8-2012

BIOMECHANICAL DIFFERENCES OF TWO COMMON FOOTBALL MOVEMENT TASKS IN STUDDED AND NON-STUDDED SHOE CONDITIONS ON INFILLED SYNTHETIC TURF

Elizabeth Anne Brock
University of Tennessee - Knoxville, ebrock4@utk.edu

Recommended Citation

Brock, Elizabeth Anne, "BIOMECHANICAL DIFFERENCES OF TWO COMMON FOOTBALL MOVEMENT TASKS IN STUDDED AND NON-STUDDED SHOE CONDITIONS ON INFILLED SYNTHETIC TURF. " Master's Thesis, University of Tennessee, 2012.
https://trace.tennessee.edu/utk_gradthes/1245

To the Graduate Council:

I am submitting herewith a thesis written by Elizabeth Anne Brock entitled "BIOMECHANICAL DIFFERENCES OF TWO COMMON FOOTBALL MOVEMENT TASKS IN STUDDED AND NON-STUDDED SHOE CONDITIONS ON INFILLED SYNTHETIC TURF." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Kinesiology.

Songning Zhang, Major Professor

We have read this thesis and recommend its acceptance:

Clare E. Milner, Jim T. Brosnan, John C. Sorochan

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

BIOMECHANICAL DIFFERENCES OF TWO COMMON FOOTBALL MOVEMENT TASKS IN STUDDED AND NON-STUDDED SHOE CONDITIONS ON INFILLED SYNTHETIC TURF

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Elizabeth Anne Brock

August 2012

Acknowledgements

I would like express my gratitude and appreciation to my masters committee, especially Dr. Zhang. I have looked to every one of my committee members for guidance and support throughout this process and I would not be where I am today without their help. Dr. Zhang has helped me with everything from cutting turf out of the ground to skyping me from China the week before my proposal. Throughout the whole process you have been nothing but respectful of my opinions and ideas and for that I'm thankful.

I would also like to thank my friends and family for their unwavering support throughout this project. The survival grocery care packages from my mom have probably kept me alive during the weeks I could not find time to go to the store. Thanks Mom! I also want to thank Lexie for her help throughout data collection and analysis. I really appreciate you helping me put down turf on Friday nights, only to spend the rest of your weekend helping me collect and clean up the lab. Thanks for everything!

Abstract

The purpose of this study was to examine kinematic and kinetic differences in three shoe conditions (traditional football shoes with natural and synthetic turf studs and a neutral running shoe) during two common football movements (a 180° cut and a land-cut movement) on infilled synthetic turf. Fourteen recreational male football players performed five trials in all three shoe conditions for a 180° cut as well as a land-cut maneuver. The kinematic and kinetic variables were analyzed with a 3 x 2 (shoe x movement) repeated measures analysis of variance (ANOVA, $p<0.05$). Peak free moment was significantly greater for the land-cut trials ($p<0.001$). Vertical GRFs were significantly greater for the land-cut trials ($p<0.001$). A cleat x movement interaction was seen for time to vertical impact GRF ($p=0.048$). A cleat main effect was found for time to vertical impact between natural turf cleat and synthetic turf cleat ($p=0.019$). Vertical loading rate was significantly greater in land-cut trials. Peak medial GRFs showed a significant cleat x movement interaction ($p=0.002$). The results from this study suggest that land-cut movement elicit greater vertical GRF and vertical impact loadings rates. The running shoe had significantly less dorsiflexion range of motion (ROM) than the synthetic turf studs. A significant cleat main effect was found for peak eversion velocity ($p=0.005$). Post hoc comparisons showed that it was significantly smaller in shoe than that natural turf stud ($p=0.016$) and synthetic turf stud ($p=0.002$). In general, there was a lack of differences between the shoe conditions for GRFs and kinematic variables. For the 180° cut movement, natural turf studs produced lowest peak medial GRF compared to the synthetic turf studs and the shoe. The results from this study suggest that land-cut movement elicit greater vertical GRF and vertical impact loadings rates. In general, there was a lack of differences of GRFs and kinematic variables between the shoe conditions. For the 180° cut movement, natural turf studs produced lowest peak medial GRF compared to the synthetic turf studs and the shoe. Overall, increased GRFs, especially in combination with rapid change of direction and deceleration may increase the chance of injury.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

In the 2003-2004 football season, there were approximately 59,980 National Collegiate Athletic Association (NCAA) varsity athletes (77) and over one million high school athletes participating each fall (93, 99). Injuries in football occur more frequently than any other sport (1, 91, 97). According to a study that investigated the epidemiology of high school and collegiate football injuries, the most commonly injured body sites were the knee (15.2%) and lower leg/ankle/foot (22.4%) (99), with 18% of all document football injuries to the knee ligaments (31, 81). Another common injury associated with football is a rupture of the anterior fibulotalar ligament in the ankle that is generated by internal rotation of the tibia and supination of the ankle (8, 42). Ankle injuries comprise 62.0% of all lower limb injuries and were the third leading site of collegiate injuries (12.7%) (99). Shankar et al. (2007) also found that the most common injury diagnosis was ligament sprain (52.9% for knee injuries and 88.0% for ankle injuries). Unfortunately, this study, which analyzed 55 high school and NCAA schools, did not distinguish the surfaces on which these injuries occurred.

There are an estimated 80,000 to 250,000 anterior cruciate ligament (ACL) injuries each year in the United States and approximately 50,000 ACL reconstructions are performed annually (10, 40). The cost of these procedures is approximately $1,000,000,000 annually (10, 40). Football players of all levels account for 100,000 to 130,000 of the ACL injuries annually (109). The primary purpose of the ACL is to control anterior translation of the tibia on the femur and also to control rotational stresses (108). The highest number of ACL injuries, along with 15 to 30% of ankle injuries, occur in pivoting sports during the fast-paced plant-and-cut movements (75). ACL ruptures often occur in noncontact maneuvers involving rapid decelerations, such as jump landing or cutting (13).

Although many ACL injuries are caused by collisions between players, the vast majority of these injuries- approximately 70%- occur in noncontact situations (10, 40) . There are two main types of non-contact injury mechanisms: 1) fatigue overload and 2) shoe-surface frictional forces (46). Some examples of non-contact ACL injuries involve foot fixation, hyperextension of the knee, and torsional stress in falling, landing, sudden stopping while running, or rapidly changing direction (12, 81). Foot fixation occurs when excessive resistance to rotation prohibits the shoe from moving during certain twisting and cutting movements, which can produce large forces in the knee during rotational movements (64) and therefore lead to ACL injury (57). The plant and cut motion is a common sports related movement and is often paired with a sudden deceleration of the player. Those two movements are capable of tearing the ACL (12).

The introduction of synthetic turf has influenced both the frequency and type of injury suffered by athletes (9, 24, 78). First generation AstroTurf® (10 mm polyester nylon mat and 10 mm turf fibers) is consistently harder than natural turf (15, 105), resulting in faster running speeds, benefiting a player’s performance but increasing the chance of injury (105). The first synthetic turf produced higher resistance to rotation and less traction than natural turf (100). Traction, according to the 2009 American Society of Testing and Materials, is the resistance to relative motion between a shoe outsole and a sport surface that does not necessarily obey classical laws of friction (2). For instance, dynamic friction is not always smaller than static friction, frictional force can actually exceed normal forces whereas traction can not, Increased traction results in a smaller probability of slipping and falling during changes of direction (100).

The three most common current types of synthetic turf, AstroTurf®, Fieldturf and Sprinturf, are constructed similarly with very minute changes to blade technology and infill specifications. The newest generation of Fieldturf consists of 50 mm polyethylene fibers and 40 mm of rubber and/or sand infill (100). Fieldturf, as of early 2012, is being used at over 1,000 high schools, 21 of 32 National Football League (NFL) teams and 100 NCAA Division-I institutions, as well as 500 recreational sites across the United States (26). As of May, 2010, AstroTurf® was used at over 250 high schools, 1 of 32 NFL teams, 70 NCAA Division-1 institutions, and approximately 100 recreational sites (52).

In a study comparing injury rates on Fieldturf compared to natural turf grass, 64.6% of all the documented injuries occurred on synthetic turf while 35.4% occurred on natural turf. The most common football related injuries occurring on synthetic turf occur to the lower extremities. More sprains and serious knee and ankle injuries were observed on natural turf compared to synthetic, while more abrasions, concussions, contusions, and strains were observed on synthetic turf (59,102). The most common season-ending injury for males on the first generation synthetic turf has been shown to be an ankle ligament tear, while knee ligament tears were the most common injury on natural turf (38). Many believe that these injuries were the result of a higher degree of traction on synthetic surfaces (57, 110).

The introduction of synthetic turf also led to the development of shoes designed to accommodate the differing characteristic of synthetic turf compared to natural turf. Muller et al. (2010) studied three different movements on synthetic turf with four different studded shoe conditions. Peak vertical force and force rate were not affected by different shoe conditions for the 45° cut. Peak vertical and shear forces for the soft ground studs (longer but fewer studs) were decreased compared to the hard ground studs (multiple shorter studs) for the 180° cut (74). Livesay et al. (2005) used natural and synthetic turf studs under controlled mechanical testing on four synthetic AstroTurf® products and found that natural turf studs resulted in increased impact forces on rubber-infilled turf. A recent study on traditional molded soccer studs and blades (edge cleats) during a 180° cut on infilled turf showed no significant results for vertical ground reaction force (GRF), but bladed cleats were 12.5% greater than traditional studs (39).

In sports with repeated impacts, such as football, it is important to minimize the force that is returned to the athlete from the surface in order to reduce injury (73). Few studies have examined biomechanical characteristics of dynamic cutting and landing movements on infilled synthetic turf. Single-leg landings produce significantly higher peak vertical GRF (116) and significantly less knee flexion compared to double-leg landings (85). Decreased knee flexion angles reduce the ability of lower extremity to absorb the compressive loads placed on the knee, putting it at risk for injury (30) . McLean et al. (2009) found that during initial contact, knee abduction was significantly increased during unanticipated single-leg landings compared to anticipated landings in a jump landing with a maximal effort 90° cut. Fatigue decreased knee flexion angles and increased knee abduction angles which was thought to increase the risk of ACL injury. Hass et al. (2005) used a lateral landing sequence in which subjects dropped from a box equal to the height of their maximum vertical jump followed by a maximal 90° cut. Post-pubescent females showed significantly less knee flexion compared to pre-pubescent females, which may help to explain the increased incidence of post-pubescent knee injuries.

Cortes et al. (2010) completed two comparable studies. The first used a drop-jump task and 45° and 180° cut at an approach speed of 3.9 ± 0.5 m/s and found the 180° cut to have increased knee abduction angles and decreased knee flexion compared to the 45° cut. The second study by Cortes et al. (2011) again used the 45° and a 180° cut, but at an approach speed of 3.5 m/s or faster. The 45° cut with a rearfoot landing increased knee abduction angles whereas the 180° cut had increased knee abduction angles with a forefoot landing. Between the two forefoot movements, GRF and knee flexion values were greater and abduction angles were smaller for the 45° cut compared to the 180° cut (27). Overall, these studies determined that the 180° cut increased knee abduction angles and in addition, suggested that large peak vertical GRFs and/or decreased knee flexion angles at initial contact could increase ACL injury incidence (27, 28). Multiple studies have also reported decreased knee flexion angles and increased knee abduction angles during cutting (13, 48, 62, 65, 84). Land-cut and 180° cut movements are both common and depending on the position played, repetitive movement patterns for football players. While each movement has different characteristics, and with all other factors held constant such as shoe and surface conditions, the land-cut movement would have a greater injury risk than the 180° cut. The land-cut is associated with greater peak vertical and medial GRF as well as greater loading rates. The combination of increased vertical and medial GRF alone would seem to increase the risk of injury, but added to the increased rate at which forces (approximately five times BW) are applied and it appears to be the more injurious movement.

Previous studies have used traction testing devices with rigid leg molds to study traction and ground reaction forces (GRFs) (21). The limited number of studies involving human subjects has not provided a comprehensive description of the kinematics and kinetics of lower extremity while wearing studded football shoes and neutral running shoes on infilled synthetic turf.

Free moment (FM) is the torque about the vertical (Z) axis caused by the friction between the foot/shoe and the ground during the stance phase (50). Milner (2006) noted that simultaneously high torque and shear forces could account for lower extremity injuries and that regardless of direction, the absolute magnitude of the FM would best represent the amount of torque. The same study also found that there was a significant relationship between tibial stress fractures and higher free moments. The magnitude of the absolute peak FM predicted 66% of previous tibial stress fractures. A similar study found that FM, in conjunction with hip adduction and rearfoot eversion successfully predicted a history of tibial stress fractures in 83% of cases (89).

Statement of Problem

To date, there have been limited studies that examined the biomechanical characteristics of dynamic cutting movements on infilled synthetic turf with human subjects. Moreover, there have been even fewer studies examining these characteristics using human subjects. The purpose of this investigation was to look at the kinematic and kinetic differences in different shoe conditions (traditional football shoes with natural and synthetic turf studs and a neutral running shoe) during two common football movements (a 180° cut and a land-cut movement) on infilled synthetic turf.

Significance of Study

The aim of this study was to provide detailed information about the kinematic and kinetic differences of the ankle and knee joints during two dynamic cutting maneuvers. The study of common football maneuvers with different football studs and running shoes on an infilled synthetic surface will provide valuable information on the kinematics and kinetics of the knee and ankle joint.

While it is well known that shoes with studs provide more traction on the synthetic surface compared to other athletic shoes (109), the results of the current study may be valuable for both the competitive athlete, as well as the recreational athlete playing on synthetic turf with and without studs. Minimal traction, achieved by wearing non-studded shoes, results in slips and falls, which expose the athlete to different, yet serious injuries compared to the foot-fixation related injuries incurred by athletes wearing shoes with studs.

The two movements that were chosen for this study were the 180° cut and the land-cut maneuvers because of the inherent risk of injury due to high and rapid loading to lower extremity joints related to foot fixation from high degrees of traction, rapid deceleration and acceleration, and quick changes of direction. Maximum effort cutting trials have previously been used with different cutting angles (113).

The following hypotheses were tested in this study:

1) The natural turf studs would produce a larger peak FM, peak vertical GRF and vertical impact loading rate compared to the synthetic turf studs and the running shoes during both movements; the two studded shoe conditions would result in greater peak FM, peak vertical GRF and loading rates than the running shoe

2) Peak FM, peak vertical GRF, vertical GRF loading rate and peak knee abduction angle would be greater and knee flexion angles would be smaller in the land-cut movement compared to the 180° movement.

Limitations

1. All the participants were recruited from a convenient sample of the student population at the University of Tennessee, Knoxville.

2. Participants may have performed dynamic cutting movements differently in the lab setting than they would have during games or practices on an actual football field.
3. The accuracy of 3D kinematics was limited by the manual placement of retroreflective markers on the surface of the skin over bony landmarks by palpation.
4. Only one brand model of football shoes with two different stud types, and running shoes were tested.
5. Only one type of synthetic turf was tested.

Delimitations

1. All participants were active, healthy and had no previous serious lower extremity injuries. They all had previous relevant football experience.
2. Each participant performed five trials in all six conditions with sufficient warm-up and resting time.
3. The turf size and the lab environment gave the participants plenty of room for both acceleration and deceleration of the tested movements.
4. Kinematic data were collected at 120 Hz using Vicon 3D motion analysis system (Vicon MX, Oxford. Metrics, Oxford, UK) and kinetic data were collected at 1200 Hz using a force platform (American Mechanical Technology Inc., MA)
5. Adidas Scorch X Low D is sold with natural turf studs. Synthetic turf studs from adidas that are made to fit any adidas model of shoe were used for the turf cleat condition.

6. The infilled synthetic turf is the most current generation of synthetic turf and is used commonly in recreation, collegiate and professional football stadiums around the U.S.

Chapter 2

Literature Review

The purpose of this investigation was to examine the kinematic and kinetic differences in different shoe conditions during two different, injury provoking, cutting mechanisms on third generation infilled synthetic turf. This literature review consists of five main sections: background information detailing the importance of the study, review on four main synthetic surfaces, different styles of studs, shoe-surface interactions, and biomechanical characteristics of the land-cut and 180° cut maneuvers associated with injury.

Injury Mechanisms

With the ever-increasing competitiveness of sports, the practice season has gone from a month or so prior to a competition season, to a year round ordeal. All weather surfaces, such as synthetic turf, are the logical result for many sporting facilities. Synthetic turf is an alternative to natural turf that provides a more reliable, consistent and weather-resistant year-round surface (76). Synthetic turf can be used in a variety of sports, such as football, baseball, soccer, lacrosse and rugby, as well as general recreation activities.

A residual, unforeseen result associated with the installation of synthetic turf was a rise in the number of non-contact injuries in football (22, 29, 59). It has been reported that both the type and frequency of sports injury have been influenced by the introduction of synthetic playing surfaces (9, 24, 53, 78). Injuries in football occur more frequently than any other sport (1, 91, 97). One study of college athletes found a statistically significant increased risk of knee and ankle injuries on synthetic surfaces compared to natural surfaces (7). There are an estimated 80,000 to 250,000 ACL injuries each year in the United States alone, and approximately 50,000 ACL reconstructions are performed annually at a cost of almost $1,000,000,000 per year (10, 40). Although many ACL tears are caused by collisions between players, the vast majority of these injuries, (approximately 70%) occur in noncontact situations (10, 40).

There are two main mechanisms for non-contact injuries: fatigue overload and shoe-surface frictional forces (46). Specifically, non-contact injury mechanisms involve foot fixation with an excessive internal rotation of the upper body, torsional stress from foot fixation, internal rotation of the upper body and hyperextension of the knee, falling, sudden stopping while running or rapidly changing direction (8, 12, 42, 81) . The most common football related injuries associated with synthetic turf occur in the lower extremity. Additionally, more knee and ankle injuries were observed on natural turf than synthetic, while more abrasions, concussions, contusions, and strains were observed on the synthetic surfaces (80). The plant and cut motion, accompanied by a sudden decelerating maneuver, is capable of tearing the ACL (12). A rapid change of direction has been cited as a noncontact injury mechanism (13, 69). A study of handball players found that 80% of ACL injuries were the result of landing from a jump or during a plant and cut motion (75). The highest number of ACL injuries in handball, along with 15 to 30% of ankle injuries, occur during fast-paced plant-and-cut movements (75). Also, basketball players subject themselves to high-risk movements such as cutting, rotating and landing during 70% of an active game (104). ACL injuries have been shown to occur more frequently with a combination of decreased knee flexion angles and knee abduction (13, 62).

In some cases, a high degree of traction is desired to allow the athlete to maximally accelerate, decelerate, and change direction (21, 32) which can also lead to a higher rate of foot fixation. As mentioned before, traction is the resistance to relative motion between a shoe outsole and a sport surface that does not necessarily obey classical laws of friction (2, 32). The classical laws of friction (Coulomb Friction) state that friction is a force of resistance acting on a body which prevents or retards slipping of the body relative to a second body or surface with which it is in contact. This force always acts tangent to the surface at points of contact with other bodies and is directed so as to oppose the possible or existing motion of the body relative to these points (49). The shoe-surface interaction is static friction when the athlete is not moving while standing on the turf. Dynamic friction, which is greater than static friction (32), would be if the athlete was moving. Dynamic friction is the force opposing the movement of the shoe and the surface which in turn decreases relative velocity (32). Frictional force is equal to the coefficient of friction multiplied by the applied vertical load.

Traction is similar to friction but not the same. Dynamic traction is always less than static traction, whereas dynamics friction is not always less than static friction (19). Also, frictional forces can exceed normal forces (Crow Hop phenomenon) (19). Rotational traction occurs with foot fixation when there is a defined axis of rotation and a torsional force (37). Translational traction occurs when the foot changes position without changing orientation in a straight or linear line (37). Translational or linear traction is most often perceived as an athlete’s foot sliding along a surface while rotational traction would be an athlete rotating about the fixed location of the foot in a twisting manner. Torque is the moment of force that tends to rotate an object (94).

Synthetic Surfaces

Synthetic turf was invented in 1964 by Monsanto and since then has become a widespread solution for many athletic, recreation and residential locations (59). In a matter of 47 years, four leading companies have developed a multitude of different synthetic surfaces. Thus far, there have been three distinct generations of synthetic surfaces.

The first generation, most commonly known as the magic carpet, was characterized by a foam mat and short, 10 mm polyvinyl chloride that was known for excessive traction and skin abrasions (68, 76). The fibers in the first generation turf were the playing surface, whereas in the second generation it was a mix between the fibers and the sand infill (59).

The second generation was much more technologically enhanced, using carpet on top of an underlying pad (98), increasing the nylon, polypropylene or polyethylene fiber length to 22 to 25 mm and creating a more soil-like base by infilling the less densely arranged fibers with sand and/or rubber (35, 44, 68). These enhancements helped mimic natural turf aesthetic and functional quality (59). Silica sand covered the majority of the fibers, which prevented the exposed fibers from being matted down (98).

The third and most current generation of synthetic turf sits atop an asphalt or crushed aggregate base and has longer fiber lengths of 40 to 70 mm and a combination of rubber and sand infill of up to 50 mm. The fiber and infill help to mimic natural turf characteristics in terms of look, feel and reaction, such as increased shock absorbency (68, 73, 98). The fibers are typically produced from nylon, polyethylene or polypropylene (98). The granular infills found in synthetic surfaces have been shown to produce significantly higher translational traction and a lower resistance to rotation, closely mimicking that of natural turf (100).

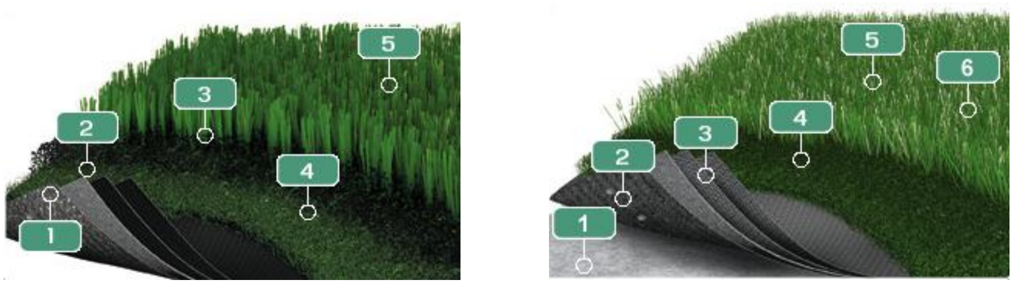
There are two types of fibers used on synthetic turf: monofilament and slit-film. Monofilament fibers protrude through the backing as singular strands. Monofilament fibers are single strands of yarn that are glued to the backing and are more resistant to matting than slit-film fibers (98). Slit-film fibers are cut from sheets of polymer and then perforated by design. These fibers are sewn or tufted into the backing (usually polyester or polypropylene) and then coated with latex and/or polyurethane (98). During slit-film installation, the perforations are fibrillated to form the individual filaments that will comprise the finished playing surface and with use, the fibers separate and help to reduce the migration of infill (98, 106). Monofilament and slit-film fibers are durable and have excellent resistance to matting (25).

The two most common materials used for infill in third generation synthetic turf are crumb rubber and silica sand. Third generation infill material stabilizes the long fibers up to 25 to 45 mm (98). The 2 to 3 mm (diameter) rubber granules are styrene butadiene rubber (SBR, a synthetic rubber copolymer) and are highly resistant to weathering and do not float. Floating would be problematic during heavy rainstorms for migration of infill (98).

