL injury. Since a large number of severe knee injuries in females are non-contact, the purpose of this study is to determine if knee and hip kinematics during a jump landing cutting task in healthy female populations differ between third generation artificial turf and natural grass playing surfaces. We hypothesized that the task performed on the artificial turf would place the subjects in a biomechanical position that places a greater load on the ACL. Thirty-one female varsity and club soccer athletes performed a 90 degree cutting maneuver immediately after landing from a box jump on a natural grass and a 3rd generation artificial turf playing surface while 3D hip and knee kinematics were assessed. Subjects showed significantly different hip excursions in the frontal ($p = 0.038$) and transverse ($p = 0.048$) planes and knee excursions in the frontal plane ($p = 0.014$) between surface conditions, resulting in increased hip adduction and relatively more internal rotation on artificial turf. Such movements with functional tasks may increase the load placed on the ACL. Therefore, future research is needed to determine the ideal in-fill percentage and type of synthetic fiber, leading to further advancements and improvements in the safety of an artificial surface. In addition, further study into muscle recruitment patterns and the effect of experience on artificial turf surfaces could lead to the development of an intervention program and analysis of its long-term effect on injury prevention.

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CHAPTER I

INTRODUCTION

Since the beginning of the 1970s and the passing of Title IX, there has been a dramatic increase in the number of female athletes participating in individual and team sports in the United States (Arendt, Agel et al. 1999). Since then, the number of anterior cruciate ligament (ACL) injuries in the country has increased to an estimated 80,000 every year (Shimokochi and Shultz 2008). Of this daunting number, female athletes have been found to experience these injuries at a rate of 2 to 6 times more often than males playing the same sport (Arendt, Agel et al. 1999). Even more overwhelming is the fact that approximately 70% of these injuries occur in non-contact situations, usually during quick deceleration before a cutting maneuver or during a jump landing (Cowley, Ford et al. 2006; Shimokochi and Shultz 2008).

Overall risk factors for non-contact knee injury include intrinsic and extrinsic factors. Of these risk factors, certain biomechanics inherent to the athlete, as well as those from the playing surface and environmental conditions, have been shown to increase the likelihood of sustaining a significant knee injury. For example, females have been shown to exhibit decreased knee flexion, as well as decreased hip flexion, at contact with the playing surface. Unfortunately, increased load is placed on the ACL when the quadriceps are activated at close to full knee extension, resulting in a greater risk for ACL injury (James, Sizer et al. 2004; Alentorn-Geli, Myer et al. 2009; Pollard, Sigward et al. 2010). Females have also been described as having “ligament dominance,” meaning that they rely more on passive restraints in the knee by limiting motion in the sagittal plane, placing more stress on their ligaments (Ford, Myer et al. 2003; Pollard, Sigward et al. 2010). This behavior typically results in increased knee valgus, which has been shown, along with hip internal rotation and knee abduction and predicted by hip adduction angles, to increase the risk for ACL injury (Imwalle, Myer et al. 2009; Pollard, Sigward et al. 2010). The strain imposed to the ACL has also been found during in vivo and cadaveric studies to increase with knee internal rotation moments and decrease with knee external rotation moments when combined with a quadriceps force, resulting in a greater risk for ACL injury during excessive knee internal rotation moments and quadriceps force in weight-bearing (Shimokochi and Shultz 2008).

Extrinsic risk factors to injury include the playing surface, environmental conditions such as temperature and amount of moisture, and the forces occurring at the shoe-surface interface. It has been shown that increased ground hardness and high rotational traction and friction at the shoe-surface interface results in a higher potential for lower extremity injury (Livesay, Reda et al. 2006; Villwock, Meyer et al. 2009).

Previous studies on the risk of injury on older generations of artificial turf are poorly documented and not easily accessible. Due to this lack of research and documentation concerning artificial turf, there seems to be an overall negative public perception and biasing against them. This prejudice is further advanced by media hysteria suggesting that artificial turfs predispose athletes to injury (Steffen, Andersen et al. 2007). Since the emergence of the first artificial turfs in the mid-1970s, turfs have been modified from the high stiffness and friction that caused them to differ greatly from natural grass to a third generation of turf that more closely imitates the properties of a natural playing surface. The development of the new generation turf resulted in greater shock absorption, to combat the higher amounts of overuse injuries seen on the first and second generation turfs, greater grass imitation, and a new in-fill system of sand and rubber to address the stiffness issues with the older turfs. The new turf also allows for an increased speed of play and is marketed to improve performance (Steffen, Andersen et al. 2007). Following these improvements, there has been an increased use in third generation turfs for multiple reasons. First, environmental and climatic conditions may make natural playing surfaces unsuitable for year-round events. In addition, the high use rates of the playing surface results in an inability to properly maintain grass, while overall maintenance costs are lower on artificial turf surfaces (Fuller, Dick et al. 2007). Recently, prospective and retrospective studies have shown no overall significant differences between the new artificial turfs and natural grass on incidence, severity, nature, and cause of acute and chronic injuries. However, no study was specific to ACL injury (Meyers and Barnhill 2004; Ekstrand, Timpka et al. 2006; Fuller, Dick et al. 2007; Fuller, Dick et al. 2007; Steffen, Andersen et al. 2007).

Even with the new advancements in turf to mimic a natural playing surface, new generation artificial turfs still have different characteristics when compared to natural grass, such as increased stiffness and friction, that have been shown to cause differences at the shoe-surface interface and on foot loading patterns (Ford, Myer et al. 2003). Any change at the shoe-surface interface caused by extrinsic differences at the playing surface could influence the kinematics of proximal joints, potentially predisposing them to injury. For example, research has shown that artificial turf influences plantar loading patterns, causing higher peak pressures within the central forefoot and lesser toes during a cutting task, increasing an inversion pattern. The load is also shifted to the medial side of the foot with the cutting task, possibly causing more valgus stress to the knee (Eils, Streyl et al. 2004). This pattern differs from that found on a grass surface, which shows higher pressures on the medial forefoot and lateral midfoot. The higher loaded areas on the turf raise concerns that they may produce higher friction at the shoe-surface interface, which is known to lead to injury (Ford, Manson et al. 2006).

Previous prospective, retrospective, and case studies have been performed to evaluate the incidence, cause, and severity of injuries across playing surfaces, leading to a prediction of risk. In the past, specific differences between surfaces have only been measured at the shoe-surface interface, not up the kinetic chain. There have been no kinetic or kinematic measurements at the knee and hip across playing surfaces. Therefore, the purpose of this study is to determine if the 3rd generation artificial turf playing surfaces alter knee and hip kinematics during a jump landing cutting task in healthy females when compared to a conventional grass surface in a manner that is consistent with ACL injury. Since a large number of severe knee injuries in females are non-contact, this study will examine if known biomechanical risk factors differ across playing surfaces in an attempt to find ways to decrease predisposition to injury through extrinsic environmental risk factors.

Variables

Independent Variables

Playing surface:

1. Natural grass surface
2. 3^{rd} generation artificial turf surface (i.e. FieldTurf)

Dependent Variables

3D knee and hip kinematics from initial contact to peak knee flexion of a jump landing cutting task:

Knee sagittal plane angles (flexion / extension)

Knee frontal plane angles (valgus / varus)

Knee transverse plane angles (internal / external rotation)

Hip sagittal plane angles (flexion / extension)

Hip frontal plane angles (adduction / abduction)

Hip transverse plane angles (internal / external rotation)

Research Questions

RQ_1: Do knee sagittal plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

RQ_2: Do knee frontal plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

RQ_3: Do knee transverse plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

RQ_4: Do hip sagittal plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

RQ_5: Do hip frontal plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

RQ_6: Do hip transverse plane angles during a jump landing cutting task in a sample of healthy female soccer players differ between third generation artificial turf and natural grass playing surfaces?

Research Hypotheses

RH_1: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly less knee flexion during the jump landing cutting task when compared to the natural grass surface.

RH_2: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly more knee valgus during the jump landing cutting task when compared to the natural grass surface.

RH$_3$: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly greater knee external rotation angle during the jump landing cutting task when compared to the natural grass surface.

RH$_4$: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly less hip flexion during the jump landing cutting task when compared to the natural grass surface.

RH$_5$: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly greater hip adduction during the jump landing cutting task when compared to the natural grass surface.

RH$_6$: We hypothesize that there will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task. The 3rd generation artificial turf will result in significantly greater hip internal rotation angle during the jump landing cutting task when compared to the natural grass surface.

Statistical Hypotheses

Null

H_o1: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_o2: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_o3: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_o4: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_o5: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_o6: There will not be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task.

Alternative

H_1: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_2: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_3: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on knee transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_4: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip sagittal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_5: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip frontal plane angles from initial contact to peak knee flexion of a jump landing cutting task.

H_6: There will be a significant difference between the natural grass surface and the 3rd generation artificial turf on hip transverse plane angles from initial contact to peak knee flexion of a jump landing cutting task.

Operational Definitions

1. *Third generation artificial turf* was defined as turfs developed since 2000 that greatly mimic the playing characteristics of a natural grass playing surface. These

turfs have imitated grass with 50-60 mm synthetic fibers and an in-fill system of siliceous sand and rubber granules.

2. *Initial contact* was defined as the instant that the dominant foot came in contact with the ground from the jumping task to initiate the cutting maneuver.
3. *Peak knee flexion* was defined as the greatest knee flexion value in the dominant leg when landing from the jumping task and initiating the cutting maneuver.
4. *Excursion* was defined as the joint motion during the time period from initial contact to peak knee flexion (weight acceptance).

Assumptions

1. Subjects studied will represent their population accurately.
2. Subjects will follow directions when performing the study, including putting forth 100% effort for each cutting task.
3. The artificial turf and natural grass fields are located in the same geographical location. Therefore, environmental conditions (moisture and temperature) are the same.

Delimitations

1. Only females were tested.
2. Only healthy individuals were tested. Those with a recent history of knee or hip surgery in their dominant leg, ACL injury in either leg, or current hip, knee, ankle, or back injury that prevents athletic participation did not participate.
3. Dominant leg was assessed for all subjects.
4. All subjects performed the cutting task at the 90 degree angle.

Limitations

1. Results may not apply to males.
2. Results may not apply to athletes that have a history of or current injury to the back or lower extremity.
3. Results may not apply to the non-dominant limb.
4. The studied athletes may not represent all athletes.
5. Results will not apply to older generation turfs.
6. Results may not apply to other types of 3^{rd} generation turfs.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

In recent years, ACL injury rate has reached a frightening level, resulting in the thousands injured annually being affected financially, physically, and psychologically for many years to come. Of these injuries, females experience noncontact ACL injury more often than their male counterparts, with the disparity between genders thought to be because of differences in knee-loading motions while performing sport-specific tasks.

Since the development of artificial playing surfaces in the 1970s, public concern and media hysteria about injury incidence on artificial turf has resulted in the emergence of a new generation of artificial turf with synthetic fibers and a rubber and sand in-fill system that closely imitates the characteristics provided by a natural playing surface. However, specific differences, such as increased stiffness and friction in artificial turfs, still exist that may cause changes in motion that could affect the biomechanics of joints proximal to the shoe-surface interface. Any changes in motion could potentially alter the load on the ACL. The purpose of this literature review is to determine factors that load the ACL, differences in motion patterns thought to increase ACL injury risk, and the risk of injury on artificial turfs. This includes examining the specific changes in movement patterns between artificial and natural surfaces to investigate extrinsic factors that influence known predispositions to ACL injury in females.

Epidemiology

Since the beginning of the 1970s and the passing of Title IX, there has been an impressive increase in the number of female athletes participating in individual and team sports in the United States (Arendt, Agel et al. 1999). Since that time, the number of ACL injuries in the country has increased to an estimated 80,000 every year, resulting in over 50,000 reconstructive ACL surgeries annually (Shimokochi and Shultz 2008). The monetary cost of these knee surgeries and the rehabilitation surrounding them has surpassed one billion dollars a year. Unfortunately, financial costs are not the only issues surrounding these devastating injuries. Short-term complications include negative effects on academic achievement, self-esteem, and psychological well-being. ACL injury also limits, if not completely eliminates, sport participation and the athletes' pre-injury level of performance. Potential long-term complications include loss of normal knee function, lesions to the meniscus, osteoarthritis, and arthrofibrosis, each of which provide a barrier against and affect overall health and activity status (Cowley, Ford et al. 2006; Livesay, Reda et al. 2006; Shimokochi and Shultz 2008; Imwalle, Myer et al. 2009).

Of the estimated 80,000 ACL injuries annually, female athletes have been found to experience these injuries at a rate of 2 to 6 times more often than males playing the same sport (Arendt, Agel et al. 1999). Another study found female soccer players experiencing an ACL tear every 7,692 exposures, while male soccer players averaged an ACL tear every 25,000 exposures (Agel, Arendt et al. 2005). Of this overwhelming number of devastating injuries, approximately 70% of female ACL tears occur in non-contact situations, usually during a quick deceleration before a cutting maneuver or during a jump landing task with the knee loaded in multiple planes of motion (Agel, Arendt et al. 2005; Cowley, Ford et al. 2006; Shimokochi and Shultz 2008).

Intrinsic Factors that Load the ACL

Overall risk factors for significant non-contact knee injury include specific intrinsic elements, or certain biomechanics inherent to the athlete, which have been shown to increase the likelihood of sustaining a significant knee injury, especially in the female population. A "position of no return" has been suggested by researchers as the situation in which an athlete is most likely to injure the ACL. This position includes knee extension, knee valgus, knee external rotation, low hip flexion, hip adduction, and hip internal rotation (Ireland 1999). In general, load is imposed on the ACL during an anteriorly directed force to the tibia as the ACL works to restrict anterior tibiofemoral shear force. The amount of anterior tibiofemoral shear force directed to the ACL is affected by sagittal plane knee angle, quadriceps and hamstring activation, and gastrocnemius muscle force (Woo, Fox et al. 1998).

