TRACTION CHARACTERISTICS OF CLEATED ATHLETIC SHOES AT VARIOUS ANGLES OF INTERNAL ROTATION ON ARTIFICIAL TURF

by

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ABSTRACT

As an alternative to natural grass playing fields, the installation of artificial turf surfaces has grown exponentially over the past several decades. Despite the growing popularity of artificial turf, little is known about the interaction between the player's shoe and the turf surface. Previous research has sited the difficulty in maximizing performance (high traction), yet minimizing the risk of injury (low traction). Due to seemingly countless factors that affect the turf-shoe interaction, determining safe traction ranges for artificial turf is very difficult. Safe ranges between performance and risk of injury need to be found. The purpose of this study was to investigate whether traction characteristics vary based on a particular cleated athletic shoe on artificial turf at various angles of internal rotation during a linear translational motion. 4 U.S. Men's size 12 cleated athletic shoes with a variety of stud styles from several different commonly used brands were tested on the artificial turf. Each cleated athletic shoe was set at various angles (0º, 30º, 60º, 90º) of internal rotation, and experienced linear translational motion while data was being collected. Significant differences were found within each cleated athletic shoe at various angles of internal rotation across all dependent variables (p=0.000). This could be attributed to a phenomenon termed the trench effect. There were no significant differences between cleated athletic shoes on artificial turf. Shoe-turf interactions are a very important consideration in athletics. This interaction is a determinant of the level of athletic performance and risk of injury. Shoe-turf interaction is a very stochastic process, and results should only be evaluated within the context of the test conditions.

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CHAPTER 1

INTRODUCTION

As an alternative to natural grass playing fields, the installations of artificial turf surfaces have grown exponentially over the past several decades. A combination of financial reasons, limited maintenance and esthetics has made artificial turf a very appealing choice[2]. Despite the growing popularity of artificial turf, little is known about the player-shoe-turf interactions that occur on these surfaces. This lack of knowledge has become a matter of great concern to researchers and many turf managers[21]. This concern has grown out of the suggestion that the properties of artificial turf can both potentially improve performance and increase the risk of injury in athletes[8, 29, 30]. This creates a paradox between needs. In the end it makes the process of forming surface standards very complicated[8].

During an athletic event the athlete interacts with a very unique complex and environment. These unique interactions experienced during an athletic event affect the performance and risk of injury for the athlete. One of the most critical interactions is the interaction between the athlete's shoe and the playing surface. The outcome of this interaction is dependent upon the kinematics of the athlete, the material and design of the shoe and the material and construction of the playing surface. These factors make the quantification and standardization of playing surfaces very complicated.

The technology involved in the study of shoe-surface interactions has evolved over the years. In 1968, Gramckow assessed linear traction by measuring the force required to pull a weighted plate with cleats protruding from the bottom across a turf surface[8]. Several years later in 1972 Milner used a similar paradigm, but measured the force required to initiate motion and maintain it using an Instron tensile test machine. Devices such as the British Pendulum Tester and the Stuttgart Sliding Test Device are accepted by much of the industry to test traction coefficients and assess the acceptable ranges for performance and injury risk on various surfaces (Figure 1)[4, 8].