There are many different brands of synthetic turf, but not all applications are practical for football. For instance, Rowlawn, Omniturf, SynLawn and Tartan turf are all residential and golf specific turfs which have very different characteristics than turf used on football fields. Many of the residential turfs and golf specific turfs only use a sand infill. Omniturf has 25.5 mm, 10,000 denier slit film polypropylene fibers atop a rubber and urethane pad (98). All but 6 mm of the fibers are stabilized by sand. Tartan Turf is characterized by a polyurethane foam pad atop an asphalt base, 40 to 60 denier and 12.7 mm thread-like nylon 6 pile fiber (73). Tartan Turf has been associated with a 1.8 times greater risk of injury compared to natural turf (72).

For NCAA football from 1997-2002, the overall injury rate of football players was 36.3 on natural turf and 41.4 on synthetic turf per 1,000 instances (31). Infilled synthetic turf surfaces have been associated with higher incidences of zero-day time loss injuries, non-contact injuries, surface/epidermal injuries, muscle-related trauma, and injuries during higher temperatures compared to natural turf surfaces (71). On the contrary, natural grass has been associated with higher incidences of one to two day time loss injuries, 22+ day time loss injuries, head and neural trauma, and ligament injuries compared to infilled synthetic turf (71).

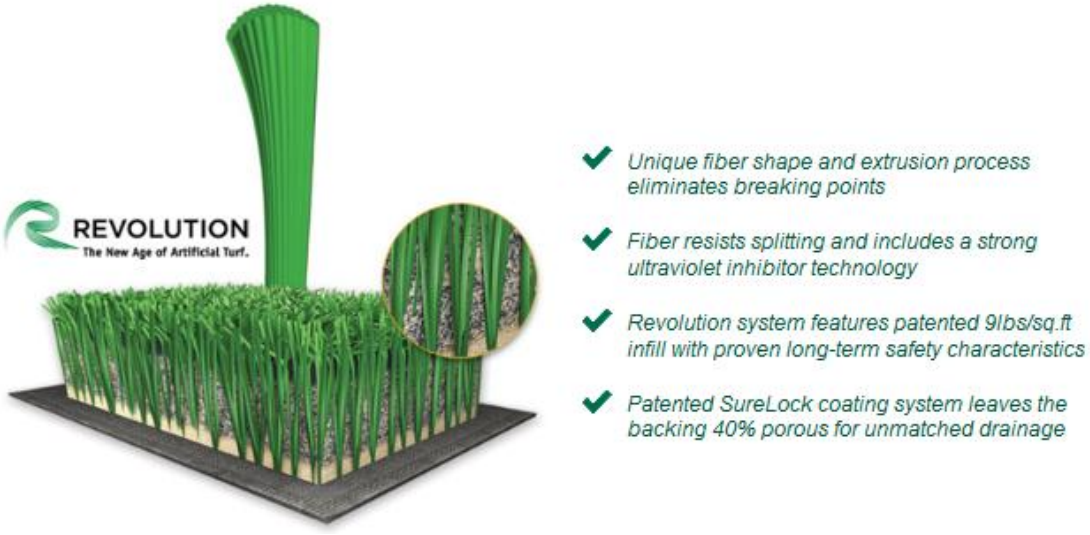
AstroTurf® - Monsanto was the original company to develop synthetic turf. AstroTurf® , founded in 1966 has developed multiple generations of synthetic turf, starting with the well-known “magic carpet” which was composed of 12.7 mm nylon ribbon pile of 500 denier (mass per length of 1 gram) upon a foam pad (polyester nylon mat, a closed cell nitrile rubber and a polyvinyl-chloride pad) that sits atop an asphalt base (105). The first generation of turf was associated with higher resistance to rotation and higher traction forces compared to natural turf (98). The length of the turf fibers in the AstroTurf® "magic carpet," were only 10 mm in length (100) which led to less impact absorption and stiffer blades (15). The stiffer blades were a result of shorter, thicker and more densely packed fibers. First generation AstroTurf® was consistently harder than natural turf (15, 105), resulting in faster running speeds, but increased injury rates (105). The magic carpet progressed through Astroplay™ (Figure 1a) and PureGrass™ (Figure 1b) to the current GameDay Grass™ that combines blade technology with a custom infill system (11). The custom infill is composed of rubber to closely mimic the aesthetic and feeling of natural turf both in terms of traction and impact absorption (68). GameDay Grass™ sits atop a multi-ply (composed of several plies) backing as seen in Figure 1. The multi-ply primary backing is covered with a heavy urethane coating (11). The double nylon root zone increases fiber support and decreases the compaction of both turf fibers and infill. The infill acts to help stabilize the turf fibers while in return the turf fibers act to prevent the infill from migrating (11). Infill migration occurs when the infill in a certain spot is worn away and pushed elsewhere during repeated usage in the same place. In a biomechanics laboratory setting, infill migration needs to be carefully monitored due to repeated movements on a specific location of turf. The infill depth is approximately 40 mm thick (100). The monofilament polyethylene fibers are 51 mm in length (100).



a b

Figure 1: a) AstroTurf® GameDay™ 1) Tufted Construction 2) Multi-ply Backing 3) Infill 4) Double Nylon Root Zone ™ 5) Monofilament Polyethylene; b) Right-AstroTurf® PureGrass™ 1) Pad 2) Tufted Construction 3) Multi-ply Backing 4) Nylon Root Zone ™ 5) Nylon Fibers 6) Monofilament Extrusion (13).

FieldTurf- FieldTurf (FieldTurf™ Tarkett, Peachtree City, GA) is composed of parallel slit polyethylene and polypropylene fibers. The fiber layer is constructed with a gauge length of 19.05 mm (112). There is a bottom layer of crushed silica sand (1:1 ratio) and a primary top layer of cryogenic, styrene-butadiene rubber (SBR). FieldTurf is used at over 1,000 high schools, 21 of 32 NFL teams, over 100 NCAA D-1 teams practice or play on it and there are over 500 applications of recreational installations across the United States. In a study comparing injury rates on FieldTurf compared to natural turf, of all the documented injuries, 64.6% occurred on FieldTurf and 35.4% occurred on natural turf (71).



- ✓ *Unique fiber shape and extrusion process eliminates breaking points*
- ✓ *Fiber resists splitting and includes a strong ultraviolet inhibitor technology*
- ✓ *Revolution system features patented 9lbs/sq.ft infill with proven long-term safety characteristics*
- ✓ *Patented SureLock coating system leaves the backing 40% porous for unmatched drainage*

Figure 2: Field Turf diagram with a multi-ply backing, 50/50 mix of silca sand and rubber granule infill and monofilament and slit-film fibers (25).

Poligras- Poligras, produced by Adolf Company in Germany (98), is mainly used for field hockey, soccer and rugby. Poligras uses turf and a pad which sits atop an asphalt base. Poligras attaches to a curbed perimeter of the field instead of gluing the turf-pad to the base (a technique also used by AstroTurf) (73). The base layer is composed of an anti-compaction system (ACS) elastic layer with 270 micron monofilament polyethylene fibers (51). The synthetic fibers also include a non-directional thatched fiber (for durability), totaling a 65 mm pile height. A re-spring technology, along with infill ensures the vertical formation of the fibers. Silica sand and SBR rubber granules stabilize the long synthetic fibers (51).

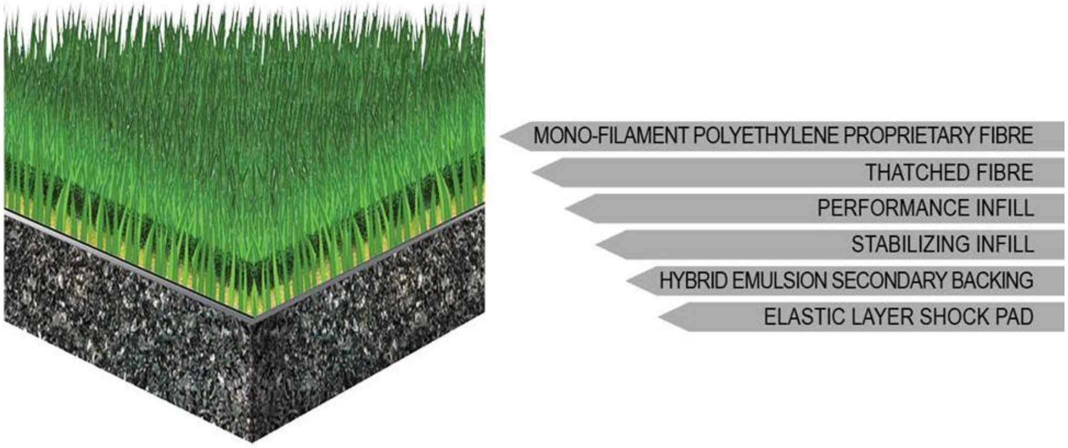


Figure 3: Six layers of Poligras Premier (51).

Polyturf- Polyturf is produced by World Recycling Surfacing Group (WRSG). Polyturf consists of a three-component system: underlying bottom layer pad, solid vinyl material in the middle and a top layer of polypropylene fibers, 12.7 mm in length and 450 denier (103). The most current turf line, Xtreme Turf, is characterized by 54 mm monofilament polyethylene fibrillated fibers with SBR rubber infill on top of a polypropylene backing (90).

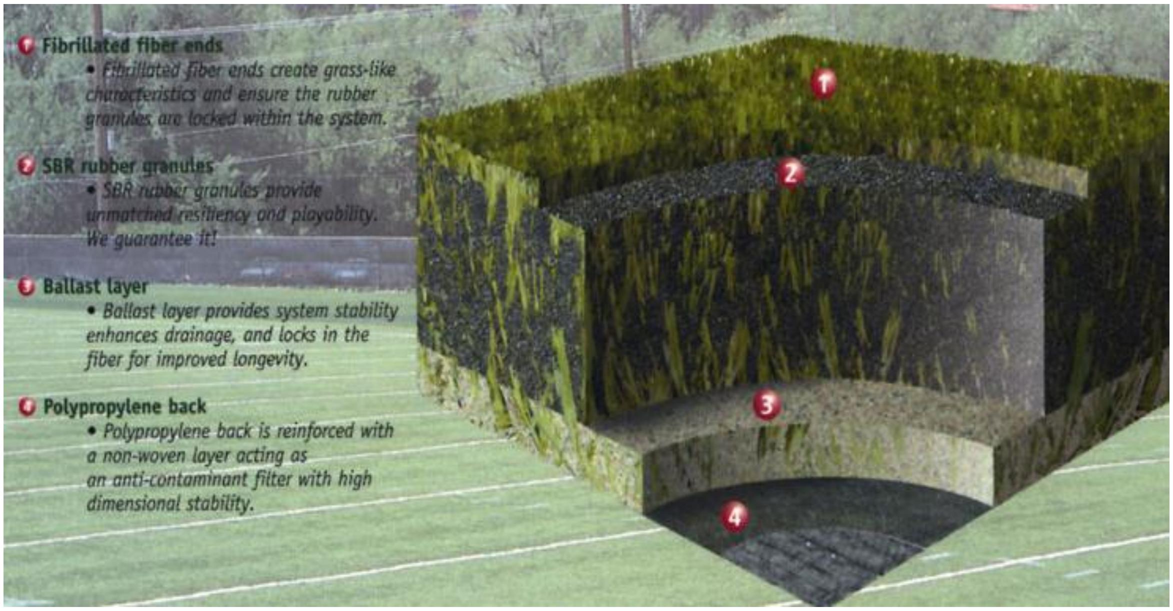


Figure 4: Four layers of Polyturf's Xtreme Turf Premiere (90).

Football Shoe Classifications

With all the different types of sports, synthetic and natural turf surfaces, one type of shoe will not suffice for all situations. Frederick (1986) found durability, cushioning, and support to be critical design factors for cleats (37). Researchers have found traction on synthetic turf to be correlated to the amount of effective stud surface area (14). There are hundreds of different shoes available for football players. Studs are very specific to sports and field applications. Different studs have different diameters, configurations between the forefoot and rear foot, length, and shape. Some studs are round while other are blade-like.

A study in 1996 compared the shoe-surface interactions of 15 different shoes, including traditional studded football shoes, molded studs and turf shoes using a pneumatic testing system with a prosthetic foot (46). An 11.35 kg load cell was used to create an even load distribution across the shoe while forces and moments were measured during translational and rotational movements produced by the pneumatic actuators (both linear and rotary) (46). The study was comparing the differences between wet and dry synthetic turf as well as natural turf and the different shoe conditions. The traditional stud produced a mean rotation of 17.96 Nm and 42.64 Nm for synthetic turf and natural turf, respectively. The turf shoe produced a mean rotation of 16.36 Nm and 14.14 Nm on synthetic turf and natural turf, respectively (46). The traditional studs produced the highest rotational and translational traction on natural grass while the molded studs produced the highest rotational and translational traction on synthetic turf. Overall, there were significant differences between synthetic turf and natural turf for the moment about the tibial axis for rotation of turf shoes and studded shoes (46). Other companies, such as Under Armor, Nike and adidas also make football specific studs. There are different studs not only for different surfaces but also for different sports. For instance, there are studs designed specifically for turf surfaces that consist of multiple smaller and shorter studs that cover the entire sole of the shoe. Also, there are very different shoes and studs for baseball and football because characteristics of sand and turf require different traction and stability stud requirements. Baseball players tend to have metal studs/cleats, whereas football players have rubber studs that can also vary in length depending on ground conditions as well as player position (18, 60). Below is a discussion of the most commonly used shoes and studs with their intended applications.

Traditional Molded Studs- This is the traditional shoe and stud design. The studs are molded to the shoe's outsole and have a peg shaped stud or bladed/edge cleats. These peg-shaped non-removable thermoplastic urethane molded studs (either round or conical) have anywhere from 7 to 12 studs with approximate dimensions of 14.25 mm for the base and 12.7 mm height for the studs (61). The edge cleats, which are blade like projections, are placed at difference angles to allow for better footing (87). The two heel blades are 1.6 cm in height, 1.4 cm in length and 0.5 cm in width. The forefoot blades are 1.3 cm in height, 1.1 cm in length and 0.5 cm width(86).

The bladed design (Figure 5b) produces significantly higher rotational traction than traditional peg shaped studs (112). On FieldTurf (sand/rubber infill) and AstroPlay (a 100% rubber infill), bladed cleats produced a peak rotational stiffness of 5.1 and 4.3 Nm/deg, respectively, compared to 3.2 Nm/deg on the poa pratensis (Kentucky bluegrass) with lolium multiflorum (ryegrass). Peak torque on the FieldTurf for the bladed design was 131.6 Nm and 118.4 on AstroPlay. These forces are associated with an ACL injury rate 3.4 times higher than that of all other designs combined (112). The turf studs produced the smallest amount of rotational stiffness and peak torque with averages of only 2.6 Nm/deg and 69.9 Nm respectively. Traditional studs produced 40 Nm of torque on synthetic turf compared to only 25.5 Nm of torque on natural turf (57). Bladed patterns produced 52 Nm of torque on synthetic turf compared to only 31 Nm of torque on natural turf (57). The researchers also found that athletes wearing bladed cleats resulted in higher injury rates compared to interchangeable screw-in studs, the pivot disk, and flat studs (57). The results from this study suggest that the higher injury rates compared to the traditional studs are due to the additional peripheral surface area covered. The edge/bladed design also produces higher torsional resistance than traditional, screw in, and pivot disk designs (57). The pivot disk was a forefoot disk with a single stud that was placed on a rotating disk, acting as a swivel so that when the athlete planted, it was easy to rotate their foot. However, researchers failed to detect differences between three studded conditions (six forefoot blades, four forefoot studs, and eight forefoot studs) when measuring rotational traction, plantarflexion, abduction, and eversion ankle joint moments with human subjects (86).

Aggressively cleated shoes (majority of sole is covered in studs), such as turf shoes, were found to produce larger values for translational and rotational traction than compared to bladed and traditional studs. In the same study, AstroPlay (50 mm synthetic fibers with 40 mm of rubber infill) and FieldTurf (50 mm synthetic fibers with 40 mm of rubber and sand infill) produced the highest translational and rotational traction compared to AstroTurf® (10 mm synthetic fibers with 10 mm foam base) and natural turf (100). There is generally no debate that longer studs increase traction and therefore the chance of injury, specifically ACL injuries (57). In fact, injuries related to torque increase with stud length (100). However, data describing the effects of stud number on injury incidence are limited.

Players wearing shoes with more than 6 to 10 studs have been found to suffer fewer injuries on natural turf, while players using shoes with 13 to 17 studs had fewer injuries on synthetic turf (14, 109). The increase in stud number decreased the number of joint injuries suffered by football players by 50% (100). Interestingly enough, traditional molded studs mandated by the NCAA were actually deemed “Probably Not Safe” yielding release coefficients of 0.44 (110). The safety determinants were recognized by Torg et al. (1974) and were found by correlating release coefficients with injury statistics from a Philadelphia High School Study. The release coefficient is equal to the force divided by the weight, where the force is the coefficient of friction multiplied by the weight. Release coefficients $\geq$ 0.49 were classified “Not Safe,” while those ranging from 0.40 to 0.49 were deemed “Probably Not Safe,” 0.31 to 0.40 were termed “Probably Safe,” and anything $<$ 0.31 was referred to as “Safe” (110).

Figure 5: a) The traditional peg shaped molded studs (3) and b) the edge studs/blades (107).

Removable/Interchangeable Studs- Interchangeable studs date back to the early 1950’s. Rudi Dassler, founder of Puma, developed the interchangeable rubber and plastic screw-in studs for athletic shoes (88). Today there are a multitude of different stud sizes and shapes that help athletes perform on all different types of terrain ranging from dry and hard to wet and muddy. Not only does the stud length vary with removable studs, but also the diameter of the stud and the shape itself. The most common length and configuration of interchangeable studs are 0.95 cm removable studs with five studs on the forefoot with two on the rear foot (Figure 6). Other removable stud lengths are also available at 1.27 cm (dry field conditions), 1.91 cm (soft or wet field conditions), and 2.54 cm (frozen fields) (16). Screw-in removable studs produced more torque (35 Nm) on synthetic turf than on natural turf (24 Nm) (57). Figure 6 illustrates one shape of stud varying in length (4). The longest stud (far right in Figure 6) would most likely be worn on soft or frozen surfaces in order to increase traction. Soft surfaces would be wet turf or turf in which the studs easily penetrate.

Figure 6: Interchangeable studs with the tool that is used to loosen and tighten the studs (4).

The studded shoe used in this study was the adidas Scorch X Low D with removable studs. In addition to an ethylene-vinyl acetate insole and midsole, these studs have a nonslip lining and were injected with thermoplastic polyurethane detachable studs. The natural turf studs are 1.27 cm in length. The natural turf studs are the original studs that came with the shoe and are made to be used on normal field conditions. Synthetic turf studs are 0.95 cm in length and screw into the adidas Scorch X soles.

Synthetic Turf Shoes- This type of shoe is specifically designed for synthetic playing surfaces only and was designed shortly after the invention of Astroturf. AstroTurf® posed a problem for traditional natural grass studs because they could not penetrate the surface (98). The differences between the synthetic turf studs and natural turf studs are very noticeable. The sole of the synthetic turf shoe is almost entirely covered with rubber studs (Figure 7), which are shorter and smaller than the elastomeric studs of the traditional cleats (5). The base diameter is 9.5 mm and the height is 9.5 mm (61). One study by Livesay et al. (2005) found that turf studs produced significantly higher peak torques on non-infilled synthetic turf (33.2 Nm) than on infilled synthetic turf and natural turf (22.0 Nm). In addition, turf shoes produced 4.34 Nm/deg of rotational stiffness on non-infilled synthetic turf, which was nearly double that of any other shoe-surface combination that was tested, including the traditional molded studs. These synthetic turf shoes have been associated with lower knee injury rates (109).

Figure 7: Synthetic turf shoe with numerous small rubber studs(5).

Shoe-Surface Interaction and the Risk of Injury

Higher rates of injury have been reported for football when comparing synthetic and natural turf (92, 93). A study of high school football players found that injury rates were 1.6 times greater on synthetic turf surfaces than compared to natural turf (96). The interaction between studded shoes and surfaces is known as shoe-surface interaction. Unfortunately, there is very fine line between the shoe and surface demands. In order for athletes to accurately and quickly perform the demands of their sport, they need to be able to change direction, accelerate and decelerate without their shoe sliding across the given surface. On the contrary, athletes also need to be able to complete the demands without fear of their shoes becoming stuck or locked in the surface during certain movements. Twisting and pivoting produce large stresses on the lower extremity joints and ligaments (73). McNitt et al. (1997) determined that components of the shoe-surface interaction were traction, friction, abrasion, and gripability. While there has been a lot of research done on the shoe-surface interaction(21, 32, 36, 40, 46, 57, 61, 71, 72, 110, 112), the majority of the research has focused on first generation synthetic surfaces or has used mechanical testing equipment, while the shoe-surface interaction is most accurately examined by means of human testing.

Mechanical testing uses both rotational and translational traction to characterize the shoe-surface interaction. Understanding the shoe-surface interaction is a direct scope into injury potentials and risks associated with different shoes, surfaces, and movements. Mechanical testing can collect additional data not captured with laboratory evaluations using human subjects. Torg and Quedenfeld (1974) used an assay device that determined release coefficients to establish a model of safety for football knee injuries (110). This device used a prosthetic foot attached to a stainless steel shaft. The shaft supported two bearing systems in which the load could vary but still be equally distributed between the heel and forefoot. The load is applied to a torque wrench which measures the force necessary to release or pivot the prosthetic foot and shoe (100). A similar device was also used in studies by Livesay et al. (2005) and

Andreasson et al. (1983). Livesay et al. (2005) used a turf shoe which had a sole completely covered with small, 9.5 mm by 9.5 mm (diameter by height) studs and found that turf shoes produced significantly higher peak torques on non-infilled synthetic turf than on infilled synthetic turf and natural turf. Also, the turf shoes produced almost twice as much rotational stiffness (the rate at which the torque across the shoe-surface interface increased as a function of applied rotation) (61) on non-infilled synthetic turf as any other shoe-surface combination that was tested, including the traditional molded studs. The Vermont Release Calibrator, originally designed for ski boots and then modified for studded shoes, has been used to test release coefficients (57). In a more recent application of the machine, Lambson et al. (1996) tested four types of football shoes (blades, molded studs, removable studs and the pivot disk) and found that the blades produced significantly higher torsional resistance and were more likely associated with knee injury on natural turf compared to the other shoes designs. Also, the blades were associated with higher ACL injury rates than the three other shoe designs combined (57).

More advanced testing systems such as the Boise State TurfBuster and Penn State PennFoot have recently been developed (Figure 8). These systems can control the weight of an applied load while inducing translational and rotational motion (56). The loads used in the Kuhlman et al. (2010) study ranged from 222 to 1780 N. Kuhlman et al. (2010) found that loads below 666 N showed similar results for static, dynamic and peak traction coefficients. Loads above 888 N found differences in traction between stud designs. Individual shoe characteristics should be tested at loads of 888 N to 1554 N. However, both machine testing and human testing are necessary in order to have a comprehensive understanding of shoe-surface interactions. Human testing is more variable than machine testing due to the extra degrees of freedom in the human body that machines do not have, but at the same time, the variability in the movement is much more realistic. Every time an athlete makes a certain cutting movement, they are not going to load the shoe in the exact same way. Human testing may be more variable but is a more accurate reflection of the kinematics and kinetics occurring in the human body. In this study, we will focus on human testing.