It has been shown that with a decreased knee flexion angle, ACL tensile forces are close in magnitude to the applied anterior shear force (Woo, Fox et al. 1998; Sakane, Livesay et al. 1999). However, as knee flexion increases, the ACL tensile forces that are created by the anterior shear force decrease. Therefore, the ACL is more susceptible to injurious loads as the knee reaches extension (Woo, Fox et al. 1998; Sakane, Livesay et al. 1999). It is thought that knee flexion angle has an impact on the increased risk for ACL injury for several reasons. Biomechanically, with decreased knee flexion, the ACL elevation angle between the tibia and the femur is much greater than in higher degrees of knee flexion where the ACL lies parallel to the tibial plateau. This difference in angle changes the load on the ACL and its capability to uphold against elastic deformation (Blackburn and Padua 2008; Alentorn-Geli, Myer et al. 2009).

Quadriceps muscle contraction, combined with knee flexion angle, is also believed to play a major role in producing anteriorly directed forces on the tibia (Pandy and Shelburne 1997; Isaac, Beard et al. 2005). With a decreased knee flexion angle, the angle between the patellar tendon and the longitudinal axis of the tibia is at its greatest. As a result, excessive quadriceps force at a decreased knee flexion angle increases the amount of strain experienced by the ACL. Conversely, hamstring muscle contraction decreases the amount of loading placed on the ACL. As knee flexion increases, the insertion angle of the hamstrings to the longitudinal axis of the tibia decreases to allow a hamstring contraction to counteract the loading placed on the ACL with anterior tibiofemoral shear force (Yu and Garrett 2007; Alentorn-Geli, Myer et al. 2009). The amount of tensile force placed on the ACL with a quadriceps contraction is decreased with the coactivation of the hamstrings, and it continues to decrease as knee flexion increases. Therefore, it seems that the protective ability of the hamstrings to combat ACL injury decreases with knee extension (Li, Rudy et al. 1999; Markolf, O'Neill et al. 2004).

Gastrocnemius muscle contraction may also play a role in the amount of anterior shear force experienced by the ACL. With gastrocnemius contraction at decreased knee flexion angles, its attachment to the posterior aspect of the femur creates a posterior femoral force with contraction and an additional anterior-directed force to the tibia with the increase in gastrocnemius size. Once again, the amount of ACL loading due to the gastrocnemius is dependent on the degree of knee flexion. ACL strain from the gastrocnemius has been found to be nonexistent at 30 degrees and beyond of knee flexion (Fleming, Renstrom et al. 2001).

Within the female population, it is indicated that females who limit knee motion in the sagittal plane rely on passive knee restraints in the frontal plane to help control the effects of movement and deceleration occurring to the body (Pollard, Sigward et al. 2010). This compensation has been termed “ligament dominance,” indicating that the musculature surrounding the knee does not absorb the necessary energy during sport-specific activities, placing additional loading on the knee ligaments. It has also been shown that those females who exhibit decreased knee flexion with landing also demonstrate increased knee valgus angles and knee adductor moments, which have been found to be predictive of ACL injury (Hewett, Myer et al. 2005; Pollard, Sigward et al. 2010).

It has also been observed that knee valgus and knee internal rotation accompany the anterior tibial displacement caused by a quadriceps contraction (DeMorat, Weinhold et al. 2004). Since the quadriceps contraction may create these moments in the frontal and transverse planes and motion rarely occurs in one plane, ACL loading must also be studied across multiple planes (Li, Rudy et al. 1999; DeMorat, Weinhold et al. 2004). In the transverse plane, the strain imposed to the ACL has been found during in vivo and cadaveric studies to increase with knee internal rotation moments and decrease with knee external rotation moments when combined with a quadriceps force (Arms, Pope et al. 1984). These results indicate that ACL strain, and subsequently, injury risk, would increase during weight-bearing with an excessive knee internal rotation moment accompanied by large quadriceps force. Several studies also agree that the ACL may be at greater risk for injury when excessive valgus and knee internal rotation are combined with a decreased knee flexion angle. ACL tensile force was found to be almost 2 times greater with valgus and knee internal rotation when compared with valgus and knee external rotation (Kanamori, Woo et al. 2000). Conversely, it is also thought that ACL stress may increase with knee external rotation accompanied by knee valgus because these motions result in ACL impingement against the intercondylar notch. Therefore, ACL injury risk may be increased with knee valgus accompanied by either knee internal or external rotation (Fung and Zhang 2003).

Hip kinematics in the sagittal, frontal, and transverse planes also affect the motions occurring at the knee that are associated with increased risk for ACL injury. During cutting maneuvers, subjects have demonstrated increased hip and knee internal rotation angles with sharper cuts, possibly initiating high-load ACL positions and increasing risk for injury (Imwalle, Myer et al. 2009). It was also found that hip adduction and knee abduction were correlated during cutting tasks. With the hip adducted, knee valgus also increased, making hip adduction a predictor of the injurious knee valgus mechanism at the knee (Imwalle, Myer et al. 2009). In the sagittal plane, higher hip, knee, and trunk flexion angles during landing results in less impact to the knee as more energy is absorbed by the musculature. Increased hip and knee flexion also result in less vertical ground reaction force with landing, decreasing anterior tibiofemoral shear to the ACL (Alentorn-Geli, Myer et al. 2009).

Gender Differences on Loading Factors

Of the intrinsic biomechanical risk factors noted above, females have been indicated in multiple studies as displaying the factors that load the ACL to an extent greater than that of males performing the same tasks. In an examination of sagittal plane knee kinematics by James et al. (2004), females initiated a cutting task with 5.8 degrees of knee flexion less than the male subjects and approximately 3 degrees less of maximum knee flexion during the entire task. However, females also showed 3.5 degrees greater overall range of motion when compared to the male subjects. Since greater knee extension is known to load the ACL, females performing this cutting task placed greater stress on their ACL during initiation of the task and at their maximum knee flexion when compared to their male counterparts. Even though there was no statistical significance in differences in overall range of motion between genders, the tendency of females having overall greater range of motion may indicate a lack of joint control and coordination or differences in muscle strength in the female population when compared with males. These results indicate that males and females do perform cutting maneuvers using different techniques and control motion in the sagittal plane differently, with females showing a pattern more indicative of ACL loading.

Pollard et al. (2010) determined that females who utilized decreased knee flexion angles with landing showed greater knee valgus and knee adductor moments as well. This necessitates relying on the passive restraints in the frontal plane, resulting in the “ligament dominance” pattern associated with females. In a comparison of female to male high school athletes during a landing task, Ford et al. (2003) found significant gender differences with maximum valgus and total valgus motion, with the females displaying more valgus motion with landing. These poor biomechanics of decreased knee flexion angle and greater valgus motion demonstrated by the female subjects show increased risk of ACL injury after examination of those factors that place additional stress on the ACL.

Extrinsic Risk Factors

Extrinsic risk factors to injury include the playing surface, environmental conditions such as temperature and amount of moisture, and the forces occurring at the shoe-surface interface. In a 7-year retrospective study by Orchard et al. (2001) on ACL injuries, extrinsic risk factors were examined to find relationships between external factors and risk for injury. They determined that a relationship exists between ACL injury and weather conditions that result in a dryer playing surface, asserting that the speed of the game increases on a dryer surface, as well as the friction and torsional resistance between cleats and grass. In the long-term, it was concluded that low water evaporation and high rainfall significantly decreased the risk of noncontact ACL injuries, possibly from the decreased traction occurring at the shoe-surface interface. Meyers and Barnhill (2004) also noted a significant increase in incidence of injury on FieldTurf during temperatures greater than 70 degrees Fahrenheit when compared to colder days and to injuries on natural grass.

Research examining plantar distribution patterns and forces at the shoe-surface interface has found differences between playing surfaces. The total loading experienced by the entire foot does not seem to change across surfaces, so differences found are thought to be caused by changes in foot motion between the new generation artificial turf and natural grass surfaces. Changes in movement at the foot can cause alterations in biomechanics in joints proximal to the foot as well. In addition, peak torque and rotational stiffness at the shoe-surface interface are affected by the playing surface, with third generation artificial turfs generally producing higher torques and rotational stiffness than grass surfaces. Further, shoe type and cleat design also produced differences in torque and rotational stiffness (Livesay, Reda et al. 2006; Villwock, Meyer et al. 2009). Therefore, extrinsic factors of increased ground hardness and high temperatures at the playing surface and elevated rotational traction and friction at the shoe-surface interface results in a higher potential for lower extremity injury.

History of Artificial Turf Use

Previous research on the risk of injury on first and second generation artificial turfs is minimal and not easily accessible. Even with the lack of research concerning these earlier generation artificial turfs, there seems to be a preconception of overall negative public opinion and biasing against their safety. This deficiency of documented research evaluating the characteristics of the earlier artificial turfs is no where near comparable to the media hysteria and abundance of newspaper and magazine articles nationwide on their safety, furthering the public prejudice that artificial turfs predispose injury (Steffen, Andersen et al. 2007). Since the emergence of the first artificial turfs in the mid-1970s, artificial turf surfaces have been modified and improved from the high stiffness and friction that caused them to differ greatly from natural grass to a third generation of turf that closely imitates the properties of a natural playing surface. This advancement to the new generation turf included greater shock absorption to combat the higher amounts of overuse injuries seen on the first and second generation turfs, greater grass imitation with synthetic fibers, and a new in-fill system of different percentages of sand and rubber to address the stiffness issues experienced with the older turfs. The new turf also allows for an increased speed of play and is marketed to improve performance; however, some authors argue that the resulting increased speed of the game may be a factor of increased probability of risk for athletes participating on these surfaces (Meyers and Barnhill 2004; Steffen, Andersen et al. 2007).

Following these improvements, there has been an increased use in third generation turfs internationally for multiple reasons. First, environmental and climatic conditions may make natural playing surfaces unsuitable for year-round events. Extreme weather, including large amounts of snow or rainfall as well as arid conditions, changes the properties of the game in addition to making field maintenance difficult and expensive. Further, high use rates of natural playing surfaces result in the inability for proper maintenance, while overall maintenance costs after installation are lower on artificial turf surfaces (Fuller, Dick et al. 2007; Fuller, Dick et al. 2007).

Risk of Injury on Third Generation Artificial Turfs

Several prospective studies have examined and compared the incidence, cause, and risk of injuries on natural grass and third generation artificial turf. Although most studies agree that there are no overall differences in the level of risk and cause of the injuries experienced on both surfaces, none have been specific to ACL injury. Specific differences in the incidence, cause, and risk of injury also continue to exist between surfaces across the research.

In a two season prospective study, Fuller et al. (Fuller, Dick et al. 2007; Fuller, Dick et al. 2007) compared the incidence, nature, and cause of injuries sustained on natural grass and the new artificial turf during soccer training and match play for both genders. They found that an ACL tear was the most common season ending injury for women during match play on both the surfaces, with 53% occurring on artificial turf and 45% on natural grass. This incidence of ACL tear was more than 3 times higher in the women than men on both the artificial turf and grass surfaces during match play. Females also had a higher mean severity of injury (11.2 days lost on artificial turf and 8.9 days lost on natural grass) than males on both surfaces. During training, knee ligament tears were also the most common season ending injury for females on both surfaces (30% on turf, 23% on grass). For the male athletes, ankle ligament tears and mild-moderate injuries were significantly greater on the new artificial turf, but females experienced significantly less ankle sprains on turf compared with grass during match play. Mean severity in days lost were also higher during training with injuries experienced on the artificial turf for both males and females, although these differences were not statistically significant. The researchers decided before data collection that an increase of injury on artificial turf had to be 33% more than the level on natural grass for it to be considered a significant effect. They used an estimated incidence of match injuries of 25/1000 exposures for male and females, and their study was also limited by a small sample size. Therefore, even though there were specific significant differences and tendencies found between the new artificial turf and grass surfaces, Fuller et al. (2007; 2007) concluded that there are no major differences in overall cause of training or match injuries or level of risk of injury on new artificial turf and grass for athletes of both genders.

In a prospective two-cohort study, Ekstrand et al. (2006) found an increased risk of ankle sprains on artificial turf, but a decreased risk of muscle strains in elite male soccer players. They also found a tendency of fewer severe injuries occurring on natural grass during training sessions. The researchers found it encouraging that the overuse injury rate on the artificial turf was similar to that on natural grass, since a major change in the new generation artificial turf was increased shock absorption to decrease chronic injury. In conclusion, Ekstrand et al. (2006) asserted that incidence of injury is similar on artificial turf and natural grass in elite male soccer players, although the study was restricted by a small sample size.

Meyers and Barnhill (2004) performed a five year prospective study in the high school football population to compare the incidence, causes, and severity of injuries on FieldTurf and natural grass. They found a higher incidence of muscle-tendon overload injuries on FieldTurf when compared to grass and asserted that these injuries could be a function of the faster play that is associated with the new artificial turfs. A significant playing surface effect by mechanism of injury was also found. There was a higher incidence of noncontact running and sprinting injuries reported on the FieldTurf than on natural grass. However, they also found a higher rate of ligament tears on grass. No significant differences in injury rates were found between playing surfaces across specific knee injury cases, but a higher incidence of knee trauma was found on grass. It was acknowledged that there was a low amount of rainfall during the season that resulted in an increased hardness of the grass playing surfaces, which is known to be an extrinsic risk factor to injury. Although no significant environmental differences were found between surfaces, a significant increase was noted in incidence of injury on FieldTurf during temperatures greater than 70 degrees Fahrenheit. Therefore, Meyers and Barnhill (2004) concluded that there were overall differences between FieldTurf and natural grass on incidence, cause, and severity of game-related injury in high school football players.

Steffen et al. (2007) performed 8 month prospective cohort study on adolescent female soccer players to determine the risk of injury on the newer artificial turf and natural grass. They concluded that there was no overall difference in the risk of acute injuries in young female soccer players on third generation artificial turf and natural grass. However, they did find that during game play, twice as many severe injuries occurred on artificial turf and that there was a trend toward more ankle and knee ligament injuries on the artificial turf than on grass. The researchers indicated that differences in friction across the surfaces may have played a role in the variations of ligament injury incidence and that they were limited by the inability to control field maintenance and weather conditions.

The overall consensus of the prospective research indicates that there are no differences in injury risk between the new generation artificial turfs and natural grass for female or male athletes. However, trends and tendencies within each study indicated that there are specific differences between playing surfaces, with the negative tendency leaning toward the artificial turf.