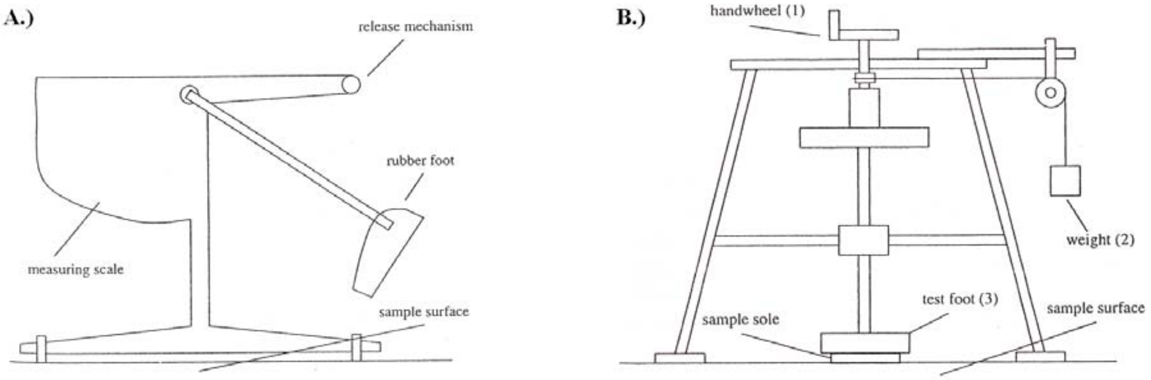


Figure 1. Simplified Schematics of the A.) British Pendulum Tester and the B.) Stuttgart Sliding Test Device[8]

Examples of sports in which standards for friction on playing surfaces have been specified include tennis, track and field, and field hockey[8]. In response to this, in 1997 McNitt et al. constructed a device that allowed for easier transport to various turf surfaces and combined both translational and rotational testing in a single device[20]. This particular device has opened the door for contemporary devices that provide an integrated system that allow for a variety of tests, enhanced transportability, and greater repeatability.

There have been attempts at developing standard testing methods like the American Society for Testing Materials (ASTM) or Deutsche Industrie Norm (DIN), but the parameters that surround these testing recommendations are vague and in some instances, don’t allow for reliable comparisons between research groups testing under similar test conditions.

Purpose Statement

The purpose of this study was to investigate whether traction characteristics vary based on a particular cleated athletic shoe style on artificial turf at various angles of internal rotation during a simulated deceleration motion. This study utilized a pneumatic and computerized system to evaluate traction characteristics between various cleated athletic shoes and the turf surface at various angles of internal rotation. Despite efforts to find research examining traction characteristics at various angles of internal rotation, none were found. All previous research conducted in the area of shoe-turf interaction has looked at traction as it relates to the shoe experiencing a rotational motion or linear translational motion with the shoe in line with the direction of the applied force. However, the large majority of studies have investigated rotational forces being applied to the cleated athletic shoe.

Research Hypothesis

1. The research hypothesis was that a variety of cleated athletic shoe styles at various angles of internal rotations would not exhibit different traction characteristics.
2. There would also be no difference in traction characteristics within cleated athletic shoes at the various angles of internal rotation.

Limitations

Limitations of the study include the assumption that the foot and the shoe are a single rigid body. In the testing method, the shoes are filled with a concrete-epoxy mix which is then attached to the testing device. This is done to limit the variability presented with an unrestrained foot in a shoe.

The location of the vertical load cell on the testing device is positioned approximately 43 cm away from the shoe-turf interface. Ideally, it would be located in the natural position of the ankle, or lateral malleolus. Since there are no moving parts between the site of the load cell and the shoe-turf interface, it is assumed that the unit between the load cell and the shoe is a rigid body.

Also, there is no internal calibration mechanism. All calibration of the load cells associated with the testing device must take place in the laboratory prior to leaving for the testing site. Past test sessions have shown that the device has been able to maintain its accuracy post-testing. This occurs when the device is brought back to the laboratory and recalibrated.

Delimitations

By using a pneumatic and computerized testing device, user error will be greatly reduced, and thus increase repeatability and reliability of the testing method.

Operational Definitions

- *Rigid body* – a body with all its parts locked together without change in its shape[13].
- *Pneumatic system* – A system devised for the application of compressed gas.
- *Friction* – 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[15].
- *Traction* – A force resistance to relative motion between a shoe outsole and a sports surface that does not necessarily obey the classical laws of friction[2].
- *Internal Rotation* – Rotation of a limb towards the midline of the body[16].

CHAPTER 2

REVIEW OF LITERATURE

Relevant information gathered for this review of literature was done using internet searches of peer-reviewed journals on the Boise State University Library website, searches at the Boise State University Library for hardcopies of various peer-reviewed journal articles, and other resources made available at the Center for Othopaedic & Biomechanics Research (COBR) Laboratory in Boise, Idaho.