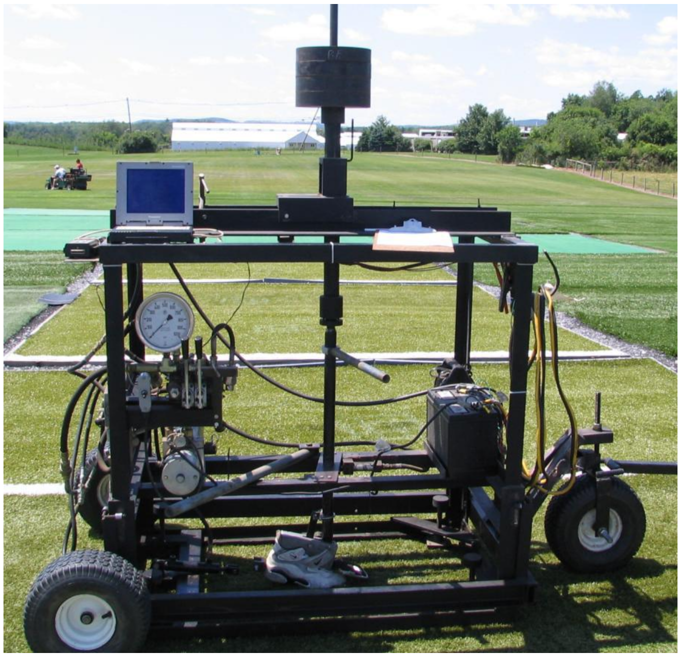


Figure 8: PennFoot traction tester (56).

Drakos et al. (2010) combined human testing with machine testing by using cadaver legs and a custom shear constrained loading assembly that measured strain and force at the ACL. The cadaver legs were outfitted with two sets of studded shoes and were then rotated on natural grass, first generation AstroTurf® and third generation synthetic turf (33). The two sets of studs that were used were traditional molded studs and interchangeable screw in studs. The screw in studs on the natural turf produced the smallest peak strain. Unfortunately, impact forces were not recorded, which play a role in ACL tears (33). Muller et al. (2010) studied three different movements on artificial turf with four different cleat conditions. A 45° cut with firm ground thermoplastic bladed cleats yielded peak vertical GRF of 2.52 BW and vertical force rate of 0.31 BW/ms while a 180° cut yielded peak vertical GRF of 2.33 BW and vertical force rate of 0.17 BW.ms. Peak vertical force and force rate were not affected by different shoe for the 45° cut. The 180° cut decreased peak vertical and shear force for the soft ground cleats compared to the hard ground cleats (74). Soft ground cleats were characterized by 6 mm longer but fewer cleats (only 6 total studs), hard ground cleats had multiple (15 total blades) shorter molded studs and firm ground cleats were bladed.

The major thrust for studies on shoe-surface interaction is athlete safety and performance. Two-thirds of noncontact soccer injuries may be due to excessive shoe-surface traction (35). There is a linear association between shoe-surface traction and effective stud surface area (14). Surfaces with higher frictional resistance, or traction, are assumed to cause fewer injuries than surfaces with lower frictional resistance (80).

It has been shown that athletes wearing studded shoes run faster on synthetic turf compared to natural turf (55) but faster speeds can also increase injury incidence (105). Increasing the speed of the game increases the chance of injury due to fatigue from greater rates of speed, acceleration and torque, as well as overexertion (70).

Frequently, the mechanism of knee injury involves a foot planted on the playing surface with excessive internal rotation of the upper body (42). Many studies have postulated a link between higher resistance to rotation, rotational traction, and increased injury rates, with some showing injury rates of 30 to 50% higher on synthetic turf compared to natural turf (17, 20, 47, 93, 102, 110, 117). It has also been shown that there is an increased risk of ankle and knee injuries in collegiate athletes on synthetic surfaces (7, 38). Increased incidence of ACL injuries in football has been associated with increased friction between the shoe and surface, due to foot fixation (109, 110).

With the increasing adoption rate of synthetic playing surfaces came an increasing number of injuries. Immediately after the adoption of the first generation synthetic surfaces, negative player perceptions were reported in relation to traction and slip resistance (101). The most common football related injuries associated with the synthetic turf occur to the lower extremity and are abrasions, concussions, contusions, and ligament strains (59, 76, 102). A study investigating the differences in injury rates between eight high schools playing on infilled synthetic turf and natural turfgrass over a five-year period found that rates of injury were similar but there were significant differences in time loss, injury mechanisms, anatomical locations of injury, and types of tissue injured on each playing surface (71). Natural turf yielded 0.52 injury rate (injuries/games) while synthetic turf had and injury rate of 0.76 (17). The type of synthetic turf was not controlled for except that the field had to be completely covered in turf for the entire season. Skovran et al. (1990) reported that injuries were 50% more likely to occur on synthetic turf than on natural turf with injury rates of 9.74 and 6.54 per 1,000 athletic exposures on synthetic and natural turf, respectively (102). In the National Football League (NFL), applications of synthetic turf between 1980 and 1989 have been associated with an increased risk for ACL and medial collateral ligament

(MCL) injuries, knee and ankle sprains (93). The same study found that 1081 game-related knee sprains occurring during NFL games between 1980 and 1989, with only 54 due to playing surface type (93). Similar results were observed for ankle injury rates where it was reported that of the 972 game related ankle injuries, only 70 could have been avoided by competing on natural turfgrass in place of synthetic turf (93). One study of college athletes found significantly increased risk of knee and ankle injuries when athletes played on synthetic surfaces (7).

The increasing rate of injury may be due to multiple reasons, such as amount of torque, number of studs, speed of movement, performance tasks or surface conditions. The amount of torque developed at the shoe-surface interface is dependent on several factors including shoe type, playing surface, weight bearing and the stance assumed (14). Traditional studded shoes have been shown to generate larger torsional and friction resistance on natural turf surfaces compared to other shoes (synthetic turf and court shoes) (21). Excessive traction between the shoe and the surface results in foot fixation and therefore a great possibility of injury, while insufficient traction results in slipping and/or falling which can lead to either decreased performance or injury (36, 59). The optimal traction coefficient for football shoe-surface combinations for injury prevention and reduction, was found by robotic/machine testing to be between 0.6 to 1.0 (80, 82, 100, 110, 111). Traction coefficients, as found by Torq et al. (1974) can be correlated with safe shoe-surface interactions. Valiant (1990) found that a lateral change of direction required a minimum traction coefficient 0.6 while stopping on infilled synthetic turf requires a traction coefficient of 0.8. The criteria for landing, takeoff and cutting are a bit different and require more traction, enhancing the athlete’s control and ability to change direction, than these values that were for running and general performance maneuvers (21, 32). In order to avoid slipping during landing and take-off, the optimal traction coefficient should be at least 1.3 (82). More traction will result in foot fixation while less traction will result in slipping which is associated with decreased performance and higher risk of epidermal abrasions (59, 76, 102).

Kinetics of Landing, Pivoting and Cutting Movements

Ground reaction forces (GRFs) are comprised of a three-component vector representing forces in the X, Y, Z directions (anterior-posterior, medial-lateral and vertical). The vertical GRF, or Z component, generally produces the highest magnitude of the three GRF components from vertical acceleration of the body (34). In sports with repeated impacts, such as football, it is important to minimize the force that is returned to the athlete from the surface in order to reduce injury (73). Different movements and surfaces introduce different GRFs. For instance, GRFs would be different between natural turf and synthetic turf because of the built in natural shock absorbency of the turf grass canopy and soil, which is mimicked in synthetic turf with foam pads, sand, and/or crushed rubber infill (35, 100) . In contrast, Feehery (1986) and Dixon et al. (1999) found that impact forces do not vary between different surfaces because runners may be subconsciously changing their gait in order to control the impact forces. One major differences is that machine testing doesn’t account for the surface, a weight is loaded onto a load cell or prosthetic foot the same way every time, but humans react to their environment and therefore may impact various surfaces in different ways so that the forces felt are relatively similar between surfaces. In 2004, Meyers and Barnhill completed a 5-year prospective study of eight high school examining injuries on synthetic turf (FieldTurf) and natural turf and found that the two different surfaces had unique injury patterns with synthetic turf providing more concussions and articular trauma (70, 71). A major limitation of this study was that the field conditions were not measured, but the researchers noted that the majority of injuries occurred on dry field conditions. Therefore, football teams that practice and play on different surfaces increase the chance for injury (95). Griffin (2000) showed that GRFs were not affected by shoe conditions or sole materials, while Livesay (2005) found that harder shoes resulted in increased impact forces.

A rapid and large force being exerted on the floor characterizes the jump and drop-land GRF. Most people will land with their toes first, followed by their heels and then a knee bend to absorb the forces. Depending on the height of the jump and the landing technique, GRFs can exceed three times body weight (45). The initial peak of the GRF, or the braking phase, is where the majority of articular cartilage damage, as well as stress fractures and overuse injuries occur (79). The braking phase is the slope of the GRF line.

Landing and cutting are very common football maneuvers. Many positions, including the offensive receivers and defensive backs are often required to jump, pivot, and cut quickly. The combination of these movements tends to produce a multitude of ACL injuries due to multiple factors (75). Non-contact ACL injuries typically happen during changes of direction such as sidestep cutting, jump-landing, or pivoting (6, 13). There are many studies that examined individual components of this land-cut movement pattern, for instance, just the land, pivot or cut, or a combination of two or all three of the movements Very few studies have investigated the entire movement sequence including approach, jump, land, and cut on third generation, infilled synthetic turf.

Landing: There are two ways to land from a jump: single-leg landing and double-leg landing. Single-leg landings produce significantly higher peak resultant GRF, as well as larger internal extensor moments in the hip and ankle joints, hip extensor and ankle plantarflexor impulses, knee abduction moments, and knee and ankle adductor impulses compared to double-leg landings from the same height of 0.6 m (116). Yeow et al (2011) had subjects step off a 0.6 m platform with their dominant limb and land with both feet for the double-leg landing, and for the single-leg landing, subjects were asked to land on their dominant limb. Higher vertical GRF were found in single-leg landings from heights of 0.3 m and 0.6 m when compared to double-leg landings (115). During single-leg landings, increased GRFs and decreased knee flexion angles reduce the ability to absorb the compressive loads placed on the knee, putting it at risk for injury (30).   Recreational athletes during single-leg landings from 0.4 m have shown greater knee abduction angles, lower hip adduction angles and reduced knee flexion compared to double-leg landings (85).   Higher GRF were associated with significantly less knee flexion compared to double-leg landings for both men and women (85). The risk of ACL injury is also elevated with the presence of large knee abduction angles during landings (48) as well as rapid deceleration and hyperextension of the knee (12).

Energy dissipation for a single-leg landing was mainly carried out by the ankle and hip in the sagittal plane, and the knee was the sole contributor to energy dissipation in the frontal plane (116). Peak ACL force was 11% greater in a stiff landing, in which energy dissipation is decreased compared to a normal or soft landing (58). A soft landing contributed to greater hip flexion at initial contact (41, 58).

Along the same lines, a more erect posture when landing has been deemed a risk factor for ACL injury (41). A study comparing single-leg and double-leg landings between men and women found that single-leg landings were associated with significantly less knee flexion compared to double-leg landings for both men and women (85). Less hip flexion during a single-leg land-and-cut landing is associated with larger peak internal rotation torque, which is an important ACL dynamic loading mechanism (41, 63). The combination of higher GRFs during a single-leg landing and the decreased knee flexion leads to a decreased capacity to absorb shock which places large compressive loads on the knee joint (30) resulting in a higher risk of ACL injury (13, 84, 114). McLean et al. (2009) used a jump landing in addition to a maximal effort 90° cut in order to look at fatigue effects on ACL injury risk and found that fatigue decreased knee flexion angles and increased knee abduction angles. Prior to fatigue, subjects averaged -58.7° of knee flexion and -3.8° of knee abduction. Fatigue decreased knee flexion angles and increased knee abduction angles, which in turn increased the risk of ACL injury. Hass et al. (2005) had participants drop from a height that was equal to their highest maximal effort jump, land on their dominant leg, and then laterally cut with maximal effort. A lateral landing sequence, which required a maximal effort lateral cut after dropping from a raised platform, indicated significantly higher knee flexion range of motion (ROM) than during a static landing trial where participants stepped off the platform and landed without any lateral or forward motion (43). They found that stride landing with a lateral cut showed post-pubescent mechanical changes that may increase injury risk (43). Post-pubescents had vertical GRFs of 2.17 N•(kg•√LH)-1), knee flexion ROM of 48° and abduction ROM of 4°. Post-pubescent females showed significantly less knee flexion compared to pre-pubescent females, resulting in increased incidence of post-pubescent knee injuries.

Cutting: Football players usually make a quick cutting movement after landing in order to avoid oncoming players. In order for cutting in a laboratory setting to mimic that of a game situation, participants needed to pass through the photocells, separated by 1.5 m, at a speed between 5.5 and 7.0 m/s (66). Other studies have found that approach speeds should be 4.5 to 5.0 m/s for an unanticipated 45° side cut (83), as well as 4.5 to 5.5 m/s for a sidestep with simulated defense (65).

O'Connor et al. (2009) used a maneuver similar to the jump, land and cut maneuver where participants leaped from the non-dominant leg to the dominant leg and then cut 45°. The knee was significantly more adducted at contact for the stride-land and cut when compared to the close-land and cut and far-land and cut (83). A factor analysis revealed a high correlation between the three constrained tasks (stride-land and cut landing on level ground, far-land and cut jumping from a box set at maximum countermovement jump height to a distance three times the box height away, and a close-land and cut with the same box height but a jump of equivalent box height length) and a low correlation to the unanticipated cutting maneuver. They also found that that there was a poor relationship between the unanticipated cutting task with a 4.5 to 5.0

m/s approach speed followed by a 45° side cut and ACL injury risk. McLean et al. (2005) found a high degree of correlation between a jump-land task and a planned side cut in terms of the peak abduction angle of the knee.

Chaudhari et al. (2005) used a run with a 90° cut in order to determine variations in arm position on single-limb knee abduction loading (23). Cortes et al. (2010) completed two comparable studies. The first used a drop-jump task and 45 and 180° cut at an approach speed of 3.9 ± 0.5 m/s and found the 180° cut to have increased knee abduction angles and decrease knee flexion compared to the 45° cut. The second study by Cortes et al. (2011) used two similar movements (sidestep cut at 45° and a 180° cut) at an approach speed of 3.5 m/s or faster. The 45° cut with a rearfoot landing increased knee abduction angles whereas the 180° cut had increased knee abduction angles with a forefoot landing. Between the two forefoot movements, GRF and knee flexion values were greater and abduction angles were smaller for the 45° cut compared to the 180° cut (27). Both studies showed increased knee abduction angles for the 180° cut compared to the 45° cut and that a combination of posture, loading, and joint angles held the potential to increase strain on the ACL for the 180° cut. Overall, these studies determined that increased knee abduction angle, large peak vertical GRFs and/or decreased knee flexion angles at initial contact could potentially increase ACL injury incidence (27, 28). Other studies have also found decreased knee flexion angles and increased knee abduction angles during cutting (13, 48, 62, 65, 84). Gehring et al. (2007) used human subjects to examine knee joint loads based on two different soccer shoe cleat constructions (traditional studs and blades) by analyzing kinematics, kinetics and electromyography (EMG). Subjects completed a 180° cut on sand and rubber infilled synthetic turf after accelerating for three to four meters. The peak vertical GRF occurred during initial weight acceptance and did not significantly differ between the two cleated conditions even though the bladed cleats showed greater values (+12.5%) (39). Overall, the bladed design did not prove to have a higher risk of non-contact ACL injury than the traditional studded design. Another study used three movement tasks: drop-jump from 30 cm, sidestep cutting at 45° and a 180° at an approach speed of 3.9 ± 0.5 m/s (28)(29)(29)(29, 30). This study found that ACL injuries could be caused by increased knee abduction angle, large peak vertical ground reaction force and decreased knee flexion angles at initial contact (28). Other studies have also found decreased knee flexion angles and increased knee abduction angles during cutting to be associated with increased risk of ACL injury (48, 65, 84).

The land-cut movement, which consists of a 3-step approach, followed by a single-leg take off, landing on the dominant leg, and cutting laterally at 90° was chosen for this study. The cut angle of 90° was chosen as it is a common football maneuver of recreational and competitive players. Common football passing plays incorporating a 90° cut are the out route (receiver runs 7 to 10 yards downfield and makes a 90° turn towards the sideline) and In/Drag route (receiver runs 7 to 10 yards downfield and makes a 90° turn towards the center of the field).

Overall, studies have found that ACL injuries could be caused by increased knee abduction angle, large peak vertical ground reaction force and decreased knee flexion angles at initial contact (27, 28). Multiple studies have also found decreased knee flexion angles and increased knee abduction angles during cutting to be associated with increased risk of ACL injury (13, 48, 62, 65, 84). The need exists to study the relationship between jumping, landing, and cutting in order to closely mimic that of an actual ACL injury.

The purpose of this investigation was to look at the kinematic and kinetic differences in different shoe conditions (removable natural and synthetic turf studs and a neutral running shoe) during two common football movements (a 180° lateral cut and a land-cut movement) on an infilled third generation synthetic turf. While it is well known that shoes with studs provide more traction on synthetic surfaces compared to other athletic shoes (109), the results of the current study may be valuable for both the competitive athlete as well as the recreational athlete that plays on synthetic turf with and without studs. This study will attempt to understand the vertical GRFs of different shoe conditions on synthetic turf and the differences in knee joint kinematics between the two studded conditions and neutral shoe. In addition, a better understanding of free moments in relation to stud differences during the 180° cut and the land-cut movement would help to evaluate the injury potential for landing and cutting movements.

Chapter 3

Methods

Participants

Fourteen active, healthy recreational male football players (defined as having at least 3 years of football experience) with a catching emphasis (preferably playing wide receiver, running back, defensive back or safety) between the ages of 18 to 25 years who were participating in recreational sport activity at least three times a week voluntarily participated in the study. More details on subject demographics can be found in Appendix D. Participants were excluded from this study if they had any previous history of serious lower extremity injury (such as ligament rupture, meniscus repair, and bone fractures). Participants were also injury free at the time of testing and were excluded from this study if they answered 'yes' to any single question of the Physical Activity Readiness Questionnaire (PAR-Q). Each participant attended a single testing session that lasted about 90 minutes. Participants provided written informed consent approved by the University of Tennessee Institutional Review Board, prior to the testing session. Participants were recruited by the use of flyers and word of mouth.

The number of subjects was determined through a power analysis using IBM SPSS Sample Power, 3.0. The variables that were used to determine the needed power were peak vertical GRF (27, 74) and peak joint angles for the knee and ankle (27, 28, 65, 116). A range of 10 to 12 participants was needed in order for statistical significance of 0.05 to be found. A 3 x 2 (Cleat x Movement) repeated analysis of variance (ANOVA) was used to examine effects of the three shoe conditions and the two movement conditions on the selected variables. Post hoc comparisons using a pair-wise t-test were performed when a significant interaction of shoe and movement or a shoe and movement main effect was found. An alpha level was set at 0.05 and a power of 0.8.

Equipment

Shoe: Participants wore a pair of neutral lab running shoes (shoe, Noveto, adidas) and a pair of football shoes with the provided injected thermoplastic polyurethane natural turf studs (natural turf studs) that are 1.27 cm in length as well as synthetic turf studs (synthetic turf studs) which are 0.95 cm in length (Scorch X Low D, adidas). The synthetic turf studs are shorter which make it easier for them to penetrate the infilled surface. Figure 9 below shoes the differences in shoe types.

Figure 9: From left to right: adidas Noveto, neutral shoe, adidas Scorch X with removable natural turf studs and, adidas Scorch X with removable synthetic turf studs.

Turf: A monofilament synthetic turf surface (AstroTurf® Gameday 3D 60, AstroTurf, Dalton, GA) was mounted to the lab surface with double-sided tape and screws. The small piece that was atop the force platform was mounted by adhering a thin rubberized liner to the backing to anchor the turf on the force platform. A pattern of double sided tape was used in order to provide stability in all directions (three squares decreasing in size with an X in the middle). Lastly, turf on the force platform was fastened with four flat head screws and then top-dressed with sand and rubber infill. These three techniques, in addition to the weight of the infill, helped to keep the turf from moving during the cutting movements. All the remaining turf was fastened with double-sided tape (Figure 11). The turf around the force platform was cut out so that it was easy to determine whether or not the participants struck the middle of the force platform. This was also done to allow the calibration wand to sit down in the gaps between the force platform and the floor. After the turf was installed directly over the force platform, the force platform piece and part of two of the runways were infilled with a sand and rubber mixture (1.0 : 2.5 lbs sand to rubber). The sand was put down first, and then then rubber was added on top. A stiff brush was used to evenly distribute the materials as well as densely pack the sand and rubber into the matted synthetic turf. Figure 13 below demonstrates where the sand and rubber infill was placed (the light are covering the force platform and portions of each runway). The infill was placed so that subjects had a minimum of two to three steps on the infilled turf before landing on the force platform so that they were comfortable with the feeling before stepping on the force platform.

Biomechanical Equipment: A nine-camera infrared motion capture system (120 Hz, Vicon Motion Analysis, Inc., Oxford, UK) was used to collect 3-dimensional (3-D) data. Anatomical reflective markers were placed bilaterally on the acromion process, iliac crest, greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and toe (most anterior aspect of the shoe). Anatomical landmarks were found by palpation for the bony landmarks. Tracking reflective markers were also placed on a semi-rigid thermoplastic shell with four tracking markers on the trunk, pelvis, thigh, and shank. Three tracking markers were attached to the posterior and lateral heel of the shoe (Figure 10). After the anatomical and tracking markers were correctly placed, a single static trial was taken for the running shoe and football shoe conditions. Once the static trial was successfully labeled, the anatomical markers were removed before dynamic movement trials begun. A single force platform (1200 Hz, Advanced Mechanical Technology, Inc., Watertown, MA 02472, USA) was used in order to measure the GRFs and moments of forces during movement. The 3-D kinematic and force platform data were collected simultaneously through the Vicon system. Two pairs of photocells (Lafayette Instrument Co., Model 63501 1R) placed 1.5 meters apart and connected to an electronic timer (Model 54035A, Lafayette Instrument) were used to measure the approaching speed during the 180° cut.

[redacted]

Figure 10: Marker Locations.

Protocol

The testing session took approximately 90 minutes. The test session began with the subject filling out the informed consent form, an information sheet, and the physical activity readiness questionnaire. The information sheet asked questions (Appendix C) about age, number of years of football experience, both recreational and competitive, preferred position, and preferred football shoe style (stud, edge, molded, removable…). In addition, the participants were asked to complete a self-directed five-minute warm up, consisting of 3 to 4 minutes of jogging on a treadmill at 5 to 6 mph and stretching of the quadriceps, hamstrings, gastrocnemius, hip flexors, and trunk, in the running shoes. Participants were asked to wear dark colored spandex shorts and a tight fitting shirt.

Participants first performed three maximum single-leg jump trials with three-step approach using a Vertec system to determine their jump height. Participants jumped from their dominant leg, which was determined by asking which foot they would kick a ball with. The maximum height was used to determine the controlled jump height for the land-cut maneuver. The information from the maximum single-leg jump height was used to place the motorized overhead bar at 90% of maximum jump height. Subjects jumped high enough to touch the bar with their opposite hand. Participants were instructed on the two movements before reflective markers were applied. For the land-cut maneuver, subjects were told to use the bar as a height reference and make sure their fingers either touched the bar or came to the height of the bar. Landing as straight forward as possible was emphasized. For the 180° cut, participants were instructed to cut from the same foot as they landed on for the land-cut maneuver. Participants were also informed about their speed and whether or not they needed to approach the force platform faster or slower. The participants were required to perform a minimum of three practice trials for each movement, but were allowed to practice more if they still felt uncomfortable with the movements. Before the movement trials, the reflective markers were applied to the trunk, pelvis and the both lower limbs. The participant performed five successful trials in each of the six testing conditions: 180° cut at a an approach speed between 3.5 to 4.5 and single-leg land-cut at 90° from a single-leg jump at 90% of their maximum jump height wearing the shoe, natural turf studs and synthetic turf studs. During the 180° cut (Figure 12 and 13), participants started approximately 7.62 to 8.23 m marked by a cone from the center of the force platform, ran forward at maximum speed, performed a 180° cut on the force platform and accelerated back through the cone before decelerating.