Differences between 3rd Generation Turfs and Natural Grass

Even though the rubber or sand in-fill systems associated with the new generation artificial turfs are meant to mimic the characteristics of natural grass, these newer artificial turfs still have different traits when compared to grass, such as stiffness, friction, and elasticity, which have been shown to cause differences on foot loading patterns and the forces at the shoe-surface interface (Ford, Manson et al. 2006).

Plantar Pressure Distribution Patterns

In a study performed by Ford et al. (2006), male football players were tested on a slalom course on natural grass and synthetic turf to measure the effect of playing surface on in-shoe foot loading patterns. It was concluded that playing surface does significantly affect plantar pressure distribution patterns during a cutting task. Peak pressure was significantly higher during the artificial turf condition within the central forefoot and lesser toes while performing the cutting task, while grass surface showed a relatively higher load in the medial forefoot and lateral midfoot. Therefore, the artificial turf surface contributes to more inversion and higher pressure in the lateral regions of the foot. These higher pressures may result in higher friction at the shoe-surface interface, leading to injury. The researchers also asserted that the load placed on the medial forefoot during the grass conditions could explain the “cleat-catch” mechanism that occurs on natural grass. The increased friction and rotation at the shoe-surface interface could then be transferred proximally to the knee. The total loading experienced by the entire foot did not change across surfaces, and there were no differences found in performance time and stance phase contact time during the cutting task. Because the total loading under the entire foot remained the same across surfaces, differences found were thought to be caused by changes in foot motion between the new generation artificial turf and natural grass surfaces.

Along with change in surface, plantar pressure distribution patterns are also altered by the type of movement being performed. In a comparison of soccer-specific movements, Eils et al. (2004) found that there was a significant shift of load to the medial heel, medial forefoot, medial midfoot, and hallux in cutting when compared to running. Peak pressures were 220% higher in the medial heel and 160% higher for the medial forefoot during cutting when compared to running alone. Eils et al. (2004) also determined that there was no overall effect of surface, comparing natural grass to a red cinder surface, on relative loads and peak pressures. However, the relative loads under the medial heel and midfoot were different between surfaces, with grass values being greater than those found on red cinder. Tessutti et al. (2008) also found differences in in-shoe plantar pressure distribution between natural grass and asphalt in recreational runners. Peak pressures, contact area, and contact time were all significantly different on the plantar surface of the foot when running on natural grass versus asphalt. These results indicate that a change in playing surface does have an effect on the motions occurring at the foot and thus, may alter the biomechanics occurring at proximal joints.

Differences at the Shoe-Surface Interface

From an injury prevention standpoint, there are a lot of risk factors and possible causes of noncontact ACL injuries, many of which have been listed above. However, one major factor often implicated in noncontact injuries is the interaction of the injured athlete's shoe with the playing surface. Several factors have been identified as influences on the torque produced at the shoe-surface interface. These include the number and size of the cleats on the shoe, the material distribution at the toe and heel of a shoe, the type of playing surface, the weight and stance of the athlete, and the effective cleat engagement. In studies performed by Torg and Quedenfeld (1971) and Lambson et al. (1996), they determined that the type of cleat was correlated with ankle and knee injuries. Torg and Quedenfeld (1971) determined that the number and size of cleats on the shoe is correlated with ankle and knee injuries and that less aggressive cleats produced fewer injuries. Lambson et al. (1996) agreed that long, irregular cleats along the outside of the shoe and smaller, pointed cleats on the inside with most associated with the incidence of ACL tears. Even though cleat design has been determined to have an impact on incidence of injury, it is hard to make generalizations about "safe" and "unsafe" cleats, since their interaction and production of torque will change with the playing surface (Livesay, Reda et al. 2006). Therefore, it is necessary to look past the shoe design and focus on the characteristics of the playing surface.

In a study performed by Livesay et al. (2006), peak torque and rotational stiffness were measured across 5 different playing surfaces and 2 shoe types. The playing surfaces included different in-fill systems of third generation artificial turf and natural grass, and the shoes were a standard grass cleat and turf shoe. Within each shoe-surface combination tested, there was a significant effect of playing surface on the peak torques and rotational stiffness developed at the interface. The highest peak torques were found on the FieldTurf surface, with the lowest peak torques found with the same cleat shoe on natural grass.

Villwock et al. (2009) found similar results when studying the effect on shoe design and playing surface on rotational traction. Peak torque and rotational stiffness at the shoe-surface interface were significantly affected by the playing surface. Third generation artificial turfs produced higher torques and rotational stiffness that the grass surface. The lower rotational stiffness on grass indicates a lower rate of loading during a maneuver, which might allow more time for neuromuscular control during a cutting task. This may provide protection to the passive restraints of lower extremity joints, while high rotational traction could lead to lower extremity injury. Livesay et al. (2006) agreed that rotational stiffness may play the most important role at the shoe-surface interface in risk for injury, and they believe that it could be a more perceptive indicator of the mechanical interactions occurring at the interface. In comparison of shoe design, Villwock et al. (2009) determined that cleat pattern showed no difference in rotational stiffness; however, peak torque was lower with the turf cleat. In addition, the shoe model did not have an effect on peak torque, but it did affect rotational stiffness.

Peak torque and rotational stiffness at the shoe-surface interface are affected by the playing surface, with third generation artificial turfs generally producing higher torques and rotational stiffness than grass surfaces. In addition, shoe type and cleat design also produced differences in torque and rotational stiffness. It is known that lower peak torques developed at the interface lessen the likelihood of injury at proximal joints, but they may also result in a decrease in performance. Either way, differences between playing surfaces do exist, both at the shoe-surface interface and on motions caused by plantar pressure distribution, necessitating further study on their effects on injury risk at proximal joints.

Clinical Significance

Unfortunately, ACL injury is a common, demoralizing injury accompanied by severe short-term and long-term complications. Because of certain inherent biomechanics, females are more likely to injure their ACL than males performing the same motion. Within these noncontact situations, there are also known extrinsic risk factors to ACL injury, including environmental factors, the playing surface, and shoe-surface interaction. Following public concern and negative perceptions of injury rate on artificial turfs, a new generation of artificial turf was created to closely mimic the characteristics associated with activity on natural grass. However, even third generation artificial turfs have properties that cause them to differ in playing characteristics from natural grass surfaces, resulting in known changes to peak torques, rotational stiffness, and plantar loading patterns across surfaces. Prospective studies have been performed to evaluate the incidence, cause, and severity of injuries between the third generation artificial turf and natural grass, leading to a prediction of ACL injury risk. Specific differences between surfaces have only been measured as torque and rotational stiffness at the shoe-surface interface and plantar distribution patterns. There have been no kinetic or kinematic measurements at the knee and hip across playing surfaces. Therefore, the purpose of this study is to determine if the third generation artificial turf playing surface when compared to a natural grass surface alters knee and hip kinematics during a jump landing cutting task in healthy females, which have been shown to be more susceptible to ACL injury through biomechanical factors that load the ACL. Since a large number of severe knee injuries in females are non-contact and weather conditions cannot be controlled, this study will examine if known biomechanical risk factors differ across playing surfaces in an attempt to find ways to decrease predisposition to injury through extrinsic environmental risk factors.

CHAPTER III

METHODOLOGY

This study is a within subjects, repeated measures design. All subjects' knee and hip sagittal, frontal, and transverse plane kinematics were evaluated during a jump landing cutting task on two different playing surfaces. Differences in knee and hip kinematics were examined within subjects and attributed to the playing surface.

Subjects

Thirty-one female Division I varsity and club soccer athletes were contacted for participation in this study (**Table 1**). Four subjects were excluded due to an inability to record initial contact as well as excessive motion artifact (i.e., noise) from the electromagnetic tracking sensors during landing (25 right dominant, 2 left dominant; 17 varsity, 10 club; age = 20.0±1.4 years; height = 167.5±6.5 cm; mass = 65.2±11.1 kg; years playing competitively = 11.6±3.3 years). Women's soccer athletes were recruited specifically because of their experience of performing jump landing and cutting tasks on new generation artificial turfs and natural grass surfaces. Subjects were excluded if they had 1) a current lower extremity injury that would not allow athletic participation, 2) a history of ACL injury in either leg, 3) a history of other knee surgery or hip surgery in their dominant leg in the past year, and 4) participated in athletic activity within one hour prior to the testing session. Athletes with a history of or current injury were excluded to avoid the effects of the injury on the hip and knee kinematics across the surfaces. Athletic activity was not allowed prior to testing to avoid the effects of fatigue.

Instrumentation

Biomechanical Analysis

Knee and hip kinematics were collected using the Flock of Birds electromagnetic motion analysis system (Ascension Technologies, Inc., Burlington, VT) during a jump landing cutting task on a natural grass surface and a 3rd generation artificial turf surface. The Motion Monitor software system (Innovative Sports Training, Inc., Chicago, IL) was used to record measurements at a kinematic sampling rate of 144 Hz. A transmitter was placed on a stationary stand between the 2 surfaces to establish the global reference frame of the system (**Figure 1**). Relative to the natural grass surface, the positive x-axis was established in the direction of the jump pre-cut, positive y-axis was to the subject's left pre-cut, and the positive z-axis was directed vertically and extending superiorly to the subject.

Each subject was instrumented with 3 electromagnetic tracking sensors, located on the apex of the sacrum, midpoint of lateral thigh, and midpoint of antero-medial shank. These locations were chosen because they are areas of the least amount of muscle mass to decrease as much motion artifact as possible. Each sensor was attached with double-sided tape. The sacral sensor was covered with a Velcro belt, while the limb sensors were covered with pre-wrap and white athletic tape to minimize sensor motion (**Figure 2**). Bony landmarks were then digitized for each subject using an additional electromagnetic sensor attached to the end of a stylus. Subjects stood in a neutral position while the landmarks were digitized as follows: medial femoral condyle, lateral femoral condyle, medial malleolus, lateral malleolus, left anterior superior iliac spine, and right anterior superior iliac spine. The digitization of the bony landmarks allowed for the definition of each segment's end points and joint centers of the lower extremity. The knee joint center was defined as the midpoint between the lateral and medial femoral condyles. The hip joint center was defined by means of the Bell method, mathematically estimating the center using the right and left anterior superior iliac spines (Bell, Pedersen et al. 1990).

Foot switches (MA-300 EMG System; Motion Lab Systems, Baton Rouge, LA), or force sensitive resistors, were used to determine the dominant leg's first foot contact from the jump landing to define initial contact on each playing surface. The one-inch in diameter switches were able to detect pressure or force changes in resistance, creating a trigger that was picked up by the Motion Monitor software. The trigger indicated initial contact. The 4 pressure sensors were placed in the athlete's dominant shoe under the great toe, first metatarsal head, fifth metatarsal head, and heel (**Figure 3 and 4**).

Testing Procedure

Setting

Before subject arrival to the testing session, a Flock of Birds electromagnetic motion analysis system was set up between the two playing surfaces to collect knee and hip kinematics during a jump landing cutting task on both surfaces. The global reference frame was established for each playing surface as described above prior to testing. A 1 x 2 foot rectangle was taped to each playing surface to act as the area in which each cut would be performed. A tape line was also placed at 90 degrees in each direction from the cutting box with a 2 foot space marked with cones to guide each subject in the direction of the cut. A 30 cm box with a non-slip surface was placed on each surface to allow for a landing task immediately prior to the cutting task (**Figure 5**).

Subjects who volunteered for participation in this study reported to the fields for one testing session. The testing session lasted approximately 30-45 minutes. On arrival to the testing session, all participants read and signed an informed consent form approved by the University of North Carolina at Chapel Hill Institutional Review Board. Subjects were also given the opportunity to discuss the study and all testing procedures.

There were five days of testing, from mid-February to March. Temperatures ranged in the sixties, and testing was only completed on sunny days to avoid moisture and humidity around the equipment. One testing session occurred following a day of rain, so 9 subjects may have performed their testing on more moist ground conditions when compared with the other 22 subjects.

Subject Preparation

Subjects were given a questionnaire to confirm eligibility status and lack of exclusion criteria (**Appendix A**). The questionnaire was also used to determine the subjects' age, shoe size, dominant leg, and possible allergies to adhesives. Dominant leg was determined as the leg the subject would choose to kick a ball as far as possible. All subjects were asked to wear athletic attire, specifically shorts, to aid in the visualization of bony landmarks during the digitizing process and to allow placement of the electromagnetic sensors and full range of motion. Subjects were also asked to bring the cleats they would choose to wear in competition on natural grass and 3rd generation artificial turf surfaces.

After the completion of the questionnaire, the subjects' height and weight were measured, and the 4 pressure sensors were placed under the great toe, first metatarsal head, fifth metatarsal head, and heel of the subject's dominant foot (Chu, Tang et al. 2009). Each subject was then given 5 minutes to warm-up on a stationary bicycle and an opportunity to stretch, and the jumping box was placed at half the subject's height away from the cutting box taped on the field. Each subject was then instrumented with the 3 electromagnetic tracking sensors and digitized for the definition of each segment's end points and joint centers of the lower extremity as described above. Subjects were given specific instructions on how to perform the trial. These instructions included jumping off the 30 cm jumping box, landing on both feet with the dominant foot in the cutting rectangle, and cutting at a 90 degree angle on the dominant leg immediately following initial contact with the playing surface (**Figure 6**). A cutting demonstration was then given to each subject, and up to 5 practice trials were allotted so that the subject would be familiar with the testing process.

Data Collection Procedure

The conditions were counterbalanced in that 15 subjects performed the natural grass condition first and 16 subjects performed the artificial turf surface condition first. Subjects began each trial standing on the jumping box, and the dominant foot plant of the cutting task occurred within the cutting rectangle upon landing. The degree of each cut occurred at 90 degrees from the direction of the jump. Five trials were performed by each subject on both surfaces. A sufficient amount of rest was given between each trial as the quality of the trial was determined on the Motion Monitor software. A trial was thrown out if the subject performed the cutting task at the wrong cutting angle, the foot switch did not record the proper initial contact, or if the whole trial was not recorded by the Motion Monitor software.