Internet searches were done using databases such as SPORTDiscus and Web of Science. Key words used to locate literature referenced in this document were shoe turf interactions, artificial playing surfaces, artificial turf testing, cleat design, shoe turf traction, and various other combinations of the previous key words. Once articles of relevance were found, a search of their references and citations was done to support key points.

Shoe Design

Athletic shoe measurements fall into two categories: physical tests and subject tests. “Physical tests” are aimed at determining the mechanical properties of the shoe. This refers to the material used to build the shoe. “Subject tests” seek to determine the body’s response to various physical properties of the shoe. Investigation of changes to an individual’s kinematics can be one way to run “subject tests” with athletic shoes.

McNitt et al. (1997) characterized the elements used to describe the interaction of the athletic shoe and an artificial or natural turf[20]. Those elements include gripability, shear strength, friction, abrasion, and traction. Frederick (1986) described critical design factors as follows: cushioning, support, and durability[12]. All of these elements and design factors influence the performance and interaction the athletic shoe has with the playing surface.

In a review published by Frederick (1986), he stated that, "… the essential truth is that most of the effects that shoes have on human biomechanics are a consequence of the body's response to the shoe and not the direct result of the shoe's mechanical properties"[12]. This has become a point of contention. Several studies state that the mechanical properties are a factor in the human biomechanics[14, 18, 26]. Those citing mechanical properties as an influence on the human biomechanics refer to cleat pattern and athletic shoe material as being the key factors. Studies supporting the theory that mechanical properties are not a factor in human biomechanics refer to differences in kinematics that may alter performance or shoe-turf interactions[7].

Turf Considerations

Though artificial athletic fields have become more popular over recent years, researchers and field mangers have had a difficult time quantifying vital quality characteristics of an athletic field[20]. In general, these vital qualities can be understood as the measured, or perceived, factors that influence the important interactions between the playing surface and the player and/or ball[20].

Sports surface materials have been characterized as either point-elastic or area-elastic. Point-elastic surfaces deform only at the location where the force is applied, for example, outdoor track surfaces, tennis courts, and soccer, football, and field hockey fields. Area-elastic surfaces deform at an area greater than the location of the force applied, for example indoor basketball and volleyball courts. For the purpose of investigating artificial turf surfaces, they may be thought of as a point-elastic surfaces[8, 25].

Even before a single player steps on the athletic field, those important interactions between the playing surface and the player and/or ball need to be considered. Those considerations include functionality for the main sports, wear, durability, chemical consistency, water permeability, price, cushioning, and frictional properties[23]. The most important aspects to consider when examining injuries and performance are cushioning and frictional properties[6, 8, 14, 18 – 21, 23]. These properties are believed to be the cause of surface-related injuries, due to the fact that loads can exceed the safe limits of the musculoskeletal system[23].

Brown (1987) stated that there are basic principal parameters that are relevant to artificial surfaces[4]. Each of these parameters is then placed in sub-sections of a particular *Test category* (Table 1).

Table 1. Test Parameters for Artificial Surfaces[4]

Test Parameters for Artificial Surfaces

Test Category	*Test Parameters*
Dimensional	Area Surface geometry Thermal stability
General safety	Fire resistance Toxicity
General performance	Porosity Staining Marking Color Reflectance
Ball/surface interaction	Resilience Rolling resistance Spin
Person/surface interaction	Friction Stiffness Energy absorption
Durability	Abrasion Fatigue Spike resistance Fiber adhesion Seam strength
Environmental resistance	Heat ageing Ozone resistance Water resistance Artificial weathering Low-temperature resistance

The *Person/surface interaction* category, as defined by Brown, identifies three parameters: friction, stiffness, energy absorption[4]. These parameters are the keys to understanding shoe-turf interactions.

Classical Laws of Friction versus Traction

The classical definition of friction, as defined by *Coulomb 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"[15]. Friction can then be divided into two different states: static and dynamic. Static friction occurs when there is a force applied, but no relative movement between the two bodies. Dynamic friction occurs when movement commences. It is the force opposing the movement of the two bodies, reducing their relative velocity[8]. Also, in the classical understanding of friction, dynamic friction is always greater than static friction[8].