Figure 11: Lab Set-Up.

The 180° cut (Figure 12 and 13) was modeled after the NFL combine and the 180° cut used in previous studies (27, 28, 39, 74). Gehring et al. (2007) subjects cut at 180° on sand and granulate infilled synthetic turf after acceleration for three to four meters in order to examine knee joint loads based on two different soccer shoe cleat constructions (traditional studs and blades). Shorten et al. (2003) also used a 180° maximal effort cut.

[redacted] [redacted] [redacted]

Figure 12: 180° Cutting Movement.

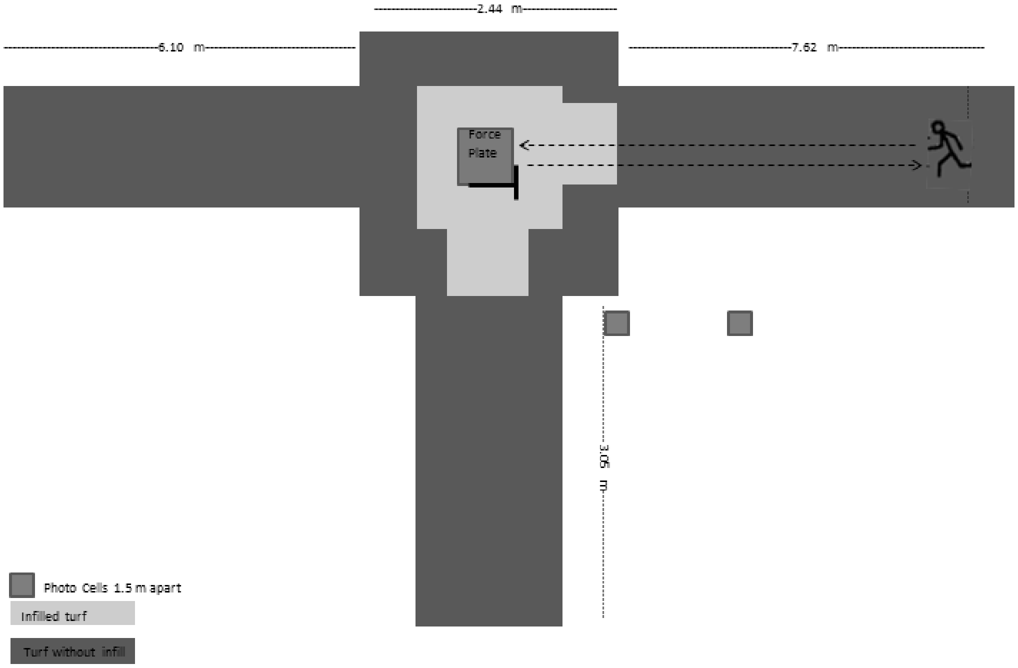


Figure 13: 180° Cut Movement Pattern.

In the land-cut movement (Figure 14 and 15), participants started three steps away from the center of the force platform. A three-step approach helps achieve greater velocity which has been shown to produce substantially greater loading (83). Participants started their first step with their dominant foot and then took off for a 90% maximum effort jump from their dominant foot, reaching with the opposite hand to touch the overhead bar. The participant then landed on the force platform with their dominant foot before cutting 90° in the direction opposite of the foot they landed on. The angle of cut was mainly controlled and guided by the turf runways, which were at right angles (Figure 13 and 15). In order for the trial to be deemed successful, the participant needed to reach the height of the bar while maintaining a balanced and full-foot contact with the force platform. The participant was asked not to rotate their body to the direction of the cut when the body is in the air facing forward prior to landing. The participant was also instructed to maximally accelerate toward a cone placed on the runway before slowing down. Participants were allowed to practice the movement on the turf until they felt comfortable.

The testing conditions were randomized so that the three shoe conditions were randomized first and the two movement conditions were then randomized within each shoe condition. The participant was given ample time to become familiar with the testing conditions prior to the actual data collection. In addition, the participants were given as much rest as needed between trials and conditions.

Figure 14: Land-cut Movement.

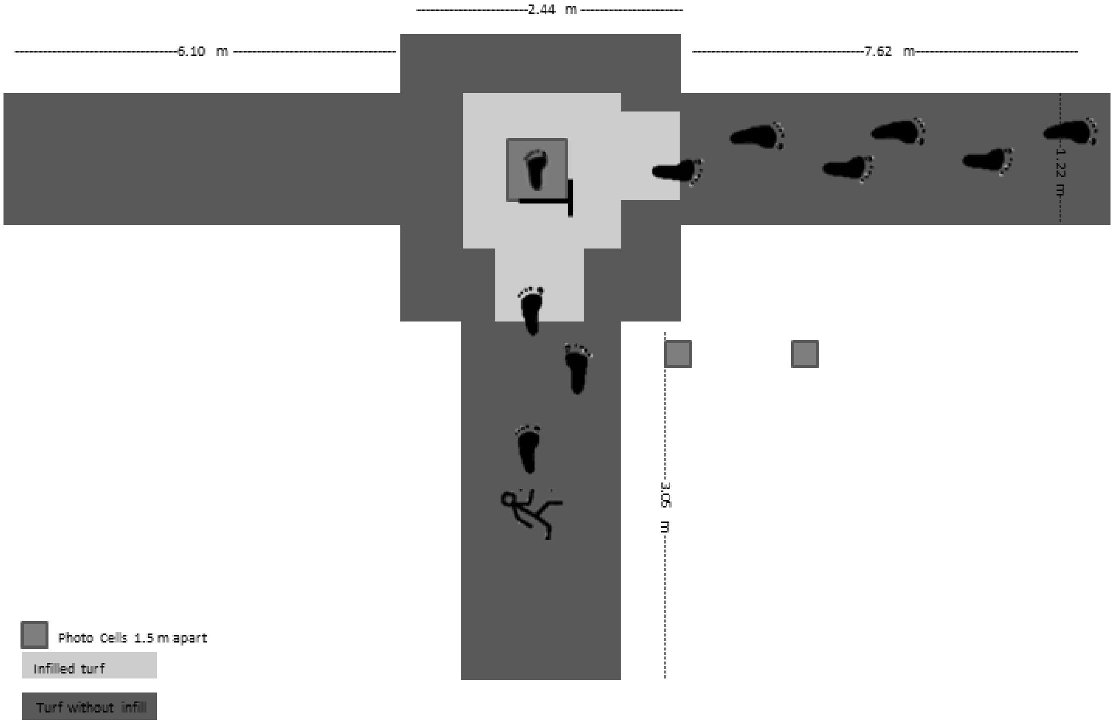


Figure 15: Land-cut Movement Pattern.

The land-cut movement was modeled after similar movements from research using dominant leg landing and a side cut from two-legged jump (28, 54, 67, 83, 85, 116). A one-legged take-off was used instead of a two-legged take-off in order to more accurately depict a football game situation where players are running while tracking the ball and avoiding defensive players. Many times, the players will be in motion before jumping to catch the ball instead of standing and taking off with both feet. The distance between the take-off position and the center of the force platform was approximately equal to one-step in order to involve both vertical and horizontal components of the jump landing movement.

Data Processing and Analysis

Visual3D software suite (C-Motion, Inc.) was used to compute three-dimensional (3D) kinematic and kinetic variables of the lower extremity joints. An X-Y-Z Cardan sequence was used in the angular computations and a right-handed rule was used to determine positive and negative signs of joint angles. GRFs were normalized to body weight (BW) and free moments were normalized to body mass (Nm/kg). Marker trajectories and force plate data were low-pass filtered with a zero-lag fourth order Butterworth filter at 12 and 10 Hz, respectively.

The variables of interest included peak absolute FM, impact vertical GRF, vertical impact loading rate, peak medial GRF, peak dorsiflexion angle and velocity, peak knee flexion angle and velocity and peak knee abduction. In order to focus on key variables, kinematic and kinetic variables were only analyzed from initial foot contact to midstance. McNair et al. (1990) concluded that 70% of non-contact ACL injuries occur at initial contact.

Chapter 4

Biomechanical Differences Among Single-leg Landing and Cutting Movements in Two Football Studs on Infilled Synthetic Turf

Introduction

Injuries in American football occur more frequently than any other sport (1, 39, 41). There are an estimated 80,000 to 250,000 anterior cruciate ligament (ACL) injuries each year in the United States alone (3, 14) with football players accounting for 100,000 to 130,000 of those injuries every year (44). The highest number of ACL injuries occur in pivoting sports during the fast-paced plant-and-cut movements that involve rapid deceleration, as well as jumping, landing or collisions (3, 5, 14). Some examples of non-contact ACL injuries involve foot fixation, hyperextension of the knee, and torsional stress in falling, landing, suddenly stopping, or rapidly changing direction (4, 35). The introduction of synthetic turf has influenced both the frequency and type of injury (2, 7, 34). In 2004, an injury rate of 64.6% of all documented injuries occurred on synthetic turf (Fieldturf) compared to 35.4% on natural turf (29). A study of high school football players found that injury rates were 1.6 times greater on synthetic turf surfaces than compared to natural turf (40).

The introduction of synthetic turf led to the development of football shoes to accommodate the differing characteristic of synthetic turf compared to natural turf. Although, it is important to note that many recreational players do not use studded shoes on synthetic turf and just play in regular tennis or running shoes. The third and most current generation of synthetic turf sits atop an asphalt or crushed aggregate base and has fiber lengths of 40 to 70 mm and a combination of rubber and sand infill of up to 50 mm. The fiber and infill help to mimic natural turf characteristics in terms of look, feel and reaction, such as increased shock absorbency (27, 31, 42). The granular infills found in synthetic surfaces have been shown to produce significantly higher translational traction and a lower resistance to rotation, closely mimicking that of natural turf (43). An epidemiological study also found that bladed cleats were associated with a higher rate of ACL injuries compared to non-bladed cleats (21). Muller et al. (2010) studied three different movements on sand/rubber infilled synthetic turf with four different studded conditions. Peak vertical force and force rate were not affected by different shoe conditions for the 45° cut. Peak vertical and shear forces for the soft ground studs (6 mm longer but fewer studs) were decreased compared to the hard ground studs (multiple shorter studs) for the 180° cut (32). Livesay et al. (2005) used natural and synthetic turf studs under controlled mechanical testing on infilled synthetic turf and found that natural turf studs resulted in increased impact forces. A recent study using traditional soccer studs and blades during a 180° cut on infilled synthetic turf showed no significant differences for vertical ground reaction force (GRF)(13).

In sports with repeated surface impacts, such as football, it is important to minimize the force that is returned to the athlete from the surface in order to reduce injury (31). Few studies have examined biomechanical characteristics of dynamic cutting and landing movements on infilled synthetic turf with human participants. Single-leg landings produce significantly higher peak vertical GRF when performed on a laboratory floor (47) and significantly less knee flexion compared to double-leg landings (38). Decreased knee flexion angles reduce the ability of lower extremity to absorb the compressive loads placed on the knee, putting it at risk for injury (10) . McLean et al. (2009) found that during initial contact, knee abduction was significantly increased during unanticipated single-leg landings compared to anticipated landings in a jump landing with a maximal effort 90° cut. Fatigue decreased knee flexion angles and increased knee abduction angles which was thought to increase the risk of ACL injury. Hass et al. (2005) used a lateral landing sequence in which participants dropped from a box equal to the height of their maximum vertical jump followed by a maximal 90° cut. Post-pubescent females showed significantly less knee flexion compared to pre-pubescent females, which may help to explain the increased incidence of post-pubescent knee injuries.

Cortes et al. (2010) found increased knee abduction angles and decreased knee flexion in a 180° cut compared to the 45° cut at an approach speed of 3.9 ± 0.5 m/s on laboratory flooring. In the second study, Cortes et al. (2011) found increased knee abduction angles with the 45° cut. Between the two forefoot movements, GRF and knee flexion values were greater and abduction angles were smaller for the 45° cut compared to the 180° cut (8). Overall, these studies suggested that large peak vertical GRFs and decreased knee flexion angles at initial contact may increase the strain placed on the ACL (8, 9). Other studies have also found the risk of ACL injury to increase with decreased knee flexion angles and increased knee abduction angles during rapid changes of direction (5, 17, 23, 24, 37). Muller et al. (2010) found that peak vertical and medial GRF for soft ground studs during a 180° cut decreased compared to the hard ground studs (32). The land-cut is associated with greater peak vertical and medial GRF as well as greater loading rates than compared to the 180° cut. Increased vertical loading rates have previously been linked to overuse injuries in runners (33) just as increased FMs have also been linked to overuse injuries (30).

To the knowledge of the authors, no studies have examined the biomechanical behaviors of human participants during a single-leg land-cut movement on infilled synthetic turf. Also, no studies have investigated free moments (FM) during the land-cut or 180° cutting movements, just running. FM is a torque applied about the vertical axis computed from the moments measured by force platform and friction at the shoe and surface interface during the stance phase of movements (18). High FM and shear forces applied simultaneously could be related to overuse injuries such as stress fractures (30). Land-cut and 180° cut movements are both frequent patterns in football that are associated with rapid deceleration and rapid changes of direction. The single-leg land-cut movement could impose a greater injury risk to ACL than the 180° cut based on the increased vertical component with the land-cut that is not seen in the 180° cut. Therefore, the purpose of this investigation was to examine the kinematic and kinetic differences in natural and synthetic turf studs compared to a running shoe during two common football movements, single-leg land-cut and 180° cut, on infilled synthetic turf. The two movements chosen include rapid changes of direction and rapid deceleration which have been linked to increased ACL injury rates (3, 5, 14). The land-cut movement was modeled after similar movements from research using dominant leg landing and a side cut from two-legged jump in recreational athletes (9, 20, 26, 36, 38, 47). The 180° cut was modeled after the NFL combine and the 180° cut used in previous studies (8, 9, 13, 32).

We hypothesized that 1) the natural turf studs would produce a larger peak FM, peak vertical GRF and vertical impact loading rate compared to the synthetic turf studs and the running shoes during both movements; the two studded shoe conditions would result in greater peak FM, peak vertical GRF and loading rates than the running shoe; 2) peak FM, peak vertical GRF, vertical GRF loading rate and peak knee abduction angle would be greater and knee flexion angles would be smaller in the land-cut movement compared to the 180° movement.

Methods

Participants

Fourteen active and healthy male recreational football players (mean ± SD age: 20.14 ± 1.41 years, height: 1.81 ± 0.04 m, mass: 85.58 ± 9.68 kg) participated in this study. The number of participants was determined through a power analysis (Sample Power 3, 3.0, IBM SPSS). The variables that were used to determine the needed power were peak vertical GRF (8, 32) and peak joint angles for the knee (8, 9, 24, 47). A range of 10 to 12 participants was needed in order to detect a statistical significance of 0.05 at a beta level of 0.8 for the repeated measures ANOVA. Participants had a minimum of three years of football experience, exercised at least three times a week, and played recreational football once a week. Participants were injury free at the time of testing and were excluded from this study if they had any previous history of major lower extremity injury (such as ligament rupture, meniscus repair, and bone fractures). Participants were also excluded if they answered ‘yes’ to any single question of the Physical Activity Readiness Questionnaire (PAR-Q). Participants provided written informed consent, which was approved by the Institutional Review Board prior to the testing session.

Instrumentation

Shoe: Participants wore a pair of neutral lab running shoes (Shoe, Noveto, adidas, Figure 1a) and a pair of football shoes (Scorch X Low D, adidas) with Pebax material outsole and replaceable injected thermoplastic polyurethane natural turf studs (Figure 1b) measures 1.27 cm in height. These were replaced with synthetic turf studs measuring 0.95 cm tall (synthetic turf studs, Figure 1c) during testing.

Turf: A 51 mm monofilament synthetic turf surface (Astroturf Gameday 3D 60, AstroTurf, Dalton, GA) was mounted around a force platform in the lab surface with double-sided tape (Figure 2). A separate piece of the turf was securely mounted on top of the force platform with four flat head screws at its corners and double-sided tape. The turf was then top-dressed with sand and rubber (1.0:2.5 lbs sand to rubber ratio).

Biomechanical Equipment: A nine-camera infrared motion capture system (120 Hz, Vicon Motion Analysis, Inc., Oxford, UK) was used to collect 3-dimensional (3D) kinematic data. Anatomical reflective markers were placed bilaterally on the acromion process, iliac crest, greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and toe (most anterior aspect of the shoe) of both sides. Tracking markers were also placed via a semi-rigid thermoplastic shell of four markers on the trunk, pelvis, thigh, and shank and attaches with Velcro to an elastic band that was placed directly on the skin. Three tracking markers were attached to the posterior and lateral heel of the shoe. Two separate static trials were taken, one for the running shoe and one for football shoe conditions, respectively. A 60 × 60 cm force platform (1200 Hz, BP600600, Advanced Mechanical Technology, Inc., Watertown, MA 02472, USA) was used to measure the GRFs, moments of forces and mount the turf piece. The 3D kinematic and force platform data were collected simultaneously using Nexus of the Vicon system.

Testing Protocol

Participants were asked to complete a self-directed five-minute warm up, consisting of jogging on a treadmill at 5 to 6 mph and stretching of hamstrings, quadriceps, gastrocnemius and lower back, in the running shoes. Participants performed three trials of maximum jump height from their dominant foot (determined by asking which foot they would kick a ball with) using a three-step approach with the Vertec Jump Training System. Participant’s 90% maximum jump height was used to set the height of an overhead bar which was used as a target during the land-cut testing. Participants were instructed and then practiced the two movements until a minimum of three successful attempts were completed before reflective markers were applied. The shoes were randomized and then the movements were randomized within the shoe conditions. The participant was given ample time to become familiar with the testing conditions prior to the actual data collection. In addition, the participants were given as much rest as needed between trials and conditions. Five successful trials were performed in each of the six testing conditions.

In the single-leg land-cut movement (Figure 2), participants started three steps away from the force platform with their dominant foot, approached and completed a single-leg jump, reaching the overhead bar with their opposite hand. Participants landed with their dominant foot on the force platform and completed a maximal effort 90° cut without their non-dominant foot touching the ground (15, 24). A successful trial consisted of the participant reaching the height of the bar while maintaining a balanced and full-footed landing on the force platform. Participants were asked to minimize rotation of their body towards the direction of cut prior to landing. The participant was instructed to maximally accelerate towards a cone placed 2 to 3 meters away from the force platform before slowing down. For the 180° cut movement (Figure 2), participants were instructed to start from approximately 7.62 to 8.23 m away from the force platform on the runway, run forward at a speed between 3.5 to 4.5 m/s (9, 24, 25, 36) and cut 180° on the force platform with their dominant foot. The approach speed was monitored by two pairs of photocells (Lafayette Instrument Co., Model 63501 1R) placed 1.5 meters apart and an electronic timer (Model 54035A, Lafayette Instrument). A successful trial consisted of the participant obtaining the approach speed of 3.5 to 4.5 m/s and fully contacting the force plate with their dominant foot.

Data Processing and Analysis

Visual3D software suite (C-Motion, Inc.) was used to compute three-dimensional (3D) kinematic variables of the lower extremity joints. An X-Y-Z Cardan sequence was used in the 3D kinematics computation and a right-handed rule was used to determine positive and negative signs of joint angular kinematic variables. A customized computer program (VB_V3D) was used to generate scripts and models to be used in Visual 3D and determine critical values of variables of interest. Another customized program (VB_Table) was used to generate statistical files and organize data tables. GRFs were normalized to body weight (BW) and free moments were normalized to body mass (Nm/kg). Marker trajectories and force platform data were filtered with a zero-lag fourth order low-pass Butterworth filter at 12 and 50 Hz, respectively. The variables of interested included peak absolute FM, impact vertical GRF, vertical impact loading rate, peak medial GRF, peak dorsiflexion angle and velocity, peak knee flexion angle and velocity and peak knee abduction. In order to focus on key variables, kinematic and kinetic variables were only analyzed from initial foot contact to midstance (28).

A 3 x 2 (Cleat x Movement) repeated measures analysis of variance (ANOVA) was used to examine effects of the three shoe and two movement conditions on the selected variables. Post hoc comparisons using a paired t-test were performed when a significant interaction of shoe and movement was detected or a shoe or movement main effect was found. An alpha level was set at 0.05. Frontal plane ankle and knee angles were compared using a one-way ANOVA instead of repeated measures due to differing movement patterns between the two conditions. For instance, during the land-cut the ankle showed an eversion angle whereas the 180° cut showed an inversion angle, since those two movements cannot be compared in a repeated measures ANOVA, a one-way ANOVA was used.

Results

No significant differences were found in jump height for the land-cut movement among the shoe conditions. Peak free moment was greater for land-cut than 180° cut ($p<0.001$, Table 1). Vertical impact GRFs were greater for land-cut trials than 180° cut ($p<0.001$). Time to vertical impact GRF showed a cleat x movement interaction for multiple conditions ($p=0.048$, Table 1). Post hoc comparisons showed that time to vertical impact GRF occurred later in natural turf studs than synthetic turf studs for the 180° cut ($p=0.019$). Time to vertical impact GRF also occured later for the shoe ($p=0.003$), natural turf stud ($p=0.001$) and synthetic turf stud ($p=0.042$) for the 180° cut compared to the land-cut. The vertical GRF loading rate was greater in the land-cut trials compared to the 180° cut. Finally, peak medial GRF showed a significant cleat x movement interaction ($p=0.002$, Table 1). The post hoc comparisons showed that peak medial GRF was greater in shoe compared to natural turf studs ($p<0.001$) and synthetic studs ($p=0.004$) and was smaller in natural studs compared to synthetic studs ($p<0.001$) only in 180° cut.

The ankle dorsiflexion ROM displayed a cleat main effect ($p=0.025$, Table 2). The shoe had significantly less dorsiflexion ROM compared to the synthetic turf studs ($p=0.032$). Land-cut movement had greater dorsiflexion ROM than the 180° cut ($p < 0.001$). The peak dorsiflexion velocity was greater in land-cut than 180° cut ($p<0.001$).

It also showed a cleat main effect (p=0.014). The peak dorsiflexion velocity was significantly smaller in natural turf studs compared to synthetic turf studs (p=0.014). No significant interactions were found at the ankle joint. A significant cleat main effect was found for peak eversion velocity (p=0.005). Post hoc comparisons showed that it was significantly smaller in shoe than that in natural turf stud (p=0.016) and synthetic turf stud (p=0.002). For the knee joint, flexion ROM was greater for the land-cut than 180° cut (p<0.001, Table 3). Peak flexion velocity was also greater for land-cut compared to 180° cut (p<0.001).

Discussion

The purpose of this investigation was to examine the kinematic and kinetic differences in different shoe and cleat conditions during two different football movements on infilled synthetic turf. The first hypothesis was that the natural turf studs would produce a larger peak FM, peak vertical GRF and vertical impact loading rate compared to the synthetic turf studs and the running shoes during both movements. Moreover, we hypothesized that the two studded shoe conditions would result in greater peak FM, peak vertical GRF and loading rates than the running shoe. No significant differences for peak FM were found between shoe conditions. The natural turf studs (1.27 cm) are slightly longer compared to the synthetic turf studs (0.95 cm) and this height difference has been previously associated with increased risk of torque-related injury based on increased release coefficients found by mechanical testing (45). Their results found that longer (1.91 cm) soccer studs produced greater release coefficients on natural turf and synthetic turfs compared to conventional shorter (1.27 cm) studs. Larger release coefficients may increase the chance of ACL injury (45).