Data Analysis

Data Processing

Embedded right-hand Cartesian coordinate systems were defined for the hip and knee to describe the three-dimensional position and orientation of the pelvis, thigh, and shank in alignment with the global reference system. Euler angles were used to calculate the hip angles between the pelvis and thigh and knee angles between the thigh and shank. Flexion and extension occurred about the y-axis, knee valgus/varus and hip abduction/adduction occurred about the x-axis, and internal and external rotation occurred about the z-axis. The kinematic data from the Motion Monitor software was exported and reduced using customized MATLAB software (The MathWorks Inc., Natick, MA). The kinematic data was low pass filtered using a 4th order Butterworth filter at 14.5 Hz. Hip extension, hip adduction, and hip internal rotation were indicated by positive values. Knee flexion, knee varus, and knee internal rotation were indicated by positive values.

Data were sampled for a 5 second interval around the instant of initial ground contact (2 seconds before and 3 seconds after initial contact). Hip and knee kinematic variables were assessed at initial contact and peak knee flexion of the jump landing cutting maneuver. Initial contact was defined as the instant that the dominant foot came in contact with the ground from the jumping task in the cutting rectangle to initiate the cutting maneuver. Peak knee flexion was defined as the greatest knee flexion value in the dominant leg when landing from the jumping task and initiating the cutting maneuver. The following variables were calculated at the instant of initial contact and peak knee flexion: hip and knee sagittal, frontal, and transverse plane angles. The peak values at initial contact and peak knee flexion for the 3 “best” trials on each surface were averaged, and the excursion was calculated as the angular change from initial contact to the time corresponding with peak knee flexion. These values were created for each subject's dependent variables on both surfaces. The 3 "best" trials were chosen by initially looking at trials 2, 3, and 4. However, trial 1 or 5 may have been used if there was increased motion artifact or if initial contact could not be determined in trials 2, 3, and 4.

Statistical Analysis

Data were analyzed using PASW Statistics 18.0 statistical software (SPSS, Inc., Chicago, IL). Descriptive statistics were run to find means and standard deviations for each of the 6 dependent variables. Six separate paired t-tests were also run to compare the means between the natural grass and artificial turf playing surfaces from initial contact to peak knee flexion (excursion values) of the jump landing cutting task for each dependent variable. The significance level was set *a priori* at an alpha of 0.05.

CHAPTER IV

RESULTS

Initial Contact

Hip and knee kinematic variables at initial contact and peak knee flexion are presented in **Table 2** (**Figures 7-12**). Qualitatively, there are minimal differences at initial contact of all kinematic variables between the two playing conditions (< 2 degrees).

Excursion

Hip and knee kinematic variables from initial contact to peak knee flexion (excursion values) are presented in **Table 3**. Although sagittal plane hip excursion angles were not significantly different between the natural grass and artificial turf surfaces ($t_{26} = -1.987$, $p = 0.058$), significant differences were observed at the hip in the frontal ($t_{26} = -2.190$, $p = 0.038$) and transverse planes ($t_{26} = -2.075$, $p = 0.048$) from initial contact to peak knee flexion (**Figure 13**). Specifically, subjects showed significantly more hip movement in the frontal plane on the artificial turf surface (grass: 0.5±7.3º; turf: 3.6±7.2º), resulting in more hip adduction on the artificial turf surface than the natural grass surface at peak knee flexion. The mean hip frontal plane angle at peak knee flexion on the grass surface was -3.2±6.6º and the mean on the artificial turf surface was 0.8±7.0º. Subjects showed significantly more hip movement in the transverse plane on the natural grass surface (grass: -6.2±7.1º; turf: -4.1±6.0º), resulting in the hip moving farther into external rotation on the natural grass surface than the artificial turf surface at peak knee flexion. The mean hip transverse plane angle at peak knee flexion on the grass surface was -5.6±8.2º and the mean on the artificial turf surface was -2.7±7.7º, meaning that the hip was more externally rotated on the natural grass surface.

Although sagittal (t_{26} = -0.293, p = 0.772) and transverse (t_{26} = 0.381, p = 0.706) plane knee excursion angles were not significantly different between the natural grass and artificial turf surfaces, significant differences were observed at the knee in the frontal (t_{26} = -2.648, p = 0.014) plane from initial contact to peak knee flexion (**Figure 14**). Specifically, subjects showed significantly more movement in the frontal plane at the knee on the natural grass surface (grass: -8.5±8.0º; turf: -5.1±6.6º), resulting in more knee valgus on the natural grass surface than the artificial turf surface at peak knee flexion. The mean knee frontal plane angle at peak knee flexion on the grass surface was -7.7±8.3º and the mean on the artificial turf surface was -5.8±6.9º.

CHAPTER V

DISCUSSION

These findings partially confirm the hypothesis that performing a jump landing and cutting task on the artificial turf surface alters lower extremity kinematics when compared to natural grass. Specifically, the performance of a jump landing and cutting task on an artificial turf surface produced more hip adduction and less hip external rotation motion during weight acceptance compared to the same task performed on a natural grass surface. In addition, there was an increased frontal plane excursion on natural grass. This altered movement pattern may have clinical implications for injury risk at the knee.

Even with the new advancements in artificial turfs, the newer generation still has different characteristics when compared to natural grass. In previous studies, these differences, such as increased rotational stiffness and friction, have been shown to cause changes at the shoe-surface interface and on foot loading patterns (Ford, Myer et al. 2003). Any change at the shoe-surface interface could influence the kinematics of proximal joints. For example, research has shown that artificial turf influences plantar loading patterns, increasing an inversion pattern with cutting tasks as the load is shifted to the medial side of the foot. This change in plantar loading can possibly lead to more valgus stress at the knee (Eils, Streyl et al. 2004). This pattern differs from that found on a grass surface, which shows higher pressures on the medial forefoot and lateral midfoot. The higher loaded areas on the turf raise concerns that they may produce higher friction at the shoe-surface interface as well as changes in proximal joint kinematics, which is known to lead to injury (Ford, Manson et al. 2006).

We are particularly concerned about the abnormal motion of the hip joint, due to its role in controlling knee movement and the subsequent increase in load on the ACL. Previous investigators have examined movement patterns in the frontal plane and established that hip adduction and knee abduction were correlated during cutting tasks. With the hip adducted, knee valgus also increased, making hip adduction a predictor of the injurious valgus mechanism at the knee (Imwalle, Myer et al. 2009). Imwalle et al. (2009) suggested that hip adduction increases the mechanism for increased load on the ACL and noncontact ACL injury during cutting tasks. In the transverse plane, Pollard et al. (2007) observed female subjects displaying greater hip internal rotation during a cutting task when compared with male subjects, and suggested that increased hip internal rotation during functional tasks alters the alignment of the lower extremity (Pollard, Sigward et al. 2007). In the present study, subjects displayed increased motion in the transverse plane at the hip resulting in more external rotation on the grass surface. Although the hip was also externally rotated on the artificial turf surface, it was relatively more internally rotated when compared with the natural grass condition. The externally rotated position is most likely due to the cutting task. Since hip angles were calculated based on the position of the thigh relative to the pelvis, the turning of the pelvis away from the dominant leg with the cut would cause the hip to appear externally rotated. On the contrary, if the subjects had been asked to cut toward their dominant side, increased internal rotation values may have been noticed, potentially increasing the load placed on the ACL.

In addition to the elevated risk for ACL injury, increased hip adduction and internal rotation with functional tasks can increase stress at the patellofemoral joint. Souza and Powers (2009) found that females with patellofemoral pain displayed increased hip internal rotation during running. In addition, Powers et al. (2003) concluded that the excessive lateral tilt and glide of the patella during a single leg squat was due to the internal rotation of the femur occurring at the hip instead of movement at the patellofemoral joint. These results suggest that the movement patterns occurring at the hip during functional tasks can influence the kinematics of the patellofemoral joints in a manner consistent with causing patellofemoral pain (Powers, Ward et al. 2003; Souza and Powers 2009).

Findings of the current study showed hip kinematic differences during the loading phase of the jump landing cutting task and altered frontal plane motion at the knee. A study performed by Pollard et al. (2006) had similar results at the hip following a drop landing task. After participating in an established season-long ACL injury prevention training program (PEP program), female soccer players demonstrated decreased peak hip internal rotation and adduction angles during landing. Even with these changes in hip kinematics, subjects did not display a change in knee kinematics, perhaps due to the ease of the drop landing testing task (Pollard, Sigward et al. 2006). Likewise, it is conceivable that changes in knee kinematics were not observed at peak knee flexion in the current study due to the task. In the present study, subjects were high-level athletes who were comfortable in performing the double-leg drop landing cutting task. A more difficult task may have resulted in more substantial changes in knee kinematics between conditions, as the increased hip adduction and internal rotation viewed on the artificial turf surface may have contributed to increased knee valgus at peak knee flexion during the performance of a more demanding quick deceleration maneuver.

It is possible that the magnitude of the changes occurring at the hip in the frontal and transverse planes may not be enough to elicit a change in biomechanical positioning at the knee. Therefore, the hip kinematic differences between landing surfaces alone may not be great enough to predispose an athlete to injury on the artificial turf surface. However, for those athletes already playing with additional or increased risk factors, competing on artificial turf may further increase the risk for ACL injury beyond the threshold for injury. Thus, the results of the current research study suggest that the performance of jump landing cutting tasks on 3rd generation artificial turf alters hip frontal and transverse plane kinematics in a manner consistent with increasing the load placed on the ACL.

Although there were no major differences noticed at the knee at initial contact or peak knee flexion between playing surfaces, there was a significant difference in knee excursion in the frontal plane. Subjects displayed more movement in the frontal plane on the natural grass surface, resulting in somewhat more valgus at peak knee flexion. However, the subjects landed in a slightly more valgus position on the artificial turf surface, which could have inflated the excursion values on the natural grass. Since motions consistent with additional load on the ACL were occurring at the hip on the artificial surface, the reduced valgus motion at the knee could have been a compensation for the increased motion at the hip to avoid injury. On the contrary, the subjects' decreased motion at the knee on the artificial surface could have contributed to altered motion at the hip (Livesay, Reda et al. 2006; Villwock, Meyer et al. 2009). The subjects may have also been more comfortable performing the cutting task on the natural grass surface, placing more effort into the task.

We suspect that any increased comfort or effort could have resulted in more movement at the knee in the frontal plane.

Even though hip kinematic differences were found between surfaces, these changes in biomechanics do not necessarily mean that more ACL injuries will occur on the artificial turf when compared to natural grass. Several prospective studies have examined and compared the incidence, cause, and risk of injuries on natural grass and third generation artificial turf (Meyers and Barnhill 2004; Ekstrand, Timpka et al. 2006; Fuller, Dick et al. 2007; Fuller, Dick et al. 2007; Steffen, Andersen et al. 2007). Although most studies agree that there are no overall differences in the level of risk and cause of the injuries experienced on both surfaces, none have been specific to ACL injury.

Limitations

Potential limitations to the current research study include the use of only female soccer players. Females were chosen specifically because it was believed that greater differences between surfaces would be noted with female subjects due to the known disparity in ACL injury rates between genders. Female athletes have been found to experience ACL injuries at a rate of 2 to 6 times more often than males playing the same sport (Arendt, Agel et al. 1999). However, the choice to test only female subjects does not allow generalizations to be made about male athletes participating in sports on these playing surfaces. Our subjects were also chosen specifically because of their experience with activities on both natural grass and artificial turf surfaces. We did not want lack of experience on one of the surfaces to alter the kinematic variables. However, this concern does not allow generalizations to be made about individuals with no experience participating on artificial surfaces.

Results also cannot be applied to other brands of 3rd generation artificial turfs. The multiple types of artificial turfs have different qualities of the synthetic grass fibers and the in-fill systems of different percentages of sand and rubber. These different qualities could lead to changes in friction and stiffness at the shoe-surface interface, possibly affecting hip and knee kinematics with landing and cutting maneuvers (Meyers and Barnhill 2004; Steffen, Andersen et al. 2007).

Excessive motion artifact (i.e., noise) from the electromagnetic tracking sensors during landing limited the ability to analyze the hip and knee kinematic data over the loading phase. Although theoretically most loading to the ACL would occur at peak knee flexion, it was not possible to verify peak kinematic values over the loading phase. Therefore, for example, higher knee valgus could have occurred prior to peak knee flexion, but was not analyzed due to the variability of the data.

It is important to note that there were differences in environmental conditions across the subjects. In the present study, one testing session occurred following a day of rain, so 9 subjects may have performed their testing on more moist ground conditions when compared with the other 22 subjects. With a repeated measures design and subjects performing the task on both surfaces on the same day, it is unlikely that the outcome of the current study was affected. However, in previous studies, it was determined that a relationship exists between ACL injury and weather conditions that result in a dryer playing surface. It was thought that the speed of the game increases on a dryer surface, as well as the friction and torsional resistance between cleats and grass. In the long-term, it was concluded that low water evaporation and high rainfall significantly decreased the risk of noncontact ACL injuries, possibly from the decreased traction occurring at the shoe-surface interface (Orchard, Seward et al. 2001). Since more moisture would be absorbed on the artificial surface when compared to natural grass, it could be suggested that the friction and torsional resistance would be higher on the artificial surface. In addition, Meyers and Barnhill (2004) noted a significant increase in incidence of injury on FieldTurf during temperatures greater than 70 degrees Fahrenheit when compared to colder days and to injuries on natural grass. The testing of the current study occurred during temperatures less than 70 degrees. Therefore, greater kinematic differences could have been noted if testing had been completed during higher temperatures.

Future Research

Future research concerning ACL injury risk on different types of playing surfaces should examine the effect of the different brands of artificial turf surfaces on movement patterns across a range of environmental conditions (including moisture and temperature). This information could allow researchers to observe if there is a type of in-fill system, synthetic grass fiber, moisture level, or temperature that increases the loading placed on the ACL during rapid deceleration tasks. Since the appearance of the first artificial turfs in the mid-1970s, artificial turf surfaces have been modified and improved from the high stiffness and friction and low shock absorption associated with an increased injury rate on the surface. These advancements combatted the higher amounts of overuse injuries seen on the first and second generation turfs and addressed the stiffness issues experienced with the older turfs (Meyers and Barnhill 2004; Steffen, Andersen et al. 2007). Advancements on artificial turf surfaces can continue to be made.

It would also be beneficial to study muscular recruitment or firing patterns during landing or cutting maneuvers on multiple playing surfaces. Different surfaces could cause changes in preparation for the task, which may not necessarily present as kinematic differences. This information may allow for the development of training programs to battle the increased risk of hip adduction and internal rotation during deceleration tasks on artificial turf surfaces.