There were no differences in peak vertical GRFs and its loading rate between cleats. The lack of difference in peak GRF was supported by the findings of Griffin et al. (2000) who found that neither sole materials nor shoe conditions significantly changed the GRFs. This was contrary to Livesay et al. (2005) finding from mechanical testing that natural turf studs resulted in increased impact forces compared to synthetic turf studs when tested on rubber infilled synthetic turf (22). Mechanical testing, while controlled, may not be directly related to the results of human testing due to performance variability and neuromuscular control of human participants. Gehring et al. (2007) also found no significant differences between traditional studs and bladed cleats, but did note a 12.5% increase in bladed cleats (approximately 19 N/kg for traditional studs and 22 N/kg for bladed cleats). The current study also revealed no significant differences but an 8.4% increase in vertical GRF between the averaged cleat conditions and the running shoe for the 180° cut. Vertical impact GRF reached an average peak of 5.019 BW for the natural turf studs during the land-cut whereas the average peak for synthetic turf studs and the running shoe were 4.949 and 4.758 BW, respectively. While studies have not examined vertical loading rates and free moments for movements such as the land-cut and the 180° cut, increased vertical loading rates have previously been linked to overuse injuries in runners (33) just as increased FMs have also been linked to overuse injuries (30).

No significant differences were found for vertical loading rate between shoe conditions. Vertical loading rate takes into account the peak vertical GRF as well as time to the peak and since neither one of those variables showed significant cleat main effects, it is not surprising that vertical loading rate was not significant between shoe conditions. The greatest loading rate was achieved by the synthetic turf studs at 108.7 BW/s in the land-cut trials, whereas the highest loading rate for the 180° cut trials was achieved in the running shoe at 30.5 BW/s. Surprisingly, for the 180° cut, loading rate, peak vertical and medial GRF were greatest for the running shoe condition. Muller et al. (2010) found higher values for vertical GRF but lower values for vertical loading rate for all cleat conditions compared to the current study. The studs differed between the two studies, with Muller et al. (2010) using both studs and blades. The average peak vertical GRF and vertical force rate were 2.40 BW and 17.5 BW/s, respectively across the four cleated conditions in Muller's 180° cut movement compared to 1.75 BW and 27.87 BW/s across the three shoe conditions in the current study. The peak vertical and medial GRF for soft ground studs decreased compared to the hard ground studs in the 180° cutting movement of Muller et al. (2010) (32). The land-cut is associated with greater peak vertical and medial GRF as well as greater loading rates. The current study did not find many significant cleat differences between the shoe conditions for land-cut or 180° cut movements, the exceptions being time to peak vertical GRF and peak medial GRF. Differences between the current study and the Muller et al. (2010) study could be due to the different cleats used as well as the different turf types. Muller et al. (2010) used a sand and rubber infilled turf with 35 mm fibers (Polytan Liga Turf 240) whereas we also used a sand and rubber infill, but with 51 mm fibers (Astroturf, Gameday 360). Differences I impact forces between the two studies could be determined by meansu of mechanical testing, such as the Tennessee Athletic Field Tester (TAFT). Additionally, approach speeds for the 180° cut were not controlled or monitored in the Muller et al. (2010) study.

Finally, peak medial GRF was significantly larger in the shoe and the synthetic turf studs compared to the natural turf studs for the 180° cut. Increased medial GRFs place greater loads on the lateral ankle ligaments during cutting movements and make them more susceptible to lateral ankle sprains (19). A simulated defensive opponent during a 30 to 40° cut has been shown to increase peak medial GRF, as well as knee flexion and abduction (24). Possible causes in different peak medial GRFs associated with the different shoe/cleat conditions could be due to a number of factors. The natural turf studs, with 0.9 cm in diameter, have the least effective contact surface area with the turf while the synthetic turf stud has a diameter of 1.5 cm (Figure 1). The football shoe has a smooth Pebax material outsole, relying mostly on penetration and gripping of the studs with the turfs to create traction. The rubber-type outsole of the running shoe with tread patterns may increase effective contact area compared with the cleated football shoes. A combination of the effective contact surface area as well as the rubber outsole and complex tread pattern of the shoe may be increase shoe-surface friction (6). Running shoes are worn on synthetic turf just as often, if not more often than studded shoes, and therefore it is important to understand the risks associated with wearing running shoes and studded shoes alike.

Ankle kinematics did not reveal any significant differences for peak dorsiflexion angle between cleat conditions. Dorsiflexion ROM was significantly larger for the synthetic turf studs compared to the shoe while dorsiflexion velocity was greater for the synthetic turf studs compared to the natural turf studs. Decreasing ROM at the ankle reduces impact attenuation capacity of the ankle and therefore increases the patellar tendon load, which can increase anterior tibial translation and strain on the ACL. The peak eversion velocity was significantly smaller in the shoe compared to the natural turf cleat and synthetic turf cleat in land-cut movement. Eversion velocity helps to slow down the eversion moment. A smaller eversion velocity would indicate that the eversion moment was smaller for the shoe compared to the studded conditions. No differences were found for the knee kinematic variables between the shoe conditions. Previous studies on shoe/cleat differences chose to only report kinetics (i.e., GRFs and knee moments) (13, 32).

Our second hypothesis was that peak FM, peak vertical GRF, vertical GRF loading rate and peak knee abduction angle would be greater and knee flexion angles would be smaller in the land-cut movement compared to the 180° movement. The peak FM was significantly larger for the land-cut movement compared to the 180° cut (0.464 and 0.258 Nm/kg, respectfully). The FM evaluates overall loading to the body in rotational related movements. Large FM could cause lower extremity overuse injuries (30).

The peak vertical GRF and its loading rate were significantly higher in the land-cut movement than the 180° cut movement. The land-cut movement averaged 4.93 BW between shoe conditions, 2.7 times greater than average 1.8 BW in the 180° cut. The land-cut movement has greater vertical displacement than does the 180° cut movement making the greater peak vertical GRF expected. Loading rates for the land-cut movement averaged 104.0 BW/s, 3.7 times larger than the 27.9 BW/s for the 180° cutting. The vertical GRF increases when changing from a double-leg landing to a single leg landing. Yeow et al. (2011) showed that double-leg landings produced approximately 2.5 BW and single-leg landings produced approximately 4.5 BW of peak vertical GRF. Since single-leg landings produce significantly higher GRF compared to double-leg landings, it would be expected that the land-cut movement would produce GRF in excess of three bodyweights (16). Increased GRF increases the compressive load placed on the knee which may be linked to increased risk of ACL injury (5, 37, 46) in addition to higher peak vertical GRF, decreased knee flexion (8-10), and increased knee abduction angles (47).

Finding an appropriate shoe/cleat and surface combination that reduces the force returned to the athlete can ultimately help to reduce the risk of injury (31). For the 180° cut, Cortes et al. (2010) found average vertical GRF of 1.51 BW, which are similar to the averaged 1.9 BW for our running shoe in the current study. Cortes had participantss perform solely in running shoes and on a regular force platform surface which may have accounted for the slightly smaller results compared to the current study. While medial GRFs were similar between the two movements, they were different among cleats for the 180° cut for the current study. The increased medial GRFs associated with the shoe and the synthetic turf studs may suggest that cutting in those shoe conditions on infilled synthetic turf may put the athlete at a greater risk of ACL injury. Using a similar participant base of female collegiate soccer players from the Cortes et al (2010) study, Cortes et al. (2011) found vertical GRF for the 180° task to be 1.2 BW. There was a difference in approach speed between the two studies, with the first study controlling the speed to 3.9 ± 0.5 m/s while the second study only set a minimum approach speed of 3.5 m/s. Since the average values for approach speed were not provided, it is hard to fully compare the two studies when approach speeds could have been significantly different from the current study. Increased risk of ACL injury can also come from increased medial GRF (32).

Ankle dorsiflexion ROM was significantly greater for the land-cut compared to the 180° cut. Peak dorsiflexion angles were similar between the two movements. Reduced dorsiflexion ROM coupled with reduced dorsiflexion velocity during the horizontal landing of a stop jump task compared to the vertical landing has been thought to increase patellar tendon load (12). Average peak dorsiflexion velocity was significantly greater for the land-cut movement (875.1 deg/s) compared to the 180° cut (460.4 deg/s).

Patella tendon force is increased when knee flexion angle is less than 30°. Increased patella tendon force increases anterior tibia translation, which in turn strains the ACL (11). For this study, the land-cut movement appeared to be safe based on knee flexion angles from the Durselen et al. (2005) study. No single participant landed with knee flexion angles of less than 30°, in fact, the average knee flexion angle for the land-cut was 66.9° with the single lowest reported value at 52.8°. For the 180° the lowest reported value was 38.6° which may make that particular participant at an increased risk of injury compared to the others. The average knee flexion angle for the 180° cut was 69.7°.

Knee movement patterns were similar between the land-cut and the 180° cut. Knee flexion ROM was significantly higher for the land-cut movement compared to the 180° cut movement, averaging values across shoes conditions of 50.2° and 37.1°, respectively. The increased ROM for the land-cut compared to the 180° cut is defined by the differing task demands associated with landing and cutting. Increased ROM for the land-cut helps to not only stabilize the participant during the single-leg landing, but also to help them immediately perform a maximal effort 90° cut. The ROM values in the land-cut movement are similar to the results reported by Hass et al. (2005) in a lateral landing sequence in which participants dropped from a box equal to the height of their maximum vertical jump followed by a maximal 90° cut and O'Connor et al. (2009) in a stride-land and cut. The knee abduction ROM of 4.2° in the land-cut was also similar to the ROM values from these two studies. It would be expected that differences in surface conditions, such natural and synthetic turf, as well as an un-turfed lab would produce different values for vertical GRFs and flexion angles based on the amount of force absorption and the traction characteristics of the given surface during these testing movements. The land-cut movement showed similar peak joint angles to the 180° cut but increased ROM and velocities at both the ankle and knee.

Limitations for this study include that participants may have performed movements differently in the lab than they would have on the field in a game-like situation. Also, skin movement due to the fast-paced, high-impact activity could have affected the accuracy of marker tracking during dynamic. Ekstrand et al. (2010) and Shorten et al. (2003) noted that GRF should be different between natural turf and synthetic turf due to the natural shock absorption capacity of turf grass and soil. Mounting the turf in the lab setting may produce different results than when synthetic turf is properly installed on a field using asphalt, base layers, and infill. Mounting the turf on laminate wooding flooring and the force platform may have influenced the results of this study. Therefore future studies should compare biomechanical differences of these and other dynamic movements on natural turf with synthetic turf. Also, future studies should include additional cleat conditions, such as bladed cleats and molded turf studs in order to have a comprehensive view of the effect of cleat types on ACL injury.

Conclusion

The results from this study suggest that the land-cut movement elicit a greater vertical GRF and vertical impact loadings rates than the 180° cut. The shoe had significantly smaller dorsiflexion ROM than the synthetic turf studs and smaller eversion velocity than both studded conditions. In general, there was a lack of differences of GRFs and kinematic variables between the shoe conditions. For the 180° cut movement, natural turf studs produced lowest peak medial GRF compared to the synthetic turf studs and the shoe. Overall, increased GRFs, especially in combination with rapid change of direction and deceleration may increase the chance of injury.

Acknowledgement

I would like to thank the UT Center for Safer Sports as well as Astroturf for donating the turf as well as Adidas for donating the cleats.

I would also like to thank Adam Thoms for his assistance with turf installation and information, I would also like to thank Lexie Liu for all of her help during data collection.

Table 1: Free moment and ground reaction force variables: mean ± SD.

	Land-Cut			180° Cut		
	Shoe	**Natural turf stud**	**Synthetic turf stud**	**Shoe**	**Natural turf stud**	**Synthetic turf stud**
Peak Free Moment (Nm/kg) ^{M}	0.448±0.13	0.485±0.099	0.460±0.154	0.309±0.177	0.221±0.094	0.244±0.094
Time _Peak Free Moment (s)	0.126±0.025	0.130±0.034	0.131±0.030	0.088±0.051	0.100±0.037	0.097±0.037
Impact vertical GRF (BW) ^{M}	4.8±0.9	5.0±0.7	5.0±0.7	1.9±0.2	1.6±0.2	1.8±0.3
Time_Impact vertical GRF(s) $^{M, \&}$	0.048±0.009 $^{\$}$	0.047±0.013 $^{\$}$	0.050±0.013 $^{\$}$	0.066±0.020	0.081±0.032 $^{\%}$	0.063±0.028
Loading rate_Impact vertical GRF (BW/s) ^{M}	103.1±38.4	108.7±38.4	103.0±44.2	30.5±13.0	25.3±12.6	27.8±13.2
Peak Medial GRF (BW) $^{C, \&}$	1.3±0.2	1.3±0.3	1.4±0.3	1.4±0.2 $^{*\#}$	1.1±0.1 $^{\%}$	1.3±0.1

C: Significant Cleat main effect (p<.05)
M: Significant Movement main effect (p<.05)
&: Cleat x Movement Interaction
*: Significant difference between Shoe and Natural turf stud
#: Significant difference between Shoe and Synthetic turf stud
%: Significant difference between Natural turf stud and Synthetic turf stud
$: Significant difference between movement of same stud condition

Table 2: Ankle kinematic variables: mean ± SD.

	Land-Cut			180° Cut		
	Shoe	**Natural turf stud**	**Synthetic turf stud**	**Shoe**	**Natural turf stud**	**Synthetic turf stud**
Peak dorsiflexion angle (°)	20.6±6.0	18.8±8.1	18.9±8.3	20.5±10.5	19.9±10.0	19.3±12.2
Dorsiflexion ROM (°) $^{C,M,\#}$	42.5±8.9	45.7±10.7	46.4±12.0	27.5±11.0	30.1±10.3	32.2±10.5
Peak dorsiflexion velocity (deg/s) $^{C,M,\%}$	833.0±207.8	860.0±190.3	932.4±174.0	501.2±219.1	406.0±108.8	474.1±152.3
Peak eversion angle (°)	-7.3±11.0	-2.6±6.8	-2.9±7.0	-	-	-
Eversion ROM (°)	-2.0±6.1	0.7±5.0	-1.3±6.4	-	-	-
Peak eversion velocity(deg/s) $^{C, *,\#}$	-160.5±43.1	-234.8±102.7	-210.3±58.8	-	-	-
Peak inversion angle (°)	-	-	-	19.1±7.8	22.8±8.1	22.9±7.0
Inversion ROM (°)	-	-	-	19.9±6.6	21.5±6.8	22.6±6.7
Peak inversion velocity(deg/s)	-	-	-	401.4±179.1	413.6±145.2	412.4±67.2

C: Significant Cleat main effect (p<.05)
M: Significant Movement main effect (p<.05)
* Significant difference between Shoe and Natural turf stud
#: Significant difference between Shoe and Synthetic turf stud
%: Significant difference between Natural turf cleat and Synthetic turf stud
-: Not applicable for the given movement

Table 3: Knee kinematic variables: mean ± SD.

	Land-Cut			180° Cut		
	Shoe	Natural turf stud	Synthetic turf stud	Shoe	Natural turf stud	Synthetic turf stud
Peak flexion angle (°)	-67.1±6.4	-68.2±9.7	-65.3±9.2	-69.8±8.8	-70.4±10.2	-68.8±12.2
Flexion ROM(°) ^{M}	-51.3±6.0	-50.5±7.8	-48.9±7.8	-37.9±10.2	-35.6±13.5	-37.9±11.5
Peak flexion velocity(deg/s) ^{M}	-629.0±90.2	-621.6±109.0	-589.0±104.0	-439.3±96.2	-401.6±100.7	-423.5±103.1
Peak abduction angle (°)	-9.3±4.6	-9.1±3.7	-8.8±4.3	-	-	-
Abduction ROM (°)	-3.4±6.7	-4.7±5.1	-4.4±5.6	-	-	-
Peak adduction angle (°)	-	-	-	-0.5±7.9	0.1±6.9	-0.3±6.6
Adduction ROM(°)	-	-	-	5.4±5.3	3.7±6.4	5.5±5.1
Peak abduction velocity (deg/s)	-118.0±70.8	-119.5±73.0	-120.1±50.8	-139.842±88.737	-131.945±64.414	-130.895±55.998

C: Significant Cleat main effect (p<.05)
M: Significant Movement main effect (p<.05)
*: Significant difference between Shoe and Natural turf stud
#: Significant difference between Shoe and Synthetic turf stud
%: Significant difference between Natural turf stud and Synthetic turf stud
-: Not applicable for the given movement

Figure 16: Testing shoes used in the study: running shoe (A, Shoe), football shoe with removable natural turf studs (B, Natural turf cleat) and, football shoe with removable synthetic turf studs (C, Synthetic turf cleat)

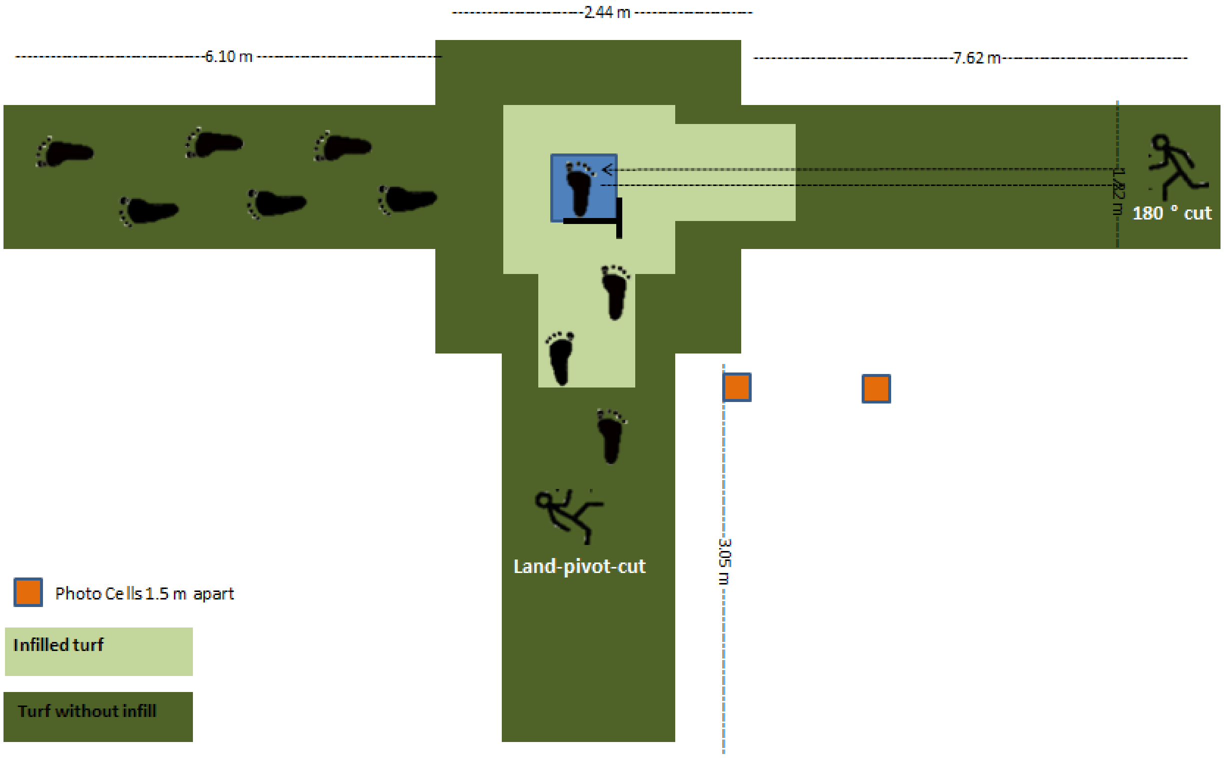


Figure 17: 180° Cut Movement Pattern. The turf was infilled (represented by the light grey area) so that participants had a minimum of two steps on the infilled turf before landing or cutting on the force platform.

BIBLIOGRAPHY

1 National Federation of State High School Associations. NFHS Participation Figures Search. In: *Book National Federation of State High School Associations. NFHS Participation Figures Search*.

2 Andreasson, G, Olofsson, B. Surface and shoe deformation in sport activities and injuries. In: B.M. Nigg and B.A. Kerr, editors. *Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary, AB; 1983. p. 55-61.

3 Andrews, JR, McLeod, WD, Ward, T, Howard, K. The cutting mechanism. *Am J Sports Med*. 1977; 5(3):111-21.

4 Baker, BE. Prevention of ligament injuries to the knee. *Exerc Sport Sci Rev*. 1990; 18:291-305.

5 Boden, BP, Dean, GS, Feagin, JAJ, Garrett, WEJ. Mechanisms of anterior cruciate ligament injury. *Orthopedics* 2000; 23(6):573-8.

6 Bonstingl, RW, Morehouse, CA, Niebel, BW. Torques developed by different types of shoes on various playing surfaces. *Med Sci Sports*. 1975; 7(2):127-31.

7 Clement, DB, Taunton, JE, Smart, GW. Achilles tendinitis and peritendinitis: Etiology and treatment. *Am J Sports Med*. 1984; 12(3):179-84.

8 Cortes, N, Morrison, S, Van Lunen, BL, Onate, JA. Landing technique affects knee loading and position during athletic tasks. *J Sci Med Sport*. 2011; 15(2):175-81.

9 Cortes, N, Onate, JA, Van Lunen, BL. Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. *J Sports Sci*. 2010; 29(1):83-92.

10 Derrick, TR, Dereu, D, McLean, SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc*. 2002; 34(6):998-1002.

11 Durselen, L, Claes, L, Kiefer, H. The influence of muscles forces and external loads on cruciate ligament strain. *Am J Sports Med*. 1995; 23(1):129-36.

12 Edwards, S, Steele, JR, Cook, JL, Purdam, CR, McGhee, DE, Munro, BJ. Characterizing patellar tendon loading during the landing phases of a stop-jump task. *Scand J Med Sci Sports*. 2012; 22(1):2-11.

13 Gehring, D, Rott, F, Stapelfeldt, B, Gollhofer, A. Effect of Soccer Shoe Cleat on Knee Joint Loads. *Int J Sports Med*. 2007; 28(12):1030-4.

14 Griffin, LY, Agel, J, Albohm, MJ, Arendt, EA, Dick, RW, Garrett, WE, Garrick, JG, Hewett, TE, Huston, L, Ireland, ML, Johnson, RJ, Kibler, WB, Lephart, S, Lewis, JL, Lindenfeld, TN, Mandelbaum, BR, Marchak, P, Teitz, CC, Wojtys, EM. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000; 8(3):131-50.

15 Hass, CJ, Schick, EA, Tillman, MD, Chow, JW, Brunt, D, Cauraugh, JH. Knee biomechanics during landings: comparison of pre- and postpubescent females. *Med Sci Sports Exerc.* 2005; 37(1):100-7.

16 Headon, R, R., C. Recognizing movements from the ground reaction force. In *Proceedings of the Workshop on Perceptive User Interfaces*. Orlando, FL, USA, 2001, p.1-8.

17 Hewett, TE, Myer, GD, Ford, KR, Heidt, RS, Colosimo, AJ, McLean, SG, van den Bogert, AJ, Paterno, MV, Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes. *Am J Sports Med*. 2005; 33(4):492-501.

18 Holden, JP, Cavanagh, PR. The free moment of ground reaction in distance running and its changes with pronation. *J Biomech*. 1991; 24(10):887-97.

19 Jenkyn, TR, Nicol, AC. Protective ankle muscle activation strategies during quick cutting movements in humans. In *Proceedings of the ASB*, 2001.

20 Kipp, K, McLean, SG, Palmieri-Smith, RM. Patterns of hip flexion motion predict frontal and transverse plane knee torques during a single-leg land-and-cut maneuver. *Clin Biomech*. 2011; 26(5):504-8.

21 Lambson, RB, Barnhill, BS, Higgins, RW. Football Cleat Design and Its Effect on Anterior Cruciate Ligament Injuries: A Three-Year Prospective Study. *Am J Sports Med*. 1996; 24(2):155-9.

22 Livesay, GA, Reda, DR, Nauman, EA. Peak Torque and Rotational Stiffness Developed at the Shoe-Surface Interface: The Effect of Shoe Type and Playing Surface. *Am J Sports Med*. 2005; 34(3):415-22.

23 Malinzak, RA, Colby, SM, Kirkendall, DT, Yu, B, Garrett, WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech*. 2001; 16(5):438-45.

24 McLean, SG, Lipfert, SW, van den Bogert, AJ. Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. *Med Sci Sports Exerc*. 2004; 36(6):1008-16.

25 McLean, SG, Myers, PT, Neal, RJ, Walters, MR. A quantitative analysis of knee joint kinematics during the sidestep cutting maneuver. Implications for non-contact anterior cruciate ligament injury. *Bull Hosp Jt Dis*. 1998; 57(1):30-8.

26 McLean, SG, Samorezov, JE. Fatigue-Induced ACL Injury Risk Stems from a Degradation in Central Control. *Med Sci Sports Exerc*. 2009; 41(8):1661-72.

27 McLeod, AJ. An assessment of the benefits of artificial turf over natural turf playing surfaces within the independent school environment. Cranfield University, Cranfield, 2003.

28 McNair, PJ, Marshall, RN, Matheson, JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J*. 1990; 103(901):537-9.

29 Meyers, MC, Barnhill, BS. Incidence, Causes, and Severity of High School Football Injuries on FieldTurf Versus Natural Grass: A 5-Year Prospective Study. *Am J Sports Med*. 2004; 32(7):1626-38.

30 Milner, CE, Davis, IS, Hamill, J. Free moment as a predictor of tibial stress fracture in distance runners. *J Biomech*. 2006; 39(15):2819-25.

31 Morehouse, CA. Artificial turf. In: D.V. Waddington, R.N. Carrow and R.C.e. Shearman, editors. *Turfgrass - Agronomy Monograph 32*. Madison, WI: ASA CSSA SSA; 1992.

32 Muller, C, Sterzing, T, Lange, J, Milani, TL. Comprehensive evaluation of player-surface interaction on artificial soccer turf. *Sports Biomech*. 2010; 9(3):193-205.

33 Munro, CF, Miller, DI, Fuglevand, AJ. Ground reaction forces in running: a reexamination. *J Biomech*. 1987; 20(2):147-55.

34 Nigg, BM. External force measurements with sport shoes and playing surfaces. In *Proceedings of the International Symposium on Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary, AB, University of Calgary, 1983.

35 Nigg, BM, Segesser, B. Biomechanical and orthopedic concepts in sport shoe construction

Med Sci Sports Exerc. 1992; 24(5):595-602.

36 O'Connor, KM, Monteiro, SK, Hoelker, IA. Comparison of selected lateral cutting activities used to assess ACL injury risk. *J Appl Biomech*. 2009; 25(1):9-21.

37 Olsen, OE, Myklebust, G, Engebretsen, L, Bahr, R. Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball. *Am J Sports Med*. 2004; 32(4):1002-12.

38 Pappas, E, Hagins, M, Sheikhzadeh, A, Nordin, M, Rose, D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med*. 2007; 17(4):263-8.

39 Powell, JW, Barber-Foss, KD. Injury patterns in selected high school sports: a review of the 1995-1997 seasons. *J Athl Train*. 1999; 34(3):277-84.

40 Ramirez, M, Schaffer, KB, Shen, H, Kashani, S, Kraus, JF. Injuries to High School Football Athletes in California. *Am J Sports Med*. 2006; 34(7):1147-58.

41 Ryan, AJ. Football (American and Canadian). In: *Book Football (American and Canadian)*. City: Macmillan, 1971, pp. 525-33.

42 Serensits, TJ, McNitt, AS, Sorochan, JC. Synthetic Turf. In: *Book Synthetic Turf*, 2011, pp. 1-46.

43 Shorten, MR, Hudson, B, Himmelsbach, JA. Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. In *Proceedings of the XIX International Congress of Biomechanics*. Dunedin, New Zealand, 2003.

44 Torg, JS, Quedenfeld, T. Effect of shoe type and cleat length on incidence and severity of knee injuries among high school football players. *Res Q*. 1971; 42(2):203-11.

45 Torg, JS, Quedenfeld, TC, Landau, S. The shoe-surface interface and its relationship to football knee injuries. *J Sports Med*. 1974; 2(5):261-9.

46 Yeow, CH, Cheong, CH, Ng, KS, Lee, PV, Goh, JC. Anterior Cruciate Ligament Failure and Cartilage Damage During Knee Joint Compression. *Am J Sports Med*. 2008; 36(5):934-42.

47 Yeow, CH, Lee, PV, Goh, JC. An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Hum Mov Sci*. 2011; 30(3):624-35.

Bibliography

1 National Federation of State High School Associations. NFHS Participation Figures Search. In: *Book National Federation of State High School Associations. NFHS Participation Figures Searc.*.

2 Annual Book of ASTM Standards. In: *Book Annual Book of ASTM Standards*. Editor (Ed.)^(Eds.) City: American Society for Testing and Materials, 2006, pp. 1412-20.

3 Adidas. Adidas Pro Intimidate D Men's High Football Cleats. In: *Book Adidas Pro Intimidate D Men's High Football Cleats*, 2008.

4 Adidas. Adidas TS-Reggie III Mid D - Mens. In: *Book Adidas TS-Reggie III Mid D - Mens*, 2011.

5 Adidas. adiNOVA 4 TRX TF Shoes. In: *Book adiNOVA 4 TRX TF Shoes*, 2011.

6 Agel, J, Arendt, EA, Bershadsky, B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005; 33(4):524-30.

7 Alles, WF, Powell, JW, Buckley, W, Hunt, EE. The national athletic injury/illness reporting system 3-year findings of high school and college football injuries*. *J Orthop Sports Phys Ther*. 1979; 1(2):103-8.

8 Andreasson, G, Lindenberger, U, Renstrom, P, Peterson, L. Torque developed at simulated sliding between sport shoes and an artificial turf. *The American Journal of Sports Medicine*. 1986; 14(3):225-30.

9 Andreasson, G, Olofsson, B. Surface and shoe deformation in sport activities and injuries. In: B.M. Nigg and B.A. Kerr, editors. *Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary, AB; 1983. p. 55-61.

10 Andrews, JR, McLeod, WD, Ward, T, Howard, K. The cutting mechanism. *Am J Sports Med*. 1977; 5(3):111-21.

11 AstroTurf. AstroTurf® GameDay Grass™. In: *Book AstroTurf® GameDay Grass™*, 2011.

12 Baker, BE. Prevention of ligament injuries to the knee. *Exerc Sport Sci Rev*. 1990; 18:291-305.

13 Boden, BP, Dean, GS, Feagin, JAJ, Garrett, WEJ. Mechanisms of anterior cruciate ligament injury. *Orthopedics* 2000; 23(6):573-8.

14 Bonstingl, RW, Morehouse, CA, Niebel, BW. Torques developed by different types of shoes on various playing surfaces. *Med Sci Sports*. 1975; 7(2):127-31.

15 Bowers, KDJ, Martin, RB. Impact absorption, new and old AstroTurf at West Virginia University. *Med Sci Sports*. 1974; 6(3):217-21.

16 Brain, M. How NFL Equipment Works. In: *Book How NFL Equipment Works*. HowStuffWorks.com, 2000.

17 Bramwell, ST, Requa, RK, Garrick, JG. High school football injuries: a pilot comparison of playing surfaces. *Med Sci Sports*. 1972; 4(3):166-9.

18 Brosnan, JT. Effects of varying surface conditions on baseball field playing surfaces. In: *Book Effects of varying surface conditions on baseball field playing surfaces*. The Pennsylvania State University, 2007, pp. 1-327.

19 Brown, RP. Performance tests for artifical sports surfaces. *Polym Test*. 1987; 7(4):279-92.

20 Cameron, BM, Davis, O. The swivel football shoe: a controlled study. *J Sports Med*. 1973; 1(2):16-27.

21 Cawley, PW, Heidt, RSJ, Scranton, PEJ, Losse, GM, Howard, ME. Physiologic axial load, frictional resistance, and the football shoe-surface interface. *Foot Ankle Int*. 2003; 24(7):551-6.

22 Chambers, RB. Orthopaedic injuries in athletes (ages 6 to 17). *Am J Sports Med*. 1979; 7(3):195-7.

23 Chaudhari, AM, Hearn, BK, Andriacchi, TP. Sport-Dependent Variations in Arm Position During Single-Limb Landing Influence Knee Loading. *Am J Sports Med*. 2005; 33(6):824-30.

24 Clement, DB, Taunton, JE, Smart, GW. Achilles tendinitis and peritendinitis: Etiology and treatment. *Am J Sports Med*. 1984; 12(3):179-84.

25 Company, TS. FieldTurf Synthetic Turf Products. In: *Book FieldTurf Synthetic Turf Products*, 2011.

26 Company, TS. FieldTurf for Football: Overview. In: *Book FieldTurf for Football: Overview*. 2012.

27 Cortes, N, Morrison, S, Van Lunen, BL, Onate, JA. Landing technique affects knee loading and position during athletic tasks. *J Sci Med Sport*. 2011; 15(2):175-81.

28 Cortes, N, Onate, JA, Van Lunen, BL. Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. *J Sports Sci*. 2010; 29(1):83-92.

29 DeHaven, KE, Lintner, DM. Athletic injuries: Comparison by age, sport, and gender. *Am J Sports Med*. 1986; 14(3):218-24.

30 Derrick, TR, Dereu, D, McLean, SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc*. 2002; 34(6):998-1002.

31 Dick, RW, Schmalz, R, Diehl, N, Newlin, C, Summers, E. A review of game injuries by surface and injury mechanism in nine NCAA intercollegiate sports. In: Nigg BM, Cole GK and Stefanyshyn DJ, editors. *Sports Surfaces*. Calgary: University of Calgary; 2003. p. 107-23.

32 Dixon, SJ, Batt, ME, Collop, AC. Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects. *Int J Sports Med*. 1999; 20(4):209-18.

33 Drakos, MC, Hillstrom, H, Voos, JE, Miller, AN, Kraszewski, AP, Wickiewicz, TL, Warren, RF, Allen, AA, O'Brien, SJ. The Effect of the Shoe-Surface Interface in the Development of Anterior Cruciate Ligament Strain. *J Biomed Eng*. 2010; 132(1):011003.

34 Durward, BR, Baer, GD, Rowe, PJ. *Functional Human Movement*. Butterworth-Heinemann, 1999.

35 Ekstrand, J, Hägglund, M, Fuller, CW. Comparison of injuries sustained on artificial turf and grass by male and female elite football players. *Scand J Med Sci Sports*. 2010; 21(6):824-32.

36 Ford, K, Manson, N, Evans, B, Myer, G, Gwin, R, Heidt, RS, Hewett, T. Comparison of in-shoe foot loading patterns on natural grass and synthetic turf. *J Sci Med Sport*. 2006; 9(6):433-40.

37 Frederick, EC. Biomechanical consequences of sport shoe design. *Exerc Sport Sci Rev*. 1986; 14:375-400.

38 Fuller, CW, Dick, RW, Corlette, J, Schmalz, R. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 2: training injuries. *Br J Sports Med*. 2007; 41(Supplement 1):i27-i32.

39 Gehring, D, Rott, F, Stapelfeldt, B, Gollhofer, A. Effect of Soccer Shoe Cleat on Knee Joint Loads. *Int J Sports Med*. 2007; 28(12):1030-4.

40 Griffin, LY, Agel, J, Albohm, MJ, Arendt, EA, Dick, RW, Garrett, WE, Garrick, JG, Hewett, TE, Huston, L, Ireland, ML, Johnson, RJ, Kibler, WB, Lephart, S, Lewis, JL, Lindenfeld, TN, Mandelbaum, BR, Marchak, P, Teitz, CC, Wojtys, EM. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg*. 2000; 8(3):131-50.

41 Griffin, LY, Albohm, MJ, Arendt, EA, Bahr, R, Beynnon, BD, DeMaio, M, Dick, RW, Engebretsen, L, Garrett, WE, Hannafin, JA, Hewett, TE, Huston, LJ, Ireland, ML, Johnson, RJ, Lephart, S, Mandelbaum, BR, Mann, BJ, Marks, PH, Marshall, SW, Myklebust, G, Noyes, FR, Powers, C, Shields, C, Shultz, SJ, Silvers, H, Slauterbeck, J, Taylor, DC, Teitz, CC, Wojtys, EM, Yu, B. Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries. *Am J Sports Med*. 2006; 34(9):1512-32.

42 Guise, ER. Rotational ligamentous injuries to the ankle in football. *Am J Sports Med*. 1976; 4(1):1-6.

43 Hass, CJ, Schick, EA, Tillman, MD, Chow, JW, Brunt, D, Cauraugh, JH. Knee biomechanics during landings: comparison of pre- and postpubescent females. *Med Sci Sports Exerc.* 2005; 37(1):100-7.

44 Hawkis, P. Developments in synthetic grasses. *Turf management*. 1984:23-5.

45 Headon, R, R., C. Recognizing movements from the ground reaction force. In *Proceedings of the Workshop on Perceptive User Interfaces*. Orlando, FL, USA, 2001, p.1-8.

46 Heidt, RS, Dormer, SG, Cawley, PW, Scranton, PEJ, Losse, G, Howard, M. Differences in Friction and Torsional Resistance in Athletic Shoe-Turf Surface Interfaces. *Am J Sports Med*. 1996; 24(6):834-42.

47 Henschen, K, Hell, J, Bean, B, Crain, S. Football injuries: is astroturf or grass the culprit? *Utah J. HPERD*. 1989; 21:5-6.

48 Hewett, TE, Myer, GD, Ford, KR, Heidt, RS, Colosimo, AJ, McLean, SG, van den Bogert, AJ, Paterno, MV, Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes. *Am J Sports Med*. 2005; 33(4):492-501.

49 Hibbeler, RC. Friction. In: *Engineering mechanics: Statics & dynamics (9th ed)*. Uppler Saddle River, New Jersey: Prentice-Hall, Inc.; 2001. p. 377-433.

50 Holden, JP, Cavanagh, PR. The free moment of ground reaction in distance running and its changes with pronation. *J Biomech*. 1991; 24(10):887-97.

51 International, ST. Poligras. In: *Book Poligras*, 2011.

52 Jackson, B. Information needed. In: *Book Information needed*. 2011.

53 James, SL, Bates, BT, Osternig, LR. Injuries to runners. *Am J Sports Med*. 1978; 6(2):40-50.

54 Kipp, K, McLean, SG, Palmieri-Smith, RM. Patterns of hip flexion motion predict frontal and transverse plane knee torques during a single-leg land-and-cut maneuver. *Clin Biomech*. 2011; 26(5):504-8.

55 Krahenbuhl, GS. Speed of movement with varying footwear conditions on synthetic turf and natural grass. *Res Q*. 1974; 45(1):28-33.

56 Kuhlman, SM, Sabick, MB, Pfeiffer, R, Cooper, B, Forhan, J. Effect of Loading Condition on Traction Coefficient Between Shoes and Artificial Turf Surfaces. *J Sport Engr Techn*. 2010; 224(2):155-65.

57 Lambson, RB, Barnhill, BS, Higgins, RW. Football Cleat Design and Its Effect on Anterior Cruciate Ligament Injuries: A Three-Year Prospective Study. *Am J Sports Med*. 1996; 24(2):155-9.

58 Laughlin, WA, Weinhandl, JT, Kernozek, TW, Cobb, SC, Keenan, KG, O'Connor, KM. The effects of single-leg landing technique on ACL loading. *J Biomech*. 2011; 44(10):1845-51.

59 Levy, IM, Skovron, ML, Agel, J. Living with artificial grass: a knowledge update. Part 1: Basic science. *Am J Sports Med*. 1990; 18(4):406-12.

60 Liebeskind, H. General Principles in Cleat Selection. In: *Book General Principles in Cleat Selection*. American Academy of Podiatric Sports Medicine.

61 Livesay, GA, Reda, DR, Nauman, EA. Peak Torque and Rotational Stiffness Developed at the Shoe-Surface Interface: The Effect of Shoe Type and Playing Surface. *Am J Sports Med*. 2005; 34(3):415-22.

62 Malinzak, RA, Colby, SM, Kirkendall, DT, Yu, B, Garrett, WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech*. 2001; 16(5):438-45.

63 Markolf, KL, Burchfield, DM, Shapiro, MM, Shepard, MF, Finerman, AM, Slauterbeck, JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995; 13(6):930-5.

64 McClay, IS, Robinson, JR. A profile of ground reaction forces in professional basketball. *J Appl Biomech*. 1994; 10:222-36.

65 McLean, SG, Lipfert, SW, van den Bogert, AJ. Effect of Gender and Defensive Opponent on the Biomechanics of Sidestep Cutting. *Med Sci Sports Exerc*. 2004; 36(6):1008-16.

66 McLean, SG, Myers, PT, Neal, RJ, Walters, MR. A quantitative analysis of knee joint kinematics during the sidestep cutting maneuver. Implications for non-contact anterior cruciate ligament injury. *Bull Hosp Jt Dis*. 1998; 57(1):30-8.

67 McLean, SG, Samorezov, JE. Fatigue-Induced ACL Injury Risk Stems from a Degradation in Central Control. *Med Sci Sports Exerc*. 2009; 41(8):1661-72.

68 McLeod, AJ. An assessment of the benefits of artificial turf over natural turf playing surfaces within the independent school environment. Cranfield University, Cranfield, 2003.

69 McNair, PJ, Marshall, RN, Matheson, JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J*. 1990; 103(901):537-9.

70 McNitt-Gray, JL. Kinematics and impulse characteristics of drop landings from three heights. *Int. J Sport Biomechanics*. 1991; 7:201-24.

71 Meyers, MC, Barnhill, BS. Incidence, Causes, and Severity of High School Football Injuries on FieldTurf Versus Natural Grass: A 5-Year Prospective Study. *Am J Sports Med*. 2004; 32(7):1626-38.

72 Milburn, PD, Barry, EB. Shoe-surface interaction and the reduction of injury in rugby union. *Sports Med*. 1998; 25(5):319-27.

73 Morehouse, CA. Artificial turf. In: D.V. Waddington, R.N. Carrow and R.C.e. Shearman, editors. *Turfgrass - Agronomy Monograph 32*. Madison, WI: ASA CSSA SSA; 1992.

74 Muller, C, Sterzing, T, Lange, J, Milani, TL. Comprehensive evaluation of player-surface interaction on artificial soccer turf. *Sports Biomech*. 2010; 9(3):193-205.

75 Myklebust, G, Mæhlum, S, Holm, I, Bahr, R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports*. 1998; 8(3):149-53.

76 Naunheim, R, Parrott, H, Standeven, J. A comparison of Artificial Turf. *J Trauma*. 2004; 57(6):1311-4.

77 NCAA. *NCAA Sports Sponsorship and Participation Rates Report*. Indianapolis, IN: National Collegiate Athlelic Association, 2(H), 1981/82-2004/05.

78 Nigg, BM. External force measurements with sport shoes and playing surfaces. In *Proceedings of the International Symposium on Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary, AB, University of Calgary, 1983.

79 Nigg, BM, Bahlsen, HA. Influence of heel flare and midsole construction on pronation, supination, and impact forces for heel-toe running. *Int J Sports Biomech*. 1988; 4(3):205-19.

80 Nigg, BM, Segesser, B. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. *Sports Med*. 1988; 5(6):375-85.

81 Nigg, BM, Segesser, B. Biomechanical and orthopedic concepts in sport shoe construction

Med Sci Sports Exerc. 1992; 24(5):595-602.

82 Nigg, BM, Stefanyshyn, DJ, Cole, GK. Criteria for functional biomechanical testing sport surfaces. In: Nigg BM, Cole GK and S. DJ., editors. *Sport Surfaces*. Calgary: University of Calgary; 2003. p. 311-34.

83 O'Connor, KM, Monteiro, SK, Hoelker, IA. Comparison of selected lateral cutting activities used to assess ACL injury risk. *J Appl Biomech*. 2009; 25(1):9-21.

84 Olsen, OE, Myklebust, G, Engebretsen, L, Bahr, R. Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball. *Am J Sports Med*. 2004; 32(4):1002-12.

85 Pappas, E, Hagins, M, Sheikhzadeh, A, Nordin, M, Rose, D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med*. 2007; 17(4):263-8.

86 Park, SK, Stefanyshyn, DJ, Lee, JS, Savage, L. The influence of soccer cleat design on ankle joint moments. In *Proceedings of the Symposium on Footwear Biomechanics*, 2005, p.126-7.

87 Parrish, R. Types of Soccer Cleats. In: *Book Types of Soccer Cleats*, 2010.

88 Paventi, J. What are Soccer Cleats. In: *Book What are Soccer Cleats*. Livestrong, 2011.

89 Pohl, MB, Mullineaux, DR, Milner, CE, Hamill, J, Davis, IS. Biomechanical predictors of retrospective tibial stress fractures in runners. *J Biomech*. 2008; 41(6):1160-5.

90 Polyturf. Sports Surface Products. In: *Book Sports Surface Products*, 2011.

91 Powell, JW, Barber-Foss, KD. Injury patterns in selected high school sports: a review of the 1995-1997 seasons. *J Athl Train*. 1999; 34(3):277-84.

92 Powell, JW, Schootman, M. A multivariate risk analysis of selected playing surfaces in the National Football League: 1980 to 1989: An epidemiologic study of knee injuries. *The American Journal of Sports Medicine*. 1992; 20(6):686-94.

93 Powell, JW, Shootman, M. Incidence of injury associated with playing surfaces in the NFL 1980-1989. *Am J Sports Med*. 1992;

94 R., B. Causes of movement– forces and torques. In: *Book Causes of movement– forces and torques*. City: Routledge, 2007, pp. 164-5.

95 Ramey, MR, Williams, KR. Ground reaction forces in the triple jump. *Int. J Sport Biomechanics*. 1985; 1:233-9.

96 Ramirez, M, Schaffer, KB, Shen, H, Kashani, S, Kraus, JF. Injuries to High School Football Athletes in California. *Am J Sports Med*. 2006; 34(7):1147-58.

97 Ryan, AJ. Football (American and Canadian). In: *Book Football (American and Canadian)*. City: Macmillan, 1971, pp. 525-33.

98 Serensits, TJ, McNitt, AS, Sorochan, JC. Synthetic Turf. In: *Book Synthetic Turf*, 2011, pp. 1-46.

99 Shankar, PR, Fields, SK, Collins, CL, Dick, RW, Comstock, RD. Epidemiology of High School and Collegiate Football Injuries in the United States, 2005–2006. *Am J Sports Med*. 2007; 35(8):1295-303.

100 Shorten, MR, Hudson, B, Himmelsbach, JA. Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. In *Proceedings of the XIX International Congress of Biomechanics*. Dunedin, New Zealand, 2003.

101 Shorten, MR, Hudson, B, Himmelsbach, JA. Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. *BioMechanica LLC*. 2006;

102 Skovron, ML, Levy, IM, Agel, J. Living with artificial grass: A knowledge update: Part 2: Epidemiology. *Am J Sports Med*. 1990; 18(5):510-3.

103 Spinney, AFJ, Warnalis, LJ. Artificial grass sports field. In: *Book Artificial grass sports field*, 1972.

104 Stacoff, A, Steger, J, Stüssi, E, Reinschmidt, C. Lateral stability in sideward cutting movements. *Med Sci Sports Exerc*. 1996; 28(3):350-8.

105 Stanitski, CL, McMaster, JH, Ferguson, RJ. Synthetic turf and grass: A comparative study. *J Sports Med*. 1974; 2(1):22-6.