Because our subjects were chosen specifically based on their experience with activities on both natural grass and artificial turf surfaces, future study is necessary to make assertions about how athletes naïve to participation on artificial surfaces would react to competing on that condition. Those athletes with familiarity on artificial surfaces may have the experience necessary to mitigate abnormal movement patterns during those tasks that place additional load on the ACL. Conversely, athletes without the experience to avoid altered movement patterns that may be related to playing on artificial turf may have a greater predisposition to injury than those athletes with an awareness of the surface. A related question would then concern if those athletes that play on artificial surfaces should practice on those surfaces as well. If the artificial turf does predispose ACL injury, additional exposures on that surface would only increase the likelihood for injury. However, increased familiarity with the surface may decrease the probability of injury during game play.

This information could also lead to an understanding about if the above mentioned training programs would be more beneficial if completed on artificial turf surfaces. This could possibly give neuromuscular pathways the experience necessary to compensate for alterations in movement patterns caused by the artificial surface. On the contrary, the training programs may be just as successful if completed on natural grass surfaces.

Clinical Significance

As excessive hip frontal and transverse plane kinematics can add to the load placed on the ACL, injury prevention programs designed to decrease the injurious biomechanical position of hip adduction and internal rotation may be necessary for those athletes continuously competing on artificial turf surfaces. In an in-season ACL injury prevention program study performed by Pollard et al. (2006), the intervention program significantly altered the hip kinematics of female soccer players. After participating in a season-long training program, female soccer players demonstrated decreased peak hip internal rotation and adduction angles during landing. Pollard et al. (2006) concluded that injury prevention training, completed with normal soccer practice, is beneficial in altering the lower extremity kinematics that otherwise would place athletes in a biomechanical position that places additional load on the ACL.

Conclusion

During a jump landing cutting task, females displayed altered movement in the frontal and transverse planes at the hip, resulting in greater hip adduction and less hip external rotation during loading on a 3rd generation artificial turf surface compared to a natural grass surface. The observed changes in kinematics at the hip could be caused by or lead to altered frontal plane motion at the knee. These findings suggest that the artificial turf surface places females in a biomechanical position at the hip that places more load on the ACL, but a position at the knee which is protective of the ACL. Future research is needed to determine the ideal in-fill percentage and type of synthetic fiber, leading to further advancements and improvements in the safety of an artificial surface. Further study into muscle recruitment patterns and the effect of experience on artificial turf surfaces could lead to the development of an intervention program and analysis of its long-term effect on injury prevention.

FIGURES

Figure 1. Transmitter placed between two playing surfaces to establish global reference frame of the system.

Figure 2. The location of the 3 electromagnetic tracking sensors.

Figure 3. The location of the 4 pressure sensors.

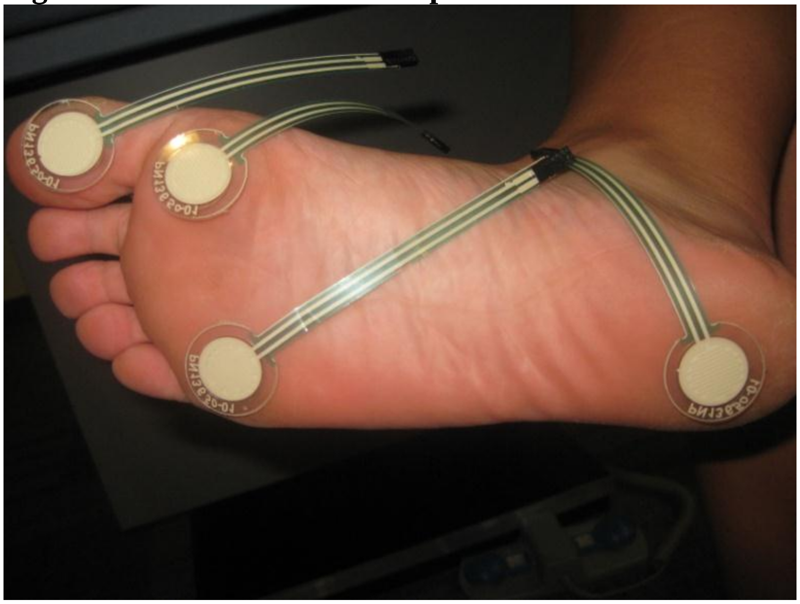


Figure 4. The attachment of the 4 pressure sensors' connection wires to the leg.

Figure 5. Field set-up.

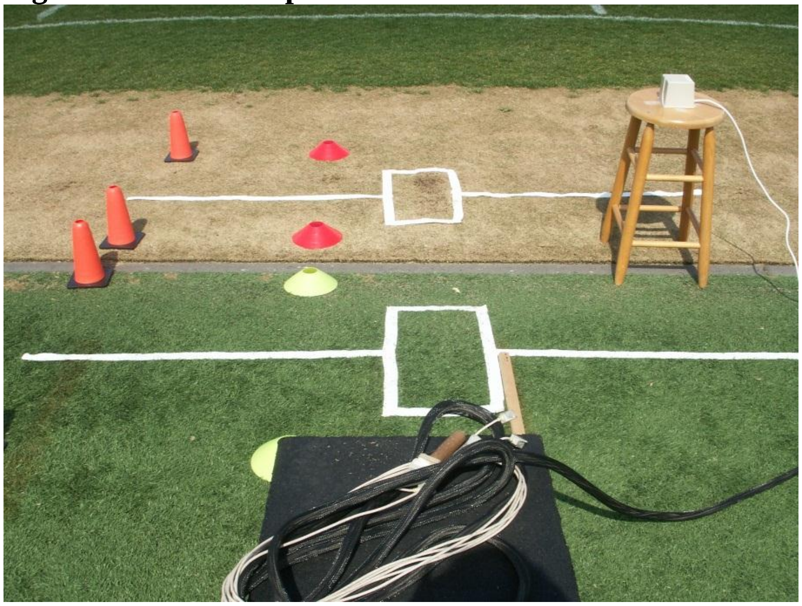


Figure 6. Jump landing and cutting task.

[redacted] [redacted] [redacted] [redacted] [redacted]

Figure 7. Means and standard deviations (SD) of hip sagittal plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

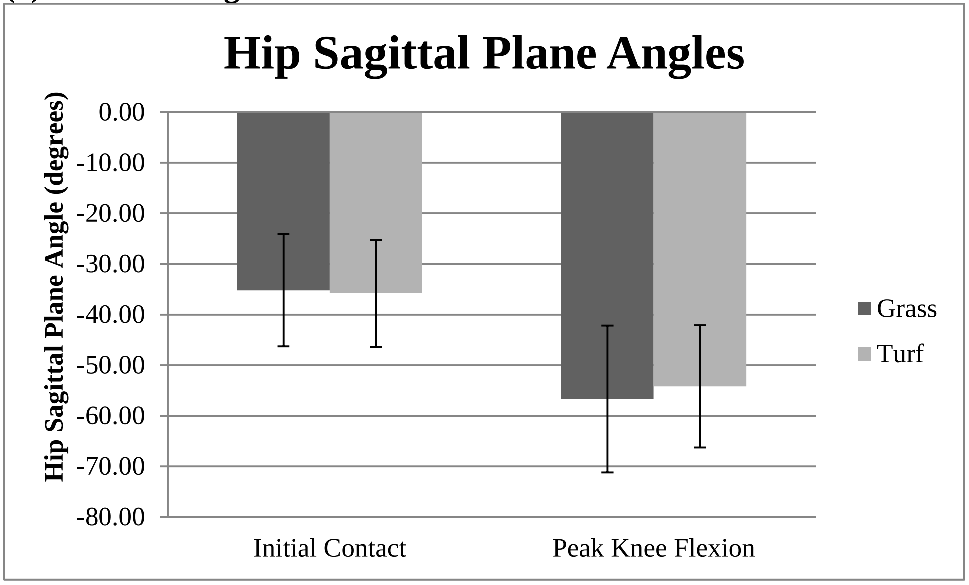


Figure 8. Means and standard deviations (SD) of hip frontal plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

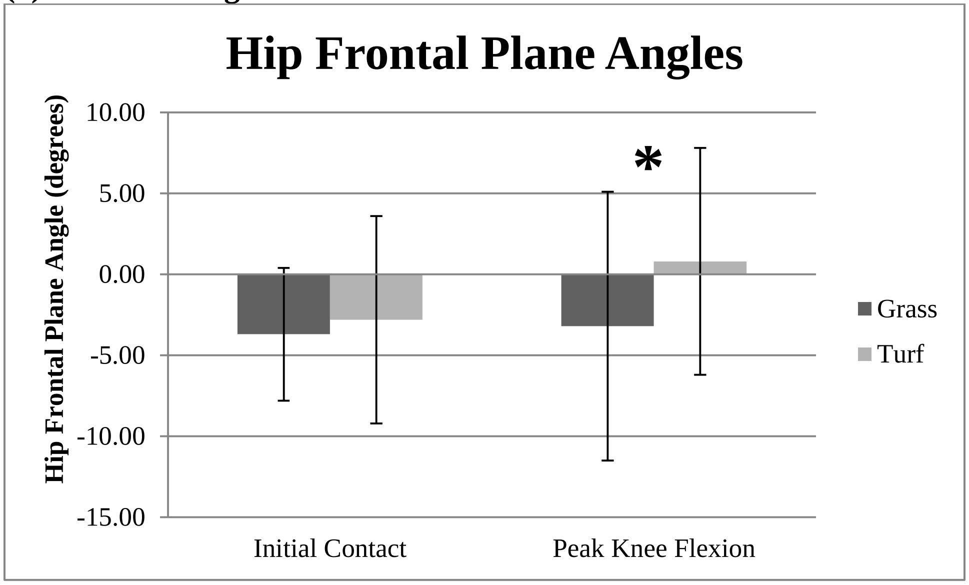


Figure 9. Means and standard deviations (SD) of hip transverse plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

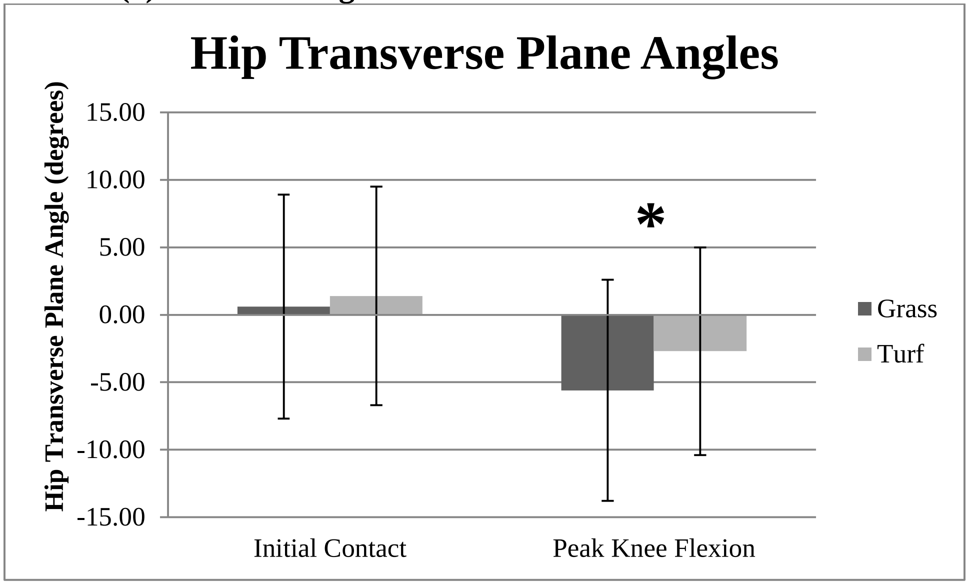


Figure 10. Means and standard deviations (SD) of knee sagittal plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

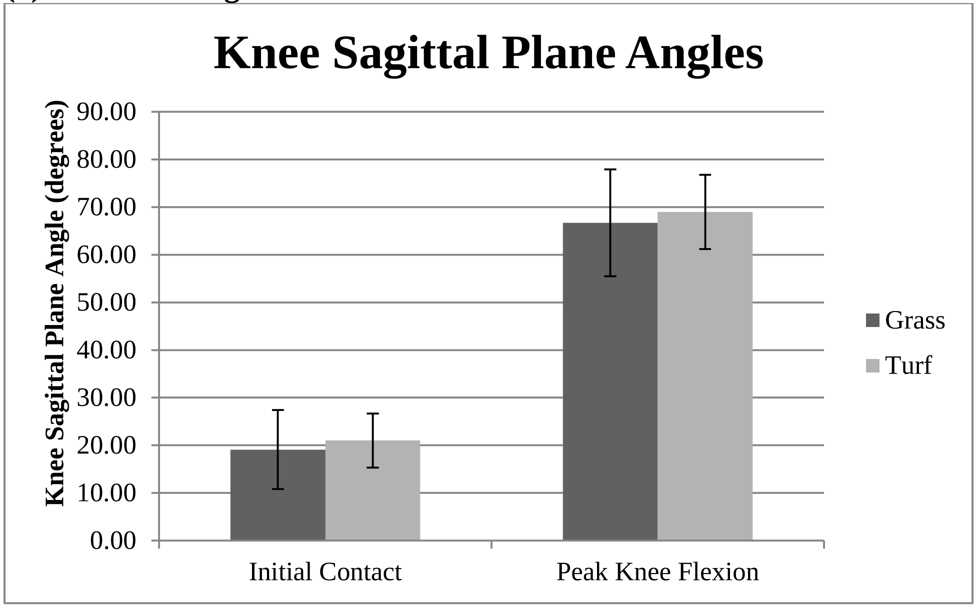


Figure 11. Means and standard deviations (SD) of knee frontal plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

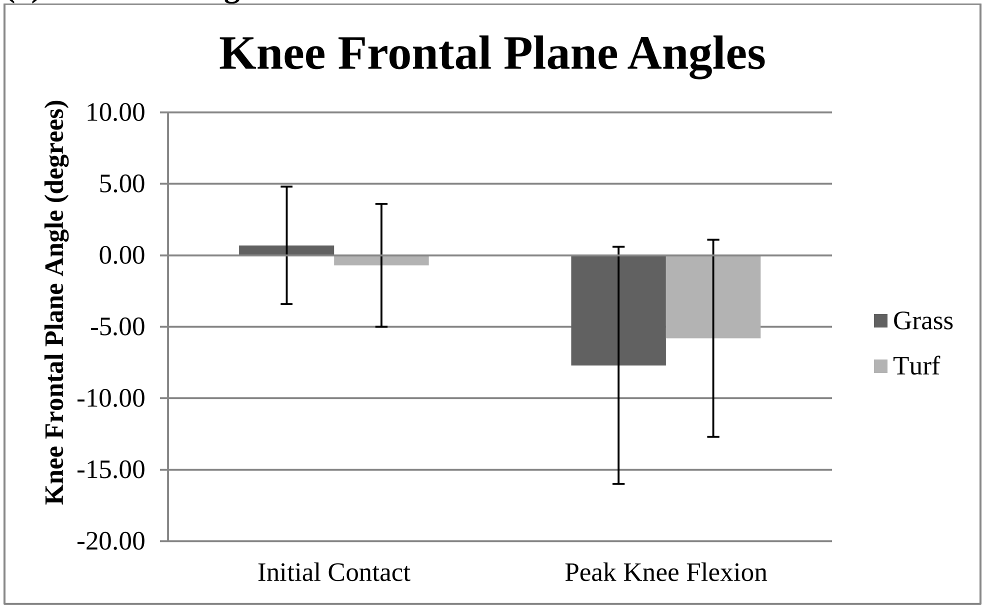


Figure 12. Means and standard deviations (SD) of knee transverse plane angles at initial contact and peak knee flexion on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

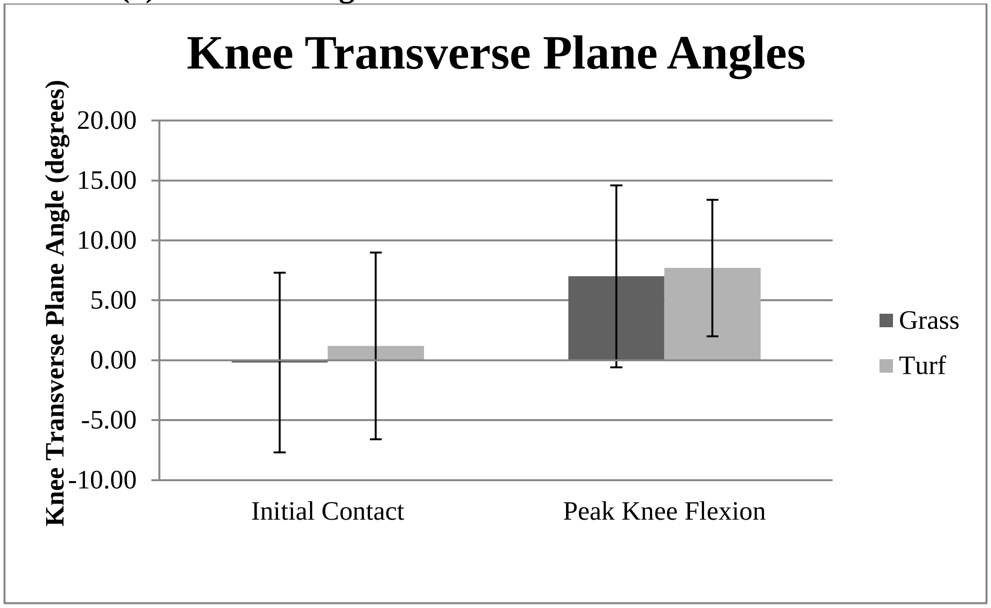


Figure 13. Means and standard deviations (SD) of hip angles from initial contact to peak knee flexion (excursion values) on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

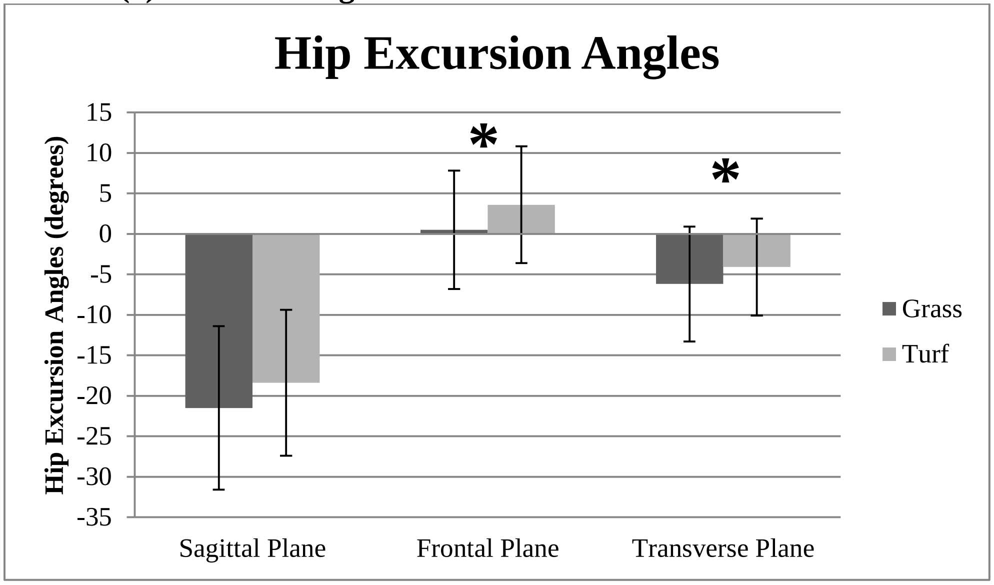
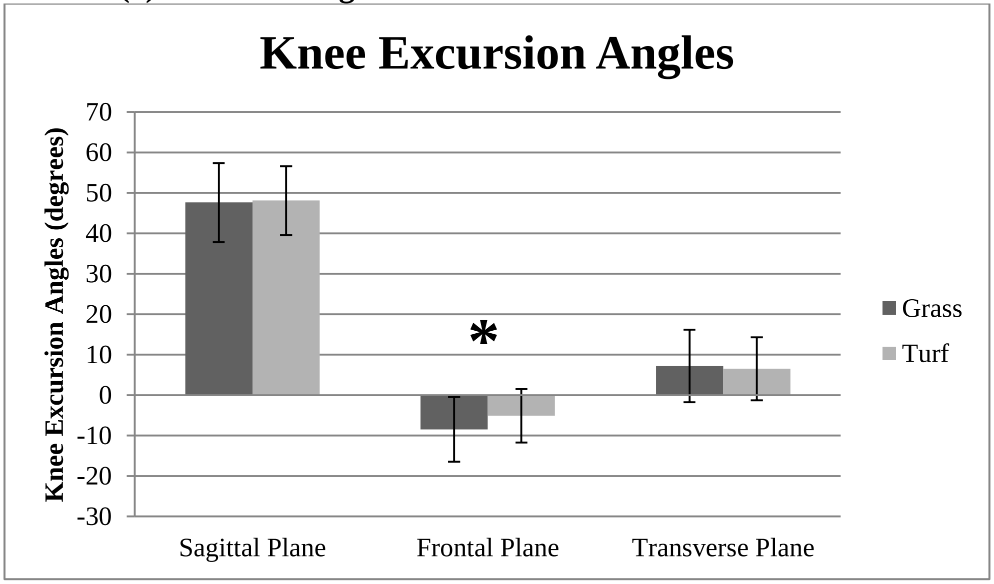


Figure 14. Means and standard deviations (SD) of knee angles from initial contact to peak knee flexion (excursion values) on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.



TABLES

Table 1. Subject Demographics.

Number of Subjects (n)	27
R Dominant/L Dominant	25/2
Varsity/Club	17/10
Age (yrs)	20.0±1.4
Height (cm)	167.5±6.5
Mass (kg)	65.2±11.1
Years Playing Competitively	11.6±3.3

Table 2. Means and standard deviations (SD) of hip and knee kinematic variables at initial contact and peak knee flexion during a jump landing cutting task on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

	Initial Contact		**Peak Knee Flexion**	
Kinematic Variables	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)
Hip Sagittal Plane	-35.2±11.1	-35.8±10.6	-56.7±14.5	-54.2±12.1
Hip Frontal Plane	-3.7±6.6	-2.8±6.4	-3.2±6.6	0.8±7.0*
Hip Transverse Plane	0.6±8.3	1.4±8.1	-5.6±8.2	-2.7±7.7*
Knee Sagittal Plane	19.1±8.3	21.0±5.7	66.7±11.2	69.0±7.8
Knee Frontal Plane	0.8±4.1	-0.7±4.3	-7.7±8.3	-5.8±6.9
Knee Transverse Plane	-0.2±7.6	1.2±7.8	7.0±7.6	7.7±5.7

Table 3. Means and standard deviations (SD) of hip and knee kinematic variables from initial contact to peak knee flexion (excursion values) during a jump landing cutting task on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

	Excursion	
Kinematic Variables	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)
Hip Sagittal Plane	-21.5±10.1	-18.4±9.0
Hip Frontal Plane	0.5±7.3	3.6±7.2*
Hip Transverse Plane	-6.2±7.1	-4.1±6.0*
Knee Sagittal Plane	47.6±9.8	48.1±8.5
Knee Frontal Plane	-8.5±8.0	-5.1±6.6*
Knee Transverse Plane	7.2±9.0	6.5±7.8

APPENDIX A: Inclusion Criteria and Demographic Information Questionnaire

Identification Number: ________

Inclusion Criteria and Demographic Information Questionnaire

Please answer the following questions honestly and to the best of your ability.

What is your gender?

How old are you?

What is your shoe size?

What sport do you play at UNC-CH? Are you a varsity or club athlete?

How many years have you been playing soccer competitively?

What is your dominant leg? *You dominant leg is defined as the leg you would choose to kick a ball as far and as hard as possible.*

Do you currently have any lower extremity of other injury that prevents or limits your athletic participation? If yes, what and why?

Do you have a history of ACL injury to your either leg?

Do you have a history of any other knee surgery to your dominant leg in the past year? If yes, what?

Did you participate in any athletic activity in the hour prior to this testing session? *Athletic activity is defined as any activity that may raise your heart rate, such as running, sport-specific activities, or resistance exercises.* If yes, what and when?

Do you have an allergy to any type of adhesive? *The tracking sensors will be applied with double-sided tape.*

Height: ___________

Weight: ___________

APPENDIX B: Manuscript formatted for Clinical Biomechanics

EFFECT OF PLAYING SURFACE ON KNEE AND HIP KINEMATICS IN HEALTHY FEMALE POPULATIONS

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Number of Tables: 3

ABSTRACT

Background. Previous research implicates specific hip and knee kinematics during functional tasks as increasing the risk of ACL injury. Since a large number of severe knee injuries in females are non-contact, the purpose of this study is to determine if knee and hip kinematics during a jump landing cutting task in healthy female populations differ between third generation artificial turf and natural grass playing surfaces. We hypothesized that the task performed on the artificial turf would place the subjects in a biomechanical position that places a greater load on the ACL.

Methods. Thirty-one female varsity and club soccer athletes performed a 90 degree cutting maneuver immediately after landing from a box jump on a natural grass and a 3rd generation artificial turf playing surface while 3D hip and knee kinematics were assessed.

Results. Subjects showed significantly different hip movement in the frontal ($p = 0.038$) and transverse ($p = 0.048$) planes and knee movement in the frontal plane ($p = 0.014$) between surface conditions.

Interpretation. Increased hip adduction and internal rotation with functional tasks can increase the load placed on the ACL. Therefore, future research is needed to determine ideal in-fill percentages and synthetic fibers, leading to further advancements in the safety of an artificial surface. In addition, further study into muscle recruitment patterns and the effect of experience on artificial turf surfaces could lead to the development of an intervention program and analysis of its long-term effect on injury prevention.

Keywords: ACL; hip kinematics; knee kinematics; artificial turf; grass; **Word Count: 250**

1. Introduction

Since the beginning of the 1970s and the passing of Title IX, there has been a dramatic increase in the number of female athletes participating in individual and team sports in the United States (Arendt, Agel et al. 1999). Since then, the number of anterior cruciate ligament (ACL) injuries in the country has increased to an estimated 80,000 every year (Shimokochi and Shultz 2008). Of this daunting number, female athletes have been found to experience these injuries at a rate of 2 to 6 times more often than males playing the same sport (Arendt, Agel et al. 1999). Even more overwhelming is the fact that approximately 70% of these injuries occur in non-contact situations, usually during quick deceleration before a cutting maneuver or during a jump landing (Cowley, Ford et al. 2006; Shimokochi and Shultz 2008).

Overall risk factors for non-contact knee injury include intrinsic and extrinsic factors. Of these risk factors, certain biomechanics inherent to the athlete, as well as those from the playing surface and environmental conditions, have been shown to increase the likelihood of sustaining a significant knee injury (James, Sizer et al. 2004; Alentorn-Geli, Myer et al. 2009; Pollard, Sigward et al. 2010). Females have been described as having "ligament dominance," meaning that they rely more on passive restraints in the knee by limiting motion in the sagittal plane, placing more stress on their ligaments (Ford, Myer et al. 2003; Pollard, Sigward et al. 2010). This behavior typically results in increased knee valgus, which has been shown to increase the risk for ACL injury (Imwalle, Myer et al. 2009; Pollard, Sigward et al. 2010).

Extrinsic risk factors to injury include the playing surface, environmental conditions such as temperature and amount of moisture, and the forces occurring at the shoe-surface interface. It has been shown that increased ground hardness and high rotational traction and friction at the shoe-surface interface results in a higher potential for lower extremity injury (Livesay, Reda et al. 2006; Villwock, Meyer et al. 2009).

Previous studies on the risk of injury on older generations of artificial turf are poorly documented and not easily accessible. Due to this lack of research and documentation concerning artificial turf, there seems to be an overall negative public perception and biasing against them (Steffen, Andersen et al. 2007). Since the emergence of the first artificial turfs in the mid-1970s, turfs have been modified from the high stiffness and friction that caused them to differ greatly from natural grass to a third generation of turf that more closely imitates the properties of a natural playing surface (Steffen, Andersen et al. 2007). Following these improvements, there has been an increased use in third generation turfs for multiple reasons (Fuller, Dick et al. 2007). Recently, prospective and retrospective studies have shown no overall significant differences between the new artificial turfs and natural grass on incidence, severity, nature, and cause of acute and chronic injuries. However, no study was specific to ACL injury (Meyers and Barnhill 2004; Ekstrand, Timpka et al. 2006; Fuller, Dick et al. 2007; Fuller, Dick et al. 2007; Steffen, Andersen et al. 2007).