106 Steinbach, P. Synthetic Turf Fields Benefitting from Latest Fiber Technology. In: *Book Synthetic Turf Fields Benefitting from Latest Fiber Technology*, 2011.

107 Therapy, BS. Burlington Soccer - Physiotherapy. In: *Book Burlington Soccer - Physiotherapy*, 2009.

108 Torg, JS, Conrad, W, Kalen, V. Clinical diagnosis of anterior cruciate ligament instability in the athlete. *Am J Sports Med*. 1976; 4(2):84-93.

109 Torg, JS, Quedenfeld, T. Effect of shoe type and cleat length on incidence and severity of knee injuries among high school football players. *Res Q*. 1971; 42(2):203-11.

110 Torg, JS, Quedenfeld, TC, Landau, S. The shoe-surface interface and its relationship to football knee injuries. *J Sports Med*. 1974; 2(5):261-9.

111 Valiant, GA. Traction characteristics of outsoles for use on artificial playing surfaces. In: Schmidt RC, Hoerner EF, Milner EM and M. CA., editors. *Natural and Artificial Playing Fields: Characteristics and Safety Features, ASTM STP 1073*. Philadelphia, PA: ASTM International, West Conshohocken; 1990. p. 61-8.

112 Villwock, MR, Meyer, EG, Powell, JW, Fouty, AJ, Haut, RC. Football Playing Surface and Shoe Design Affect Rotational Traction. *Am J Sports Med*. 2009; 37(3):518-25.

113 Wannop, JW, Worobets, JT, Stefanyshyn, DJ. Footwear traction and lower extremity joint loading. *Am J Sports Med*. 2010; 38(6):1221-8.

114 Yeow, CH, Cheong, CH, Ng, KS, Lee, PV, Goh, JC. Anterior Cruciate Ligament Failure and Cartilage Damage During Knee Joint Compression. *Am J Sports Med*. 2008; 36(5):934-42.

115 Yeow, CH, Lee, PV, Goh, JC. Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *Knee*. 2010; 17(2):127-31.

116 Yeow, CH, Lee, PV, Goh, JC. An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Hum Mov Sci*. 2011; 30(3):624-35.

117 Zemper, ED. Injury rates in a national sample of college football teams: A two year prospective study. *Physician Sportsmed*. 1989; 17(11):100-13.

Appendices

Appendix A

Informed Consent Form

INFORMED CONSENT FORM

Biomechanical differences of two common football movement tasks in studded and non-studded shoe conditions on an artificial turf.

Investigator: Elizabeth Brock		Faculty Advisor: Songning Zhang, Ph.D.
Address:	Biomechanics/Sports Medicine laboratory Kinesiology, Recreation, and Sport Studies 1914 Andy Holt Avenue Knoxville, TN 37996	Kinesiology, Recreation, and Sport Studies The University of Tennessee 1914 Andy Holt Avenue 341 HPER Knoxville, TN 37996
Phone:	(865) 974-2091	

Introduction

You are invited to participate in a research study entitled, "Biomechanical differences of two common football movement tasks in studded and non-studded shoe conditions on artificial turf" because you are currently a recreational football player with a focus on catching and aged between 18 and 25 years old. You have a minimum of three years of football experience. You also participate in recreational activities at least three times a week, are healthy, and are not currently injured. The purpose of this research project is to examine differences in lower limb kinematics and kinetics between a studded and non-studded shoe condition. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol and Duration

You will be asked to attend one testing session that will take approximately 1.5 hours. At the beginning of the test session, you will be asked to read and sign this informed consent form, and fill out an information sheet and a physical activity readiness questionnaire. If your responses to the questionnaire indicate you are ready for activity, the study will proceed. We will ask you to complete a warm up jog in the neutral running shoe on a treadmill and do some stretching for 5 minutes in order to get used to the shoes as well as to reduce the chance for injury. After the warm up, we will ask you to wear only spandex shorts and a tight fitting shirt so that we can proceed with data collection.

Before the movement trials, several silver balls will be placed on your back, hips, legs, and feet. A trial will be collected where we ask you to stand still in each of the two shoes. During the movement trials, you will perform five successful trials in each of the four testing conditions: 180° cut at a specified speed and a land-pivot-cut at 90° completing the single-leg jump at 90% of your maximum jump height wearing both shoes. A bar will be placed above you so you know how high to jump. You will be given enough time to become familiar with the testing conditions prior to the actual data collection. You will also be allowed to rest as needed through the study. If you have any further questions, interests, or concerns about any instrumentation, please feel free to ask the investigator.

Potential Risks

Risks associated with this study are minimal for you. The movements you will be performing are normal for recreational football players. Risks for cutting with both shoe conditions for the 180° cut and the land-pivot-cut are minimal because they are within the normal activities for you as a recreational player. You will have five minutes to sufficiently warm-up and stretch. Practice time will be provided for you to become familiar with running and cutting in each shoe and to minimize the possibility of soft tissue injuries. You will not be required to engage in any movement activities that are unusual or unfamiliar. Your participation in the study will be finished if you feel uncomfortable with any of the movements required. All tests will be conducted and the equipment will be utilized by qualified research personnel in the Biomechanics/Sports Medicine lab.

The University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, or for more information, please notify Elizabeth Brock (865) 974-2091.

Benefits of Participation

Potential benefits to you include the opportunity to try out these two pairs of shoes on the infilled synthetic turf. Your participation in this study will help provide valuable information as to the potential injury mechanisms associated with the movement to the ankle and knee.

Participant Initials: __________

Voluntary Participation and Withdrawal

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty or loss of benefits to which you are otherwise entitled. Your participation in this study may be stopped if you fail to follow the study procedures or if the investigator feels that it is in your best interest to stop participation.

Confidentiality

Your identity will be held in strict confidence through the use of a coded subject number during data collection, data analysis, and in all references made to the data, both during and after the study, and in the reporting of the results. The results will be disseminated in the form of presentations at conferences, and publications in journals. The consent form containing your identity information will be destroyed three years after the completion of the study. If you decide to withdraw from the study before data collection is completed, your data will be destroyed at the time of withdrawal.

Contact Information

If you have any questions at any time about the study or the procedures (or you experience adverse effects as a result of participation in this study) you can contact Elizabeth Brock, 144 HPER, (865) 974-2091 . Questions about your rights as a participant can be addressed to the Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-3466.

Consent Statement

I have read the above information. I have received a copy of this form. I agree to participate in this study.

Subject's Name:	Signature:	Date:
______________________	___________________________	_____________

Please Print Clearly

Investigator's Signature:	Date:
_________________________	_____________

Subject Number ___________

Appendix B

Physical Activity Readiness Questionnaire

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age and you are not used to being very active, check with your doctor.

No	Yes	
☐	☐	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2. Do you feel pain in your chest when you do physical activity?
☐	☐	3. In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6. Is your doctor currently prescribing drugs (for example water pills) for your blood pressure of heart condition?
☐	☐	7. Do you know of <u>any other reason</u> why you should not do physical activity?

Please note: If your health changes so that you then answer YES to any of these questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

If you answered YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active of BEFORE you have a fitness appraisal. Tell you doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk to your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

If you answered NO to all questions

If you have answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physical active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part if a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active if:

- You are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better, or If you are or may be pregnant – talk to your doctor before you start becoming more active.

I understand that my signature signifies that I have read and understand all the information on the questionnaire, that I have truthfully answered all the questions, and that any question/concerns I may have had have been addressed to my complete satisfaction.

____
Name (please print)

____ ____________________
Signature Date

Appendix C

Subject Information Questionnaire

Subject Information questionnaire:

Name: ______________________________

Date:____________

Age: __________

Number of years of football experience:

- Competitive: ___________
- Recreational: ____________

Preferred position: __________________________________

Preferred shoe style, circle one

- Traditional studs
- Blade studs
- Interchangeable studs
- Turf studs
- Other: Please specify ____________________________________

Subject Information Questionnaire Results

Table 4: Years of Football Experience

	Mean	Standard Deviation
Competitive Years Played	8.21	2.73
Recreational Years Played	3.64	4.24

Table 5: Football Position Distribution

Position	Preferred Position Count	Played Position Count
Center	1	3
Cornerback	2	2
Defensive Tackle	1	2
Linebacker	4	5
Quarterback	1	2
Safety	4	4
Tight End	0	2
Wide Receiver	4	7

** Some subjects had multiple answers for both sections

Table 6: Cleat Preferences

Preferred Cleat style	Count
Traditional	5
Blade	0
Interchangeable	8
Turf	1

Appendix D

Subject Demographics

Table 7: Subject Demographics

	Mean	**Standard Deviation**
Age	20.14	1.41
Height (m)	1.81	0.04
Weight (kg)	85.58	9.68
BMI	26.06	2.70
Reach Height (m)	2.34	0.05
Maximum Jump Height (m)	2.94	0.08
90% of Max Jump Height (m)	2.65	0.07

Appendix E

Individual Subject Information

Table 8: Peak Free Moment (Nm/kg)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	0.592 ± 0.041	0.589 ± 0.045	0.236 ± 0.101	0.118 ± 0.074	0.178 ± 0.042	0.241 ± 0.091
2	0.784 ± 0.162	0.447 ± 0.137	0.721 ± 0.005	0.348 ± 0.085	0.208 ± 0.054	0.172 ± 0.055
3	0.470 ± 0.057	0.714 ± 0.017	0.599 ± 0.191	0.311 ± 0.045	0.251 ± 0.070	0.276 ± 0.022
4	0.397 ± 0.098	0.424 ± 0.125	0.378 ± 0.077	0.193 ± 0.043	0.139 ± 0.134	0.354 ± 0.064
5	0.498 ± 0.184	0.441 ± 0.069	0.347 ± 0.019	0.286 ± 0.158	0.330 ± 0.034	0.170 ± 0.091
6	0.380 ± 0.049	0.561 ± 0.043	0.612 ± 0.056	0.818 ± 0.021	0.472 ± 0.048	0.171 ± 0.056
7	0.438 ± 0.092	0.471 ± 0.060	0.491 ± 0.035	0.157 ± 0.010	0.215 ± 0.102	0.251 ± 0.031
8	0.231 ± 0.126	0.356 ± 0.092	0.215 ± 0.096	0.314 ± 0.161	0.102 ± 0.047	0.500 ± 0.041
9	0.408 ± 0.063	0.456 ± 0.051	0.433 ± 0.089	0.458 ± 0.161	0.185 ± 0.013	0.193 ± 0.150
10	0.422 ± 0.107	0.400 ± 0.032	0.336 ± 0.039	0.273 ± 0.057	0.283 ± 0.045	0.317 ± 0.050
11	0.520 ± 0.036	0.505 ± 0.051	0.373 ± 0.066	0.188 ± 0.057	0.171 ± 0.039	0.171 ± 0.039
12	0.431 ± 0.231	0.502 ± 0.135	0.558 ± 0.198	0.406 ± 0.137	0.169 ± 0.043	0.221 ± 0.057
13	0.389 ± 0.095	0.575 ± 0.257	0.637 ± 0.133	0.313 ± 0.096	0.244 ± 0.039	0.190 ± 0.042
14	0.316 ± 0.053	0.351 ± 0.048	0.507 ± 0.156	0.147 ± 0.079	0.144 ± 0.030	0.196 ± 0.076
Mean	0.448 ± 0.130	0.485 ± 0.099	0.460 ± 0.154	0.309 ± 0.177	0.221 ± 0.094	0.244 ± 0.094

Table 9: Time to Peak Free Moment (s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	0.139 ± 0.032	0.114 ± 0.007	0.104 ± 0.047	0.083 ± 0.041	0.163 ± 0.083	0.093 ± 0.048
2	0.106 ± 0.015	0.105 ± 0.045	0.128 ± 0.046	0.033 ± 0.011	0.078 ± 0.087	0.064 ± 0.017
3	0.144 ± 0.015	0.147 ± 0.020	0.155 ± 0.025	0.090 ± 0.004	0.077 ± 0.003	0.124 ± 0.063
4	0.084 ± 0.045	0.056 ± 0.006	0.063 ± 0.007	0.208 ± 0.031	0.144 ± 0.044	0.153 ± 0.049
5	0.130 ± 0.016	0.126 ± 0.017	0.115 ± 0.026	0.124 ± 0.054	0.122 ± 0.058	0.147 ± 0.062
6	0.073 ± 0.039	0.150 ± 0.039	0.107 ± 0.029	0.058 ± 0.005	0.072 ± 0.026	0.025 ± 0.000
7	0.163 ± 0.060	0.170 ± 0.023	0.177 ± 0.039	0.090 ± 0.012	0.075 ± 0.009	0.092 ± 0.006
8	0.160 ± 0.028	0.150 ± 0.019	0.121 ± 0.013	0.140 ± 0.051	0.083 ± 0.046	0.117 ± 0.046
9	0.138 ± 0.025	0.181 ± 0.036	0.170 ± 0.031	0.057 ± 0.006	0.063 ± 0.009	0.082 ± 0.015
10	0.130 ± 0.007	0.136 ± 0.022	0.150 ± 0.038	0.017 ± 0.000	0.043 ± 0.053	0.043 ± 0.062
11	0.148 ± 0.010	0.138 ± 0.008	0.158 ± 0.024	0.133 ± 0.061	0.092 ± 0.016	0.092 ± 0.016
12	0.125 ± 0.048	0.112 ± 0.012	0.144 ± 0.024	0.046 ± 0.004	0.127 ± 0.063	0.133 ± 0.079
13	0.119 ± 0.010	0.085 ± 0.033	0.123 ± 0.052	0.119 ± 0.034	0.172 ± 0.025	0.122 ± 0.034
14	0.108 ± 0.024	0.155 ± 0.027	0.120 ± 0.012	0.029 ± 0.004	0.092 ± 0.014	0.070 ± 0.007
Mean	0.126 ± 0.025	0.130 ± 0.034	0.131 ± 0.030	0.088 ± 0.051	0.100 ± 0.037	0.097 ± 0.037

Table 10: Vertical Impact GRF (BW)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	5.840±0.297	6.484±0.298	5.944±0.586	1.635±0.164	1.647±0.136	1.842±0.132
2	5.793±0.390	5.907±0.437	6.130±0.116	1.978±0.323	2.133±0.268	2.255±0.419
3	3.748±0.283	4.946±0.272	5.668±0.342	1.637±0.028	1.389±0.093	1.502±0.111
4	4.667±0.506	4.934±0.315	4.201±0.540	1.844±0.101	1.604±0.264	1.748±0.486
5	3.672±0.099	4.014±0.300	3.907±0.170	1.804±0.161	1.661±0.174	1.810±0.155
6	4.289±0.425	5.297±0.691	4.865±0.293	1.652±0.146	1.614±0.134	1.665±0.099
7	4.622±0.830	4.455±0.387	4.781±0.863	1.835±0.133	1.565±0.099	1.610±0.007
8	3.437±0.259	5.434±0.909	3.904±0.282	1.747±0.185	1.467±0.100	1.616±0.214
9	5.068±0.399	4.976±0.635	5.070±0.370	1.933±0.176	1.568±0.025	1.601±0.041
10	4.721±0.334	5.597±0.920	5.566±0.697	2.044±0.152	1.710±0.166	2.407±0.225
11	4.175±0.548	3.929±0.549	4.836±1.126	2.187±0.117	1.929±0.130	2.127±0.115
12	4.871±1.062	4.656±0.388	4.746±0.561	2.049±0.408	1.748±0.164	1.762±0.058
13	6.800±0.716	4.584±0.447	4.258±0.272	1.784±0.272	1.619±0.349	1.176±0.388
14	4.915±0.970	5.059±0.632	5.416±0.728	1.768±0.100	1.322±0.095	1.609±0.185
Mean	4.758±0.923	5.019±0.700	4.949±0.724	1.850±0.169	1.641±0.206	1.766±0.318

Table 11: Time to Vertical Impact GRF (s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	0.040±0.003	0.041±0.002	0.042±0.004	0.068±0.016	0.065±0.004	0.064±0.006
2	0.043±0.005	0.040±0.002	0.040±0.002	0.046±0.019	0.019±0.005	0.025±0.013
3	0.051±0.003	0.042±0.002	0.041±0.002	0.070±0.004	0.084±0.034	0.099±0.038
4	0.058±0.007	0.063±0.004	0.066±0.007	0.081±0.007	0.102±0.034	0.085±0.019
5	0.067±0.011	0.058±0.005	0.064±0.008	0.091±0.010	0.079±0.024	0.071±0.016
6	0.044±0.003	0.037±0.003	0.047±0.004	0.052±0.019	0.033±0.014	0.027±0.005
7	0.055±0.007	0.059±0.005	0.059±0.006	0.087±0.006	0.068±0.017	0.088±0.013
8	0.045±0.005	0.032±0.007	0.051±0.005	0.074±0.009	0.132±0.035	0.089±0.032
9	0.045±0.007	0.048±0.004	0.047±0.003	0.052±0.005	0.088±0.034	0.049±0.002
10	0.040±0.007	0.031±0.008	0.029±0.006	0.042±0.015	0.076±0.018	0.013±0.004
11	0.058±0.005	0.058±0.003	0.060±0.010	0.081±0.010	0.107±0.007	0.087±0.009
12	0.045±0.006	0.041±0.003	0.048±0.007	0.041±0.009	0.057±0.018	0.045±0.009
13	0.037±0.010	0.073±0.010	0.075±0.012	0.098±0.012	0.131±0.030	0.088±0.046
14	0.043±0.010	0.041±0.007	0.032±0.011	0.036±0.014	0.091±0.019	0.062±0.008
Mean	0.048±0.009	0.047±0.013	0.050±0.013	0.066±0.020	0.081±0.032	0.063±0.028

Table 12: Vertical Impact Loading Rate (BW/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	145.553±18.790	157.676±13.755	141.612±19.870	25.265±6.254	25.640±3.434	29.318±4.345
2	-	-	-	-	-	-
3	73.728±2.475	117.400±10.530	138.678±14.535	23.542±1.649	18.694±6.636	16.639±5.562
4	81.813±17.189	79.189±10.103	64.502±14.456	22.969±1.999	18.156±10.629	22.399±11.257
5	56.331±9.125	69.707±10.259	61.753±7.273	20.095±3.580	22.893±9.444	26.273±4.672
6	98.376±13.334	144.683±31.631	104.708±16.999	34.138±9.719	56.597±28.866	62.585±8.615
7	85.087±16.988	76.633±9.583	81.134±13.778	21.180±1.887	23.940±5.126	18.690±2.707
8	78.313±14.930	179.306±64.101	77.748±12.612	23.938±2.817	11.616±2.525	19.295±5.006
9	116.522±25.478	105.554±21.015	109.303±14.379	37.621±5.570	20.013±7.813	32.595±1.649
10	-	-	-	-	-	-
11	72.717±15.619	68.551±10.794	84.975±36.502	27.255±4.418	18.135±2.459	24.771±3.749
12	113.182±40.962	113.280±12.229	101.243±25.517	53.640±24.151	32.528±9.202	40.497±7.589
13	195.126±62.111	63.578±10.480	57.855±11.993	18.655±4.791	40.679±14.301	14.222±2.382
14	120.487±43.116	128.372±40.868	212.499±157.109	57.465±32.620	15.000±3.281	26.510±4.492
Mean	103.103±38.427	108.661±38.423	103.001±44.171	30.480±12.962	25.324±12.589	27.816±13.153

Table 13: Peak Medial GRF (BW)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	1.249±0.238	1.319±0.224	1.101±0.222	1.251±0.088	1.120±0.076	1.319±0.107
2	1.117±0.258	1.257±0.309	1.166±0.209	1.381±0.177	1.237±0.101	1.366±0.095
3	1.218±0.051	1.749±0.309	2.158±0.151	1.151±0.019	0.985±0.070	1.111±0.021
4	1.375±0.197	1.595±0.203	1.181±0.169	1.207±0.076	0.968±0.231	1.058±0.269
5	1.463±0.146	1.805±0.168	1.766±0.189	1.201±0.180	1.021±0.146	1.265±0.082
6	1.430±0.278	1.342±0.222	1.612±0.254	1.265±0.135	0.964±0.100	1.173±0.176
7	1.196±0.444	1.208±0.246	1.324±0.392	1.380±0.099	1.047±0.087	1.129±0.041
8	0.979±0.193	0.721±0.116	1.282±0.051	1.351±0.156	1.057±0.106	1.140±0.148
9	1.473±0.005	1.463±0.040	1.478±0.017	1.391±0.135	1.136±0.076	1.242±0.134
10	1.313±0.321	0.757±0.084	1.402±0.148	1.546±0.136	1.284±0.201	1.406±0.251
11	1.234±0.197	1.199±0.297	1.592±0.339	1.760±0.056	1.418±0.115	1.595±0.111
12	0.854±0.286	0.942±0.130	1.071±0.131	1.557±0.198	1.212±0.057	1.240±0.035
13	1.692±0.076	1.463±0.366	1.431±0.068	1.313±0.280	0.918±0.444	1.337±0.215
14	1.146±0.259	1.305±0.124	1.352±0.059	1.301±0.015	0.947±0.094	1.119±0.135
Mean	1.267±0.215	1.295±0.325	1.423±0.293	1.361±0.165	1.094±0.148	1.250±0.145

Table 14: Peak Dorsiflexion Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	26.943±3.083	25.511±5.181	28.129±3.505	33.809±2.325	34.011±2.382	32.694±1.630
2	14.385±2.400	8.229±1.256	6.612±1.166	14.749±5.382	5.485±5.469	3.393±2.520
3	26.037±2.788	17.053±2.755	15.678±2.182	26.977±0.657	19.399±5.498	18.768±2.546
4	15.309±0.378	8.413±1.095	7.802±0.977	2.727±1.499	7.068±2.078	2.611±3.851
5	27.021±4.380	32.261±4.542	29.437±3.197	34.202±3.627	31.613±6.443	30.596±1.559
6	18.231±1.995	13.285±4.128	19.344±1.291	21.249±2.219	22.513±5.825	22.788±2.193
7	18.958±4.541	23.613±4.573	24.125±2.267	25.236±3.687	27.037±4.997	32.589±3.346
8	27.653±3.208	30.731±4.673	28.193±1.893	37.104±3.440	35.832±2.127	38.665±2.631
9	28.805±3.326	25.382±2.329	26.486±3.041	18.460±2.115	24.048±2.503	25.249±3.641
10	9.949±0.814	8.125±5.327	10.524±2.280	3.489±3.801	7.715±2.408	8.430±2.142
11	21.941±3.982	14.964±2.229	10.400±7.461	13.695±5.277	14.555±5.100	11.136±4.926
12	19.810±1.864	18.136±1.426	20.791±6.081	15.762±4.499	14.010±2.557	9.701±3.120
13	14.254±9.694	22.720±2.294	25.551±3.761	22.719±1.746	25.711±4.134	26.450±3.695
14	19.476±1.312	14.900±1.603	11.882±2.436	16.413±1.582	9.688±3.219	6.890±0.774
Mean	20.627±5.951	18.809±8.076	18.925±8.282	20.471±10.519	19.906±9.995	19.283±12.153