Even with the new advancements in turf to mimic a natural playing surface, new generation artificial turfs still have different characteristics when compared to natural grass, such as increased stiffness and friction, that have been shown to cause differences at the shoe-surface interface and on foot loading patterns (Ford, Myer et al. 2003; Eils, Streyl et al. 2004; Ford, Manson et al. 2006). Any change at the shoe-surface interface caused by extrinsic differences at the playing surface could influence the kinematics of proximal joints, potentially predisposing them to injury.

The purpose of this study is to determine if the 3^{rd} generation artificial turf playing surfaces alter knee and hip kinematics during a jump landing cutting task in healthy females when compared to a conventional grass surface in a manner that is consistent with ACL injury. Since a large number of severe knee injuries in females are non-contact, this study will examine if known biomechanical risk factors differ across playing surfaces in an attempt to find ways to decrease predisposition to injury through extrinsic environmental risk factors. It was hypothesized that the artificial turf surface would place the subjects in a biomechanical position that places more load on the ACL, specifically decreased hip and knee flexion angles and increased hip adduction, knee valgus, hip internal rotation, and knee external rotation angles, when compared to a natural grass surface.

2. Methods

2.1 Subjects

Thirty-one female Division I varsity and club soccer athletes participated in this study (Table 1). Four subjects were excluded due to an inability to record initial contact as well as excessive motion artifact (i.e., noise) during landing (25 right dominant, 2 left dominant; 17 varsity, 10 club; age = 20.0±1.4 years; height = 167.5±6.5 cm; mass = 65.2±11.1 kg; years playing competitively = 11.6±3.3 years). Subjects were excluded if they had 1) a current lower extremity injury that would not allow athletic participation, 2) a history of ACL injury in either leg, 3) a history of other knee or hip surgery in their dominant leg in the past year, and 4) participated in athletic activity within one hour prior to the testing session. All participants read and signed an informed consent form approved by the University of North Carolina at Chapel Hill Institutional Review Board.

2.2 Instrumentation

Knee and hip kinematics were collected using the Flock of Birds electromagnetic motion analysis system (Ascension Technologies, Inc., Burlington, VT). The Motion Monitor software system (Innovative Sports Training, Inc., Chicago, IL) was used to record measurements at a kinematic sampling rate of 144 Hz. Global and segment axis systems were established relative to the natural grass surface (the positive x-axis was established in the direction of the jump pre-cut, positive y-axis was to the subject's left pre-cut, and the positive z-axis was directed vertically and extending superiorly to the subject).

Each subject was instrumented with 3 electromagnetic tracking sensors, located on the apex of the sacrum, midpoint of lateral thigh, and midpoint of antero-medial shank. Each sensor was attached with double-sided tape, pre-wrap, and white athletic tape. Subjects stood in a neutral position while the landmarks were digitized to define the knee joint center as the midpoint between the lateral and medial femoral condyle and the hip joint center by means of the Bell method (Bell, Pedersen et al. 1990).

Foot switches (MA-300 EMG System; Motion Lab Systems, Baton Rouge, LA), or force sensitive resistors, were used to determine the dominant leg's first foot contact from the jump landing to define initial contact on each playing surface, by detecting pressure changes that were picked up by the Motion Monitor software. The 4 pressure sensors were placed in the athlete's dominant shoe under the great toe, first metatarsal head, fifth metatarsal head, and heel.

2.3 Experimental procedures

Before subject arrival to the testing session, a 1 x 2 foot rectangle was taped to each playing surface to act as the area in which each cut would be performed. A tape line was also placed at 90 degrees in each direction from the cutting box with a 2 foot space marked with cones to guide each subject in the direction of their cut. A 30 cm box with a non-slip surface was placed on each surface to allow for a landing task immediately prior to the cutting task (Figure 1).

Subjects reported to the fields for one 30-45 minute testing session and completed a questionnaire to confirm eligibility status, demographic information, and dominant leg. Dominant leg was determined as the leg the subject would choose to kick a ball as far as possible. Subjects were also asked to bring the cleats they would choose to wear in competition on natural grass and 3rd generation artificial turf surfaces. Height and weight were measured, and the 4 pressure sensors were placed in the shoe. Each subject was then given 5 minutes to warm-up on a stationary bicycle and an opportunity to stretch, and the jumping box was placed at half the subject’s height away from the cutting box taped on the field. Each subject was then instrumented with the 3 electromagnetic tracking sensors and digitized. Subjects were given specific instructions on how to perform the trial. These instructions included jumping off the 30 cm jumping box, landing on both feet with the dominant foot in the cutting rectangle, and cutting at a 90 degree angle on the dominant leg immediately following initial contact with the playing surface (Figure 2). A cutting demonstration was then given to each subject, and up to 5 practice trials were allotted so that the subject would be familiar with the testing process.

The conditions were counterbalanced in that 15 subjects performed the natural grass condition first, and 16 subjects performed the artificial turf surface condition first. Five trials were performed by each subject on both surfaces. A sufficient amount of rest was given between each trial as the quality of the previous trial was determined by the researcher on the

Motion Monitor software. A trial was thrown out if the subject performed the cutting task at the wrong cutting angle, the foot switch did not record the proper initial contact, or if the whole trial was not recorded by the Motion Monitor software.

2.4 Data sampling and processing

Embedded right-hand Cartesian coordinate systems were defined for the hip and knee, and Euler angles were used to calculate the hip angles between the pelvis and thigh and knee angles between the thigh and shank. Flexion and extension occurred about the y-axis, knee valgus/varus and hip abduction/adduction occurred about the x-axis, and internal and external rotation occurred about the z-axis. The kinematic data from the Motion Monitor software was exported and reduced using customized MATLAB software (The MathWorks Inc., Natick, MA). The kinematic data was low pass filtered using a 4th order Butterworth filter at 14.5 Hz. Hip extension, hip adduction, and hip internal rotation were indicated by positive values. Knee flexion, knee varus, and knee internal rotation were indicated by positive values.

Data were sampled for a 5 second interval around the instant of initial ground contact (2 seconds before and 3 seconds after initial contact). Hip and knee kinematic variables were assessed at initial contact and peak knee flexion of the jump landing cutting maneuver. Initial contact was defined as the instant that the dominant foot came in contact with the ground from the jumping task in the cutting rectangle to initiate the cutting maneuver. Peak knee flexion was defined as the greatest knee flexion value in the dominant leg when landing from the jumping task and initiating the cutting maneuver. The following variables were calculated at the instant of initial contact and peak knee flexion: hip and knee sagittal, frontal, and transverse plane angles. The peak values at initial contact and peak knee flexion for the

3 “best” trials on each surface were averaged, and the excursion was calculated as the angular change from initial contact to the time corresponding with peak knee flexion. These values were created for each subject’s dependent variables on both surfaces. The 3 “best” trials were chosen by initially looking at trials 2, 3, and 4. However, trial 1 or 5 may have been used if there was increased motion artifact or if initial contact could not be determined in trials 2, 3, and 4.

2.5 Statistical analysis

Data were analyzed using PASW Statistics 18.0 statistical software (SPSS, Inc., Chicago, IL). Descriptive statistics were run to find means and standard deviations for each of the 6 dependent variables. Six separate paired t-tests were also run to compare the means between the natural grass and artificial turf playing surfaces from initial contact to peak knee flexion (excursion values) of the jump landing cutting task for each dependent variable. The significance level was set *a priori* at an alpha of 0.05.

3. Results

Significant differences were observed at the hip in the frontal ($t_{26} = -2.190$, $p = 0.038$) and transverse planes ($t_{26} = -2.075$, $p = 0.048$) from initial contact to peak knee flexion (excursion values) (Figure 3). Specifically, subjects showed significantly more hip movement in the frontal plane on the artificial turf surface, resulting in more hip adduction on the artificial turf surface than the natural grass surface at peak knee flexion. Subjects showed significantly more hip movement in the transverse plane on the natural grass surface, resulting in the hip moving farther into external rotation on the natural grass surface than the artificial turf surface at peak knee flexion, meaning that the hip was more externally rotated on the natural grass surface.

Significant differences were observed at the knee in the frontal (t_{26} = -2.648, p = 0.014) plane from initial contact to peak knee flexion between the surface conditions (Figure 4). Specifically, subjects showed significantly more movement in the frontal plane at the knee on the natural grass surface, resulting in more knee valgus on the natural grass surface than the artificial turf surface at peak knee flexion. Hip and knee kinematic variables at initial contact and peak knee flexion are presented in Table 2. Qualitatively, there are minimal differences at initial contact of all kinematic variables between the two playing conditions (< 2 degrees). Hip and knee kinematic variables from initial contact to peak knee flexion (excursion values) are presented in Table 3.

4. Discussion

These findings partially confirm the hypothesis that performing a jump landing and cutting task on the artificial turf surface alters lower extremity kinematics when compared to natural grass. Specifically, the performance of a jump landing and cutting task on an artificial turf surface produced more hip adduction and less hip external rotation motion during weight acceptance compared to the same task performed on a natural grass surface. In addition, there was an increased frontal plane excursion on natural grass. This altered movement pattern may have clinical implications for injury risk at the knee.

Even with the new advancements in artificial turfs, the newer generation still has different characteristics when compared to natural grass. In previous studies, these differences, such as increased rotational stiffness and friction, have been shown to cause changes at the shoe-surface interface and on foot loading patterns (Ford, Myer et al. 2003). Any change at the shoe-surface interface could influence the kinematics of proximal joints (Eils, Streyl et al. 2004; Ford, Manson et al. 2006).

We are particularly concerned about the abnormal motion of the hip joint, due to its role in controlling knee movement and the subsequent increase in load on the ACL. Previous investigators have examined movement patterns in the frontal plane and established that hip adduction and knee abduction were correlated during cutting tasks. With the hip adducted, knee valgus also increased, making hip adduction a predictor of the injurious valgus mechanism at the knee (Imwalle, Myer et al. 2009). Imwalle et al. (2009) suggested that hip adduction increases the mechanism for increased load on the ACL and noncontact ACL injury during cutting tasks. In the transverse plane, Pollard et al. (2007) observed female subjects displaying greater hip internal rotation during a cutting task when compared with male subjects, and suggested that increased hip internal rotation during functional tasks alters the alignment of the lower extremity (Pollard, Sigward et al. 2007). In the present study, subjects displayed increased motion in the transverse plane at the hip resulting in more external rotation on the grass surface. Although the hip was also externally rotated on the artificial turf surface, it was relatively more internally rotated when compared with the natural grass condition. The externally rotated position is most likely due to the cutting task. Since hip angles were calculated based on the position of the thigh relative to the pelvis, the turning of the pelvis away from the dominant leg with the cut would cause the hip to appear externally rotated. On the contrary, if the subjects had been asked to cut toward their dominant side, increased internal rotation values may have been noticed, potentially increasing the load placed on the ACL.

In addition to the elevated risk for ACL injury, increased hip adduction and internal rotation with functional tasks can increase stress at the patellofemoral joint. Souza and Powers (2009) found that females with patellofemoral pain displayed increased hip internal rotation during running. In addition, Powers et al. (2003) concluded that the excessive lateral tilt and glide of the patella during a single leg squat was due to the internal rotation of the femur occurring at the hip instead of movement at the patellofemoral joint. These results suggest that the movement patterns occurring at the hip during functional tasks can influence the kinematics of the patellofemoral joints in a manner consistent with causing patellofemoral pain (Powers, Ward et al. 2003; Souza and Powers 2009).

Findings of the current study showed hip kinematic differences during the loading phase of the jump landing cutting task and altered frontal plane motion at the knee. A study performed by Pollard et al. (2006) had similar results at the hip following a drop landing task. After participating in an established season-long ACL injury prevention training program (PEP program), female soccer players demonstrated decreased peak hip internal rotation and adduction angles during landing. Even with these changes in hip kinematics, subjects did not display a change in knee kinematics, perhaps due to the ease of the drop landing testing task (Pollard, Sigward et al. 2006). Likewise, it is conceivable that changes in knee kinematics were not observed at peak knee flexion in the current study due to the task. In the present study, subjects were high-level athletes who were comfortable in performing the double-leg drop landing cutting task. A more difficult task may have resulted in more substantial changes in knee kinematics between conditions, as the increased hip adduction and internal rotation viewed on the artificial turf surface may have contributed to increased knee valgus at peak knee flexion during the performance of a more demanding quick deceleration maneuver.

It is possible that the magnitude of the changes occurring at the hip in the frontal and transverse planes may not be enough to elicit a change in biomechanical positioning at the knee. Therefore, the hip kinematic differences between landing surfaces alone may not be great enough to predispose an athlete to injury on the artificial turf surface. However, for those athletes already playing with additional or increased risk factors, competing on artificial turf may further increase the risk for ACL injury beyond the threshold for injury. Thus, the results of the current research study suggest that the performance of jump landing cutting tasks on 3^{rd} generation artificial turf alters hip frontal and transverse plane kinematics in a manner consistent with increasing the load placed on the ACL.

Although there were no major differences noticed at the knee at initial contact or peak knee flexion between playing surfaces, there was a significant difference in knee excursion in the frontal plane. Subjects displayed more movement in the frontal plane on the natural grass surface, resulting in somewhat more valgus at peak knee flexion. However, the subjects landed in a slightly more valgus position on the artificial turf surface, which could have inflated the excursion values on the natural grass. Since motions consistent with additional load on the ACL were occurring at the hip on the artificial surface, the reduced valgus motion at the knee could have been a compensation for the increased motion at the hip to avoid injury. On the contrary, the subjects' decreased motion at the knee on the artificial surface could have contributed to altered motion at the hip (Livesay, Reda et al. 2006; Villwock, Meyer et al. 2009). The subjects may have also been more comfortable performing the cutting task on the natural grass surface, placing more effort into the task. We suspect that any increased comfort or effort could have resulted in more movement at the knee in the frontal plane.

Even though hip kinematic differences were found between surfaces, these changes in biomechanics do not necessarily mean that more ACL injuries will occur on the artificial turf when compared to natural grass. Several prospective studies have examined and compared the incidence, cause, and risk of injuries on natural grass and third generation artificial turf (Meyers and Barnhill 2004; Ekstrand, Timpka et al. 2006; Fuller, Dick et al. 2007; Fuller, Dick et al. 2007; Steffen, Andersen et al. 2007). Although most studies agree that there are no overall differences in the level of risk and cause of the injuries experienced on both surfaces, none have been specific to ACL injury.

4.1 Limitations

Potential limitations to the current research study include the use of only female soccer players. Females were chosen specifically because it was believed that greater differences between surfaces would be noted with female subjects due to the known disparity in ACL injury rates between genders. Female athletes have been found to experience ACL injuries at a rate of 2 to 6 times more often than males playing the same sport (Arendt, Agel et al. 1999). However, the choice to test only female subjects does not allow generalizations to be made about male athletes participating in sports on these playing surfaces. Our subjects were also chosen specifically because of their experience with activities on both natural grass and artificial turf surfaces. We did not want lack of experience on one of the surfaces to alter the kinematic variables. However, this concern does not allow generalizations to be made about individuals with no experience participating on artificial surfaces.

Results also cannot be applied to other brands of 3rd generation artificial turfs. The multiple types of artificial turfs have different qualities of the synthetic grass fibers and the in-fill systems of different percentages of sand and rubber. These different qualities could lead to changes in friction and stiffness at the shoe-surface interface, possibly affecting hip and knee kinematics with landing and cutting maneuvers (Meyers and Barnhill 2004; Steffen, Andersen et al. 2007).

Excessive motion artifact (i.e., noise) from the electromagnetic tracking sensors during landing limited the ability to analyze the hip and knee kinematic data over the loading phase. Although theoretically most loading to the ACL would occur at peak knee flexion, it was not possible to verify peak kinematic values over the loading phase. Therefore, for example, higher knee valgus could have occurred prior to peak knee flexion, but was not analyzed due to the variability of the data.

It is important to note that there were differences in environmental conditions across the subjects. In the present study, one testing session occurred following a day of rain, so 9 subjects may have performed their testing on more moist ground conditions when compared with the other 22 subjects. With a repeated measures design and subjects performing the task on both surfaces on the same day, it is unlikely that the outcome of the current study was affected. However, in previous studies, it was determined that a relationship exists between ACL injury and weather conditions that result in a dryer playing surface. It was thought that the speed of the game increases on a dryer surface, as well as the friction and torsional resistance between cleats and grass. In the long-term, it was concluded that low water evaporation and high rainfall significantly decreased the risk of noncontact ACL injuries, possibly from the decreased traction occurring at the shoe-surface interface (Orchard, Seward et al. 2001). Since more moisture would be absorbed on the artificial surface when compared to natural grass, it could be suggested that the friction and torsional resistance would be higher on the artificial surface. In addition, Meyers and Barnhill (2004) noted a significant increase in incidence of injury on FieldTurf during temperatures greater than 70 degrees

Fahrenheit when compared to colder days and to injuries on natural grass. The testing of the current study occurred during temperatures less than 70 degrees. Therefore, greater kinematic differences could have been noted if testing had been completed during higher temperatures.

4.2 Future research

Future research concerning ACL injury risk on different types of playing surfaces should examine the effect of the different brands of artificial turf surfaces on movement patterns across a range of environmental conditions (including moisture and temperature). This information could allow researchers to observe if there is a type of in-fill system, synthetic grass fiber, moisture level, or temperature that increases the loading placed on the ACL during rapid deceleration tasks. Since the appearance of the first artificial turfs in the mid-1970s, artificial turf surfaces have been modified and improved from the high stiffness and friction and low shock absorption associated with an increased injury rate on the surface. These advancements combatted the higher amounts of overuse injuries seen on the first and second generation turfs and addressed the stiffness issues experienced with the older turfs (Meyers and Barnhill 2004; Steffen, Andersen et al. 2007). Advancements on artificial turf surfaces can continue to be made.

It would also be beneficial to study muscular recruitment or firing patterns during landing or cutting maneuvers on multiple playing surfaces. Different surfaces could cause changes in preparation for the task, which may not necessarily present as kinematic differences. This information may allow for the development of training programs to battle the increased risk of hip adduction and internal rotation during deceleration tasks on artificial turf surfaces.

Because our subjects were chosen specifically based on their experience with activities on both natural grass and artificial turf surfaces, future study is necessary to make assertions about how athletes naïve to participation on artificial surfaces would react to competing on that condition. Those athletes with familiarity on artificial surfaces may have the experience necessary to mitigate abnormal movement patterns during those tasks that place additional load on the ACL. Conversely, athletes without the experience to avoid altered movement patterns that may be related to playing on artificial turf may have a greater predisposition to injury than those athletes with an awareness of the surface. A related question would then concern if those athletes that play on artificial surfaces should practice on those surfaces as well. If the artificial turf does predispose ACL injury, additional exposures on that surface would only increase the likelihood for injury. However, increased familiarity with the surface may decrease the probability of injury during game play.

This information could also lead to an understanding about if the above mentioned training programs would be more beneficial if completed on artificial turf surfaces. This could possibly give neuromuscular pathways the experience necessary to compensate for alterations in movement patterns caused by the artificial surface. On the contrary, the training programs may be just as successful if completed on natural grass surfaces.

4.3 Clinical significance

As excessive hip frontal and transverse plane kinematics can add to the load placed on the ACL, injury prevention programs designed to decrease the injurious biomechanical position of hip adduction and internal rotation may be necessary for those athletes continuously competing on artificial turf surfaces. In an in-season ACL injury prevention program study performed by Pollard et al. (2006), the intervention program significantly altered the hip kinematics of female soccer players. After participating in a season-long training program, female soccer players demonstrated decreased peak hip internal rotation and adduction angles during landing. Pollard et al. (2006) concluded that injury prevention training, completed with normal soccer practice, is beneficial in altering the lower extremity kinematics that otherwise would place athletes in a biomechanical position that places additional load on the ACL.

4.4 Conclusion

During a jump landing cutting task, females displayed altered movement in the frontal and transverse planes at the hip, resulting in greater hip adduction and less hip external rotation during loading on a 3rd generation artificial turf surface compared to a natural grass surface. The observed changes in kinematics at the hip could be caused by or lead to altered frontal plane motion at the knee. These findings suggest that the artificial turf surface places females in a biomechanical position at the hip that places more load on the ACL, but a position at the knee which is protective of the ACL. Future research is needed to determine the ideal in-fill percentage and type of synthetic fiber, leading to further advancements and improvements in the safety of an artificial surface. Further study into muscle recruitment patterns and the effect of experience on artificial turf surfaces could lead to the development of an intervention program and analysis of its long-term effect on injury prevention.

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FIGURES

Figure 1. Field set-up.

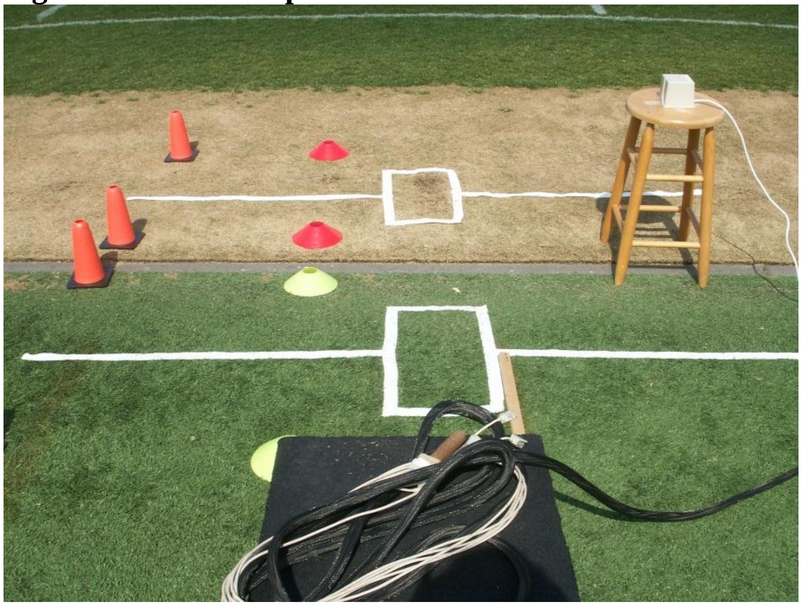


Figure 2. Jump landing and cutting task.

Figure 3. Means and standard deviations (SD) of hip angles from initial contact to peak knee flexion (excursion values) on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

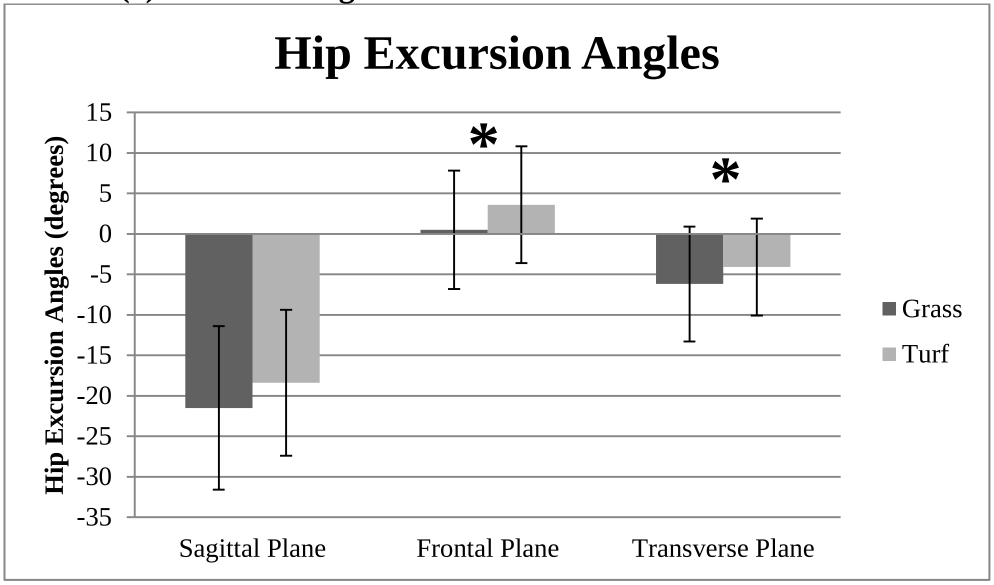
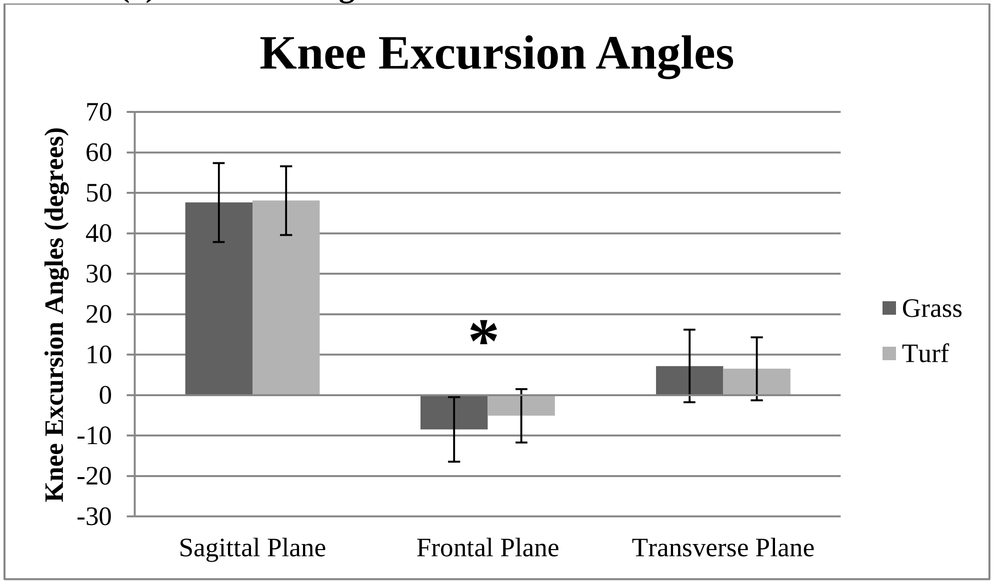


Figure 4. Means and standard deviations (SD) of knee angles from initial contact to peak knee flexion (excursion values) on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.



TABLES

Table 1. Subject Demographics.

Number of Subjects (n)	27
R Dominant/L Dominant	25/2
Varsity/Club	17/10
Age (yrs)	20.0±1.4
Height (cm)	167.5±6.5
Mass (kg)	65.2±11.1
Years Playing Competitively	11.6±3.3

Table 2. Means and standard deviations (SD) of hip and knee kinematic variables at initial contact and peak knee flexion during a jump landing cutting task on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

	Initial Contact		Peak Knee Flexion	
Kinematic Variables	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)
Hip Sagittal Plane	-35.2±11.1	-35.8±10.6	-56.7±14.5	-54.2±12.1
Hip Frontal Plane	-3.7±6.6	-2.8±6.4	-3.2±6.6	0.8±7.0*
Hip Transverse Plane	0.6±8.3	1.4±8.1	-5.6±8.2	-2.7±7.7*
Knee Sagittal Plane	19.1±8.3	21.0±5.7	66.7±11.2	69.0±7.8
Knee Frontal Plane	0.8±4.1	-0.7±4.3	-7.7±8.3	-5.8±6.9
Knee Transverse Plane	-0.2±7.6	1.2±7.8	7.0±7.6	7.7±5.7

Table 3. Means and standard deviations (SD) of hip and knee kinematic variables from initial contact to peak knee flexion (excursion values) during a jump landing cutting task on natural grass and artificial turf surfaces. The asterisk (*) indicates a significant difference between surface conditions.

	Excursion	
Kinematic Variables	Grass Mean±SD (degrees)	Turf Mean±SD (degrees)
Hip Sagittal Plane	-21.5±10.1	-18.4±9.0
Hip Frontal Plane	0.5±7.3	3.6±7.2*
Hip Transverse Plane	-6.2±7.1	-4.1±6.0*
Knee Sagittal Plane	47.6±9.8	48.1±8.5
Knee Frontal Plane	-8.5±8.0	-5.1±6.6*
Knee Transverse Plane	7.2±9.0	6.5±7.8

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