Table 15: Dorsiflexion ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	55.098±3.900	55.091±5.586	58.800±4.551	42.863±8.765	41.247±2.729	43.738±3.149
2	41.243±2.517	41.850±1.796	42.620±1.680	12.543±9.082	11.312±8.144	17.644±11.179
3	47.556±1.325	53.412±3.708	51.263±2.439	25.113±1.397	25.577±4.326	26.513±4.082
4	49.850±1.665	47.717±0.380	47.073±2.012	29.772±2.369	36.597±2.708	31.350±4.911
5	37.898±5.245	57.713±5.056	57.028±3.121	36.980±4.483	36.371±5.299	40.626±2.617
6	47.186±1.807	43.705±4.963	51.853±1.933	29.880±1.791	20.794±7.295	22.665±4.070
7	52.926±2.742	54.749±4.703	49.300±2.258	26.079±3.970	32.754±4.723	47.413±5.119
8	41.410±1.577	26.564±25.347	36.521±3.820	34.401±6.062	28.185±4.184	37.011±3.152
9	43.527±4.617	53.409±1.953	54.739±3.177	26.229±5.593	38.368±2.937	39.065±4.696
10	26.994±8.299	25.694±7.925	24.428±6.844	7.661±2.693	12.734±2.727	11.131±2.559
11	48.887±5.904	47.851±2.674	45.841±7.355	36.171±3.849	42.561±3.716	40.447±6.460
12	44.193±4.959	43.025±1.500	50.581±8.194	30.473±7.564	32.883±2.151	31.872±3.133
13	27.690±19.691	55.679±1.921	59.311±6.840	37.816±2.115	40.092±7.664	36.490±5.177
14	30.981±6.679	33.115±3.886	19.999±19.990	8.559±4.736	22.053±0.940	24.329±1.234
Mean	42.531±8.901	45.684±10.714	46.383±12.008	27.467±10.955	30.109±10.281	32.164±10.503

Table 16: Peak Dorsiflexion Velocity (deg/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	928.191±159.232	855.136±77.161	945.669±158.138	644.073±109.083	408.798±20.786	493.647±32.770
2	867.424±155.503	835.058±64.982	853.906±72.292	275.056±32.207	269.551±51.685	269.504±81.155
3	906.526±123.529	966.315±40.921	1001.342±22.168	441.016±7.773	424.951±56.477	454.127±37.661
4	1034.537±49.415	1083.661±48.241	1045.046±50.328	528.048±36.633	496.665±80.037	529.318±118.720
5	653.171±98.985	1109.399±68.188	1114.906±61.590	568.802±64.126	406.180±42.659	541.262±12.030
6	964.928±72.330	803.042±191.846	1039.298±36.763	418.393±46.265	219.820±75.510	291.492±101.854
7	1146.817±110.862	1054.851±60.993	1068.144±59.064	694.303±66.064	508.792±59.264	605.101±64.998
8	1003.459±127.310	659.999±248.266	887.889±120.022	1002.689±92.966	558.458±91.829	799.082±98.294
9	737.447±106.215	899.831±88.349	967.381±111.905	404.665±96.610	424.875±60.927	510.509±79.216
10	559.299±215.267	548.578±113.990	479.909±253.431	224.157±37.805	220.984±45.445	217.959±34.264
11	1042.990±126.608	1003.409±64.405	961.182±114.390	638.358±72.580	543.842±65.921	621.951±48.379
12	767.982±76.342	634.755±540.448	1015.954±188.417	369.485±34.176	437.206±32.909	434.771±28.802
13	472.772±365.943	1000.673±49.245	1027.204±82.670	635.552±58.281	417.542±58.778	405.515±37.682
14	576.786±199.970	584.677±132.387	646.044±269.262	172.682±88.242	345.682±34.365	463.667±52.646
Mean	833.024±207.796	859.956±190.313	932.419±174.023	501.234±219.144	405.953±108.844	474.136±152.284

Table 17: Peak Eversion Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-9.901±2.766	-7.964±1.129	-11.065±4.892	-	-	-
2	0.629±6.047	0.228±7.096	-3.572±3.768	-	-	-
3	4.557±2.562	8.348±4.315	13.320±2.904	-	-	-
4	-2.034±1.570	-3.707±1.594	-4.269±2.141	-	-	-
5	-36.944±4.589	3.117±6.641	3.557±1.313	-	-	-
6	-19.521±3.842	-17.321±2.352	-13.597±3.598	-	-	-
7	3.607±2.253	4.527±3.411	0.897±4.539	-	-	-
8	-4.728±2.102	-2.951±1.530	-7.200±2.466	-	-	-
9	-1.455±1.293	1.509±0.481	-2.820±0.842	-	-	-
10	-0.469±4.032	-5.510±3.652	-4.643±2.423	-	-	-
11	-4.529±3.558	-0.959±2.371	1.870±0.452	-	-	-
12	-16.229±3.654	-12.654±4.430	-11.704±3.497	-	-	-
13	-8.549±2.340	0.855±2.819	0.795±2.182	-	-	-
14	-6.019±1.440	-3.337±2.568	-2.134±1.941	-	-	-
Mean	-7.256±10.965	-2.558±6.792	-2.897±7.009	-	-	-

Table 18: Peak Inversion Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-	-	-	15.359±3.622	26.361±3.026	22.740±3.154
2	-	-	-	41.510±2.441	37.942±3.391	33.139±5.200
3	-	-	-	19.016±0.119	37.756±3.041	37.986±1.923
4	-	-	-	11.633±0.823	16.726±3.183	15.567±3.522
5	-	-	-	21.805±3.704	19.939±2.574	19.406±2.403
6	-	-	-	11.804±2.556	24.436±5.893	26.404±3.084
7	-	-	-	24.671±3.825	20.190±2.419	17.757±3.290
8	-	-	-	11.501±1.190	10.246±3.552	14.475±3.763
9	-	-	-	16.678±1.273	25.877±4.658	27.452±4.049
10	-	-	-	25.607±0.569	27.657±0.798	27.357±1.314
11	-	-	-	16.142±3.034	14.726±2.719	19.054±4.507
12	-	-	-	17.510±2.377	14.730±1.618	14.591±1.005
13	-	-	-	17.614±5.727	21.584±5.403	22.226±3.116
14	-	-	-	16.892±3.023	20.913±1.170	23.029±2.187
Mean	-	-	-	19.125±7.785	22.792±8.068	22.942±6.978

Table 19: Eversion ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-14.497±3.390	-6.040±0.784	-10.451±7.656	-	-	-
2	-2.100±6.338	2.004±8.209	0.126±3.537	-	-	-
3	3.909±4.766	-4.540±4.959	3.047±2.406	-	-	-
4	-2.988±0.808	-0.222±0.879	-0.859±2.149	-	-	-
5	-	-	-	-	-	-
6	-3.596±4.696	-5.639±1.582	-1.217±4.168	-	-	-
7	-5.463±4.359	5.457±3.851	2.795±4.549	-	-	-
8	-7.881±3.965	1.500±5.294	-5.972±3.310	-	-	-
9	1.955±2.025	-2.517±2.115	-3.746±4.524	-	-	-
10	6.293±3.283	5.062±0.645	5.280±1.559	-	-	-
11	6.282±1.945	6.504±2.839	13.240±6.536	-	-	-
12	-7.125±3.056	1.996±4.874	4.322±2.854	-	-	-
13	2.469±1.409	9.362±3.397	10.815±1.791	-	-	-
14	-2.820±1.773	-3.311±5.824	-0.901±9.870	-	-	-
Mean	-5.289±13.730	0.740±4.960	1.268±6.436	-	-	-

Table 20: Inversion ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-	-	-	16.123±4.313	27.980±3.953	24.835±4.317
2	-	-	-	29.984±5.418	35.488±3.789	37.088±1.939
3	-	-	-	16.966±3.823	23.073±3.800	23.492±1.169
4	-	-	-	13.075±1.413	14.175±2.478	14.757±5.070
5	-	-	-	-	-	-
6	-	-	-	24.727±3.235	28.933±3.998	32.950±3.110
7	-	-	-	30.658±4.342	24.253±6.070	24.840±2.777
8	-	-	-	12.050±5.460	21.187±2.364	20.549±4.968
9	-	-	-	17.404±2.404	17.627±3.197	21.804±4.540
10	-	-	-	24.357±1.285	22.769±1.178	23.407±2.491
11	-	-	-	21.831±8.233	21.015±5.186	22.285±3.902
12	-	-	-	18.158±5.942	12.318±2.180	14.620±1.994
13	-	-	-	23.127±6.043	17.968±5.602	17.240±4.191
14	-	-	-	9.658±5.400	12.513±4.550	15.901±1.655
Mean	-	-	-	19.855±6.582	21.485±6.777	22.598±6.660

Table 21: Peak Eversion Velocity (deg/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-219.860±54.217	-275.323±78.053	-279.345±70.773	-	-	-
2	-167.126±117.248	232.140.±.103.341	-206.545±85.287	-	-	-
3	-173.182±43.421	-319.344±37.790	-239.500±54.566	-	-	-
4	-104.715±27.867	-129.642±24.858	-116.799±42.509	-	-	-
5	-	-	-	-	-	-
6	-141.969±59.904	-216.252±71.144	-186.844±33.892	-	-	-
7	-155.076±36.888	-187.929±83.099	-172.969±37.297	-	-	-
8	-91.954±94.820	-105.560±31.252	-138.833±38.918	-	-	-
9	-123.847±55.522	-214.657±50.068	-243.001±112.617	-	-	-
10	-165.192±46.040	-258.184±40.447	-225.129±154.065	-	-	-
11	-247.835±141.557	-348.508±111.663	-247.548±90.724	-	-	-
12	-137.209±18.070	-149.570±48.653	-173.775±81.658	-	-	-
13	-169.991±39.264	-140.778±128.295	-198.891±70.838	-	-	-
14	-187.870±7.559	-474.694±156.591	-343.901±83.914	-	-	-
Mean	-160.448±43.095	-234.814±102.727	-210.341±58.775	-	-	-

Table 22: Peak Inversion Velocity (deg/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-	-	-	283.035±67.760	435.082±27.688	432.917±54.245
2	-	-	-	-	-	-
3	-	-	-	389.596±71.359	452.916±98.415	403.190±66.384
4	-	-	-	243.383±30.306	276.226±41.738	351.975±78.912
5	-	-	-	446.687±70.519	487.021±96.070	463.999±79.922
6	-	-	-	548.901±61.233	519.929±54.355	567.453±135.509
7	-	-	-	424.249±89.924	428.619±61.465	382.214±30.463
8	-	-	-	452.958±146.048	272.405±99.994	355.903±71.357
9	-	-	-	405.042±50.918	364.381±82.316	444.264±90.430
10	-	-	-	-	-	-
11	-	-	-	355.593±168.146	309.915±25.386	279.345±73.530
12	-	-	-	506.576±70.430	258.770±54.240	308.810±56.461
13	-	-	-	284.141±64.900	319.663±59.386	369.405±75.038
14	-	-	-	54.362±20.352	364.779±179.749	425.767±71.334
Mean	-	-	-	401.360±179.073	413.581±145.205	412.384±67.188

Table 23: Peak Flexion Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-70.467±6.921	-68.112±3.434	-72.699±3.831	-74.868±1.328	-78.233±3.638	-80.862±4.665
2	-66.134±5.027	-74.050±12.752	-72.631±7.321	-73.809±2.583	-79.094±4.744	-68.180±7.209
3	-72.700±6.611	-83.395±5.970	-75.499±4.962	-81.363±3.415	-84.452±6.049	-79.606±5.125
4	-73.505±7.296	-79.648±4.206	-80.008±4.273	-75.028±3.432	-71.236±4.485	-76.158±2.042
5	-59.021±4.309	-65.621±7.515	-54.092±6.788	-65.441±2.178	-79.580±7.424	-72.433±3.253
6	-77.823±5.086	-78.565±2.258	-72.102±4.372	-68.981±1.041	-69.522±6.877	-68.171±3.965
7	-56.910±7.807	-56.010±5.209	-55.103±8.067	-63.738±2.199	-65.946±6.684	-64.650±1.250
8	-67.476±5.796	-76.846±4.941	-58.187±4.634	-73.841±5.716	-67.740±6.541	-75.961±9.033
9	-61.057±2.976	-61.577±1.995	-63.638±2.206	-65.316±4.106	-70.079±5.280	-63.542±4.035
10	-58.692±2.024	-56.702±7.809	-57.653±2.482	-60.928±6.068	-63.403±8.135	-55.147±5.521
11	-64.383±5.383	-59.134±5.216	-52.787±5.822	-62.639±4.689	-66.129±3.222	-65.109±4.471
12	-67.509±3.808	-68.483±3.880	-67.468±3.722	-64.448±2.172	-61.968±2.952	-65.699±5.295
13	-70.270±7.227	-53.796±12.984	-58.485±4.098	-56.817±4.618	-45.586±9.166	-38.606±7.766
14	-73.625±7.928	-72.092±5.625	-74.420±5.510	-89.479±4.095	-82.886±1.733	-88.579±1.845
Mean	-67.112±6.423	-68.145±9.666	-65.341±9.229	-69.764±8.815	-70.418±10.217	-68.765±12.213

Table 24: Flexion ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-59.165±7.686	-52.986±3.014	-58.304±4.391	-46.114±6.096	-41.892±1.349	-48.705±4.710
2	-50.976±6.007	-56.926±12.714	-53.165±7.141	-52.812±4.364	-52.869±2.387	-48.100±7.704
3	-54.433±4.563	-65.896±4.543	-58.328±4.617	-39.231±35.705	-31.006±8.679	-37.882±8.375
4	-56.319±5.819	-57.600±3.213	-57.041±4.852	-46.214±6.679	-37.673±4.667	-41.404±5.948
5	-41.254±6.721	-39.252±5.038	-36.740±6.456	-36.991±3.665	-39.517±2.337	-46.042±5.064
6	-50.679±6.488	-53.763±1.873	-43.609±4.760	-41.514±2.305	-40.238±6.114	-40.924±6.786
7	-59.173±9.626	-57.811±5.064	-58.229±9.049	-12.382±13.223	-40.702±5.796	-41.252±10.071
8	-56.787±5.478	-51.244±11.753	-46.892±4.296	-26.042±5.418	0.534±11.471	-21.509±4.810
9	-48.466±2.469	-48.548±0.538	-49.984±1.665	-45.139±3.719	-46.805±4.757	-40.208±5.260
10	-40.468±2.638	-43.167±7.120	-43.464±2.810	-35.412±5.580	-37.099±8.736	-27.845±5.054
11	-50.757±7.191	-44.451±6.160	-37.862±6.419	-38.871±7.856	-43.411±4.720	-42.744±5.219
12	-45.150±5.901	-44.453±1.048	-43.171±2.327	-38.713±4.788	-36.270±3.445	-37.466±4.039
13	-49.433±9.808	-39.147±12.777	-42.491±4.636	-27.761±10.916	-14.483±7.263	-7.845±7.704
14	-55.393±5.845	-52.053±5.074	-55.156±7.666	-42.889±5.893	-37.562±2.418	-47.898±1.623
Mean	-51.318±6.039	-50.521±7.786	-48.888±7.817	-37.863±10.207	-35.642±13.504	-37.845±11.508

Table 25: Peak Flexion Velocity (deg/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-775.021±67.445	-616.333±18.436	-648.456±47.814	-427.869±38.188	-377.102±11.374	-437.373±51.964
2	-801.999±39.291	-774.943±94.474	-746.335±93.974	-661.971±62.062	-605.843±28.893	-532.209±104.819
3	-651.290±60.240	-738.958±49.536	-690.014±39.043	-281.703±20.317	-392.781±102.742	-448.278±69.411
4	-560.025±36.325	-532.788±55.842	-554.179±59.794	-441.359±26.375	-363.455±35.974	-394.956±25.542
5	-484.456±121.261	-501.808±18.303	-478.112±104.481	-400.574±38.980	-420.211±22.255	-440.405±65.440
6	-559.509±68.263	-693.912±33.361	-487.207±49.131	-430.257±42.517	-542.259±76.505	-581.293±26.229
7	-659.598±85.410	-642.914±30.746	-526.765±110.326	-392.834±66.195	-353.356±16.473	-393.109±37.671
8	-636.068±81.318	-838.837±121.927	-554.403±42.507	-442.297±87.429	-360.124±139.629	-479.044±55.855
9	-570.348±62.763	-546.582±37.543	-543.253±90.225	-467.047±46.375	-427.985±57.487	-395.566±52.279
10	-591.297±103.008	-653.262±113.146	-705.541±93.829	-483.689±34.964	-477.311±33.534	-429.425±18.113
11	-531.483±63.107	-539.952±48.089	-488.378±70.584	-393.559±60.442	-413.762±41.100	-455.964±36.371
12	-670.840±100.209	-574.680±53.723	-546.611±67.369	-462.150±101.914	-382.858±25.771	-388.731±49.431
13	-706.472±52.745	-463.705±128.005	-495.766±70.773	-296.841±139.671	-173.753±46.081	-119.612±40.194
14	-607.053±133.595	-583.373±41.222	-780.881±252.191	-567.474±48.921	-331.391±47.102	-433.712±50.698
Mean	-628.961±90.221	-621.575±108.952	-588.993±103.975	-439.259±96.229	-401.585±100.689	-423.548±103.092

Table 26: Peak Abduction Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-6.732±0.630	-1.378±2.143	-1.218±0.597	-	-	-
2	-7.168±2.693	-7.927±2.828	-9.078±2.780	-	-	-
3	-3.132±2.213	-5.533±2.346	-4.227±2.685	-	-	-
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-7.400±1.190	-7.698±1.320	-10.760±1.018	-	-	-
7	-3.453±0.828	-10.470±2.287	-5.259±1.119	-	-	-
8	-	-	-	-	-	-
9	-12.456±0.670	-12.852±1.507	-13.049±2.581	-	-	-
10	-15.523±1.952	-12.713±1.631	-13.789±2.253	-	-	-
11	-16.213±3.616	-11.571±3.454	-9.710±1.220	-	-	-
12	-5.914±1.019	-9.451±0.682	-9.251±1.595	-	-	-
13	-10.221±4.738	-6.821±2.581	-5.323±2.840	-	-	-
14	-13.657±2.062	-13.730±2.785	-14.916±2.488	-	-	-
Mean	-9.261±4.634	-9.104±3.709	-8.870±4.340	-	-	-

Table 27: Abduction ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-4.938±0.961	-1.421±2.279	-1.081±1.437	-	-	-
2	-6.723±1.582	-8.206±2.650	-8.008±4.192	-	-	-
3	-0.978±1.186	-3.735±2.476	-3.045±3.665	-	-	-
4	8.098±1.724	8.999±2.531	-4.360±2.689	-	-	-
5	-0.608±2.106	-2.383±2.362	1.047±2.851	-	-	-
6	-6.136±1.561	-5.776±1.512	-8.580±1.783	-	-	-
7	-1.830±0.940	-5.423±1.912	-2.538±1.944	-	-	-
8	12.580±6.060	-0.837±2.451	9.594±0.466	-	-	-
9	-7.494±0.953	-7.744±1.150	-9.018±2.245	-	-	-
10	-9.704±1.516	-9.169±1.937	-9.453±1.769	-	-	-
11	-7.688±3.315	-5.580±2.721	-3.985±1.203	-	-	-
12	-1.864±0.230	-4.405±1.135	-3.750±1.211	-	-	-
13	-8.309±5.128	-7.027±3.921	-6.200±0.639	-	-	-
14	-11.478±2.634	-13.035±3.029	-11.637±5.048	-	-	-
Mean	-3.362±6.743	-4.696±5.104	-4.358±5.580	-	-	-

Table 28: Peak Adduction Angle (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-	-	-	-8.425±1.582	-6.913±1.423	-7.114±2.433
2	-	-	-	1.027±0.573	-3.057±1.647	-6.187±0.937
3	-	-	-	-1.157±0.923	7.516±1.465	8.055±1.771
4	-	-	-	12.872±1.835	15.071±2.194	12.566±2.784
5	-	-	-	8.418±1.916	5.450±1.125	5.780±2.469
6	-	-	-	1.136±0.580	0.871±1.159	-0.957±0.212
7	-	-	-	5.238±1.252	2.338±2.207	3.917±2.784
8	-	-	-	13.365±2.312	7.138±1.122	5.570±3.203
9	-	-	-	-4.662±1.825	-3.562±0.746	-1.876±1.541
10	-	-	-	-9.200±1.067	-10.384±0.961	-9.441±1.541
11	-	-	-	-9.998±2.252	-3.563±0.928	-3.925±1.870
12	-	-	-	-4.544±1.383	-5.408±1.526	-4.583±0.272
13	-	-	-	-3.761±1.719	0.856±1.694	0.299±2.486
14	-	-	-	-7.139±2.174	-5.262±1.185	-6.182±1.687
Mean	-	-	-	-0.488±7.874	0.078±6.897	-0.291±6.555

Table 29: Adduction ROM (°)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-	-	-	3.226±0.861	2.654±1.266	3.031±1.968
2	-	-	-	1.179±1.165	-3.257±3.593	0.520±1.293
3	-	-	-	0.567±2.782	3.093±3.602	4.728±5.575
4	-	-	-	14.447±2.429	13.523±2.070	10.690±2.539
5	-	-	-	9.907±2.063	0.506±1.080	7.795±2.695
6	-	-	-	1.093±3.518	0.174±0.516	2.319±0.000
7	-	-	-	9.793±4.707	12.273±4.350	15.527±4.093
8	-	-	-	5.866±1.508	-8.643±5.433	-0.381±4.647
9	-	-	-	14.063±5.230	9.839±2.187	11.986±1.431
10	-	-	-	-2.858±0.798	-2.790±1.462	-1.537±1.358
11	-	-	-	1.440±1.682	2.675±2.599	2.540±2.769
12	-	-	-	5.657±1.555	4.090±2.773	3.116±1.373
13	-	-	-	2.736±1.198	6.384±0.944	8.104±2.185
14	-	-	-	9.061±2.729	10.861±2.699	8.644±1.148
Mean	-	-	-	5.441±5.303	3.670±6.411	5.506±5.051

Table 30: Peak Abduction Velocity (deg/s)

	Land-Pivot-Cut			180° Cut		
Subject	Shoe	Natural Turf	Synthetic Turf	Shoe	Natural Turf	Synthetic Turf
1	-50.679±19.227	-50.372±20.825	-48.925±13.859	-97.680±18.090	-100.988±55.266	-124.725±30.052
2	-202.749±21.957	-183.036±32.181	-197.138±53.423	-160.144±61.152	-188.042±56.534	-199.060±14.252
3	-55.956±40.177	-18.095±2.827	-77.738±20.694	-326.945±164.304	-149.946±71.733	-121.116±45.010
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-92.530±20.660	-87.080±37.862	-160.614±32.998	-103.969±14.641	-176.261±22.085	-133.745±30.658
7	-54.951±27.810	-68.646±37.569	-59.741±18.046	-70.315±32.938	-103.275±38.821	-165.501±101.742
8	-	-	-	-	-	-
9	-64.768±35.051	-74.942±34.325	-126.406±21.678	-175.636±29.696	-59.362±13.298	-64.962±34.322
10	-209.017±27.298	-236.273±37.144	-159.798±43.983	-126.383±28.805	-190.595±66.311	-225.031±53.166
11	-177.361±90.420	-163.484±40.374	-142.909±72.008	-97.345±4.059	-79.751±37.834	-82.402±40.789
12	-75.799±37.324	-88.635±28.253	-102.172±70.179	-68.084±18.665	-58.067±11.807	-78.971±31.139
13	-229.134±54.630	-114.984±25.881	-71.940±36.363	-40.788±6.597	-88.624±29.559	-63.165±68.253
14	-84.602±80.221	-229.062±97.656	-174.083±135.649	-270.969±106.993	-256.484±63.400	-181.177±55.645
Mean	-117.956±70.765	-119.510±72.985	-120.133±55.998	-139.842±88.737	-131.945±64.414	-130.895±55.998

Vita

Elizabeth Brock was born in LaCrosse, WI on November 17th, 1987 to Tom and Jan Brock. She grew up in Onalaska, WI where she graduated from Onalaska High School in 2006. She went on to pursue a Bachelors degree in Kinesiology and Health with a concentration in Biomechanics and a minor in business from Iowa State University. To pursue a Master degree, she enrolled in the University of Tennessee, Knoxville in 2010. After graduating with a concentration in Biomechanics/Sports Medicine in 2012, she will continue to the University of Oregon for a MBA in Sports Marketing.