There are two types of frictional coefficients: translational and rotational. Translational refers to the repositioning of the foot along a linear path with no change in orientation, for example a foot sliding along the ground[12]. Rotational refers to the foot fixed in a defined axis of rotation with a torsional force being applied to it, for example the body rotating about the position of the foot in contact with the ground. For the purpose of this study, translational friction will be the primary focus[12]. Translational friction is determined by the magnitude of both the normal force (N) and the contact area[8, 23]. The translational coefficient of friction can be calculated with the following equation[2]:

Equation 1. Calculation of the Translational Coefficient of Friction

$$F = \mu W$$

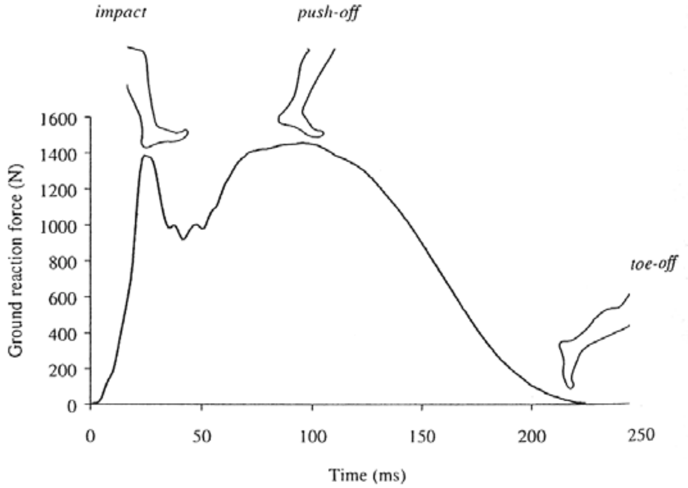
F = Frictional force
μ = Coefficient of friction
W = Applied vertical load

In the case of athletic shoes and artificial surface interactions, classical laws of friction are not obeyed[8]. Several studies have supported this claim[4, 8, 12]. This introduces the concept of traction. Traction can be thought of as the resistance to movement between different shoes and surfaces[12]. Traction retains the core concept of friction, except it aids in the characterization of the unique behaviors exhibited in shoe-turf interactions. These unique differences between friction and traction are: 1.) dynamic friction is not always less than static friction, 2.) the frictional force can exceed the normal force, 3.) the interference of a playing surface and studded or deeply patterned shoes creates a nonclassical approach to friction[4]. Traction is calculated in a similar fashion to friction, the difference is that the previous considerations need to be made when interpreting the data.

Shoe-Turf Interactions

During a stride there are typically two distinct peaks on a ground reaction force (GRF) curve. The first peak on the GRF curve is generally associated with the initial contact, or impact, the foot makes with the ground (Figure 2). This peak can be attributed to the high decelerations the foot and leg encounter as the foot meets the ground[8, 12]. Research has shown that this peak has been associated with the incidence of overuse injuries such as lower limb stress fractures, tendonitis and damage to articular cartilage[24]. The second peak, known as the active peak on the GRF curve, corresponds with the "push-off" (Figure 2). Generally, this is a relatively slow and controlled application of force and is associated with the acceleration of the entire body mass. This phase has not been linked to overuse injuries[8, 12].

Figure 2. Typical Ground Reaction Forces of a Stride[8]



The resultant GRF signifies the acceleration of the entire mass, a summation of the kinematics of each body segment. Thus, GRF data are not necessarily a direct reflection of loads experienced by individual parts of the lower extremity. Studies have shown that impact forces have not varied based on differences in running surface, but acceleration of the lower extremities have been shown to vary[8, 10].

The requirements for optimal performance between the athletic shoe and the playing surfaces are complicated and conflicting at times. In terms of performance, a high degree of traction is required to facilitate maximum control during the acceleration phase and to enhance the ability to change direction[6, 8]. However, traction should be sufficiently low to ensure loads do not exceed safe limits of the musculoskeletal system. If contact forces exceed that safe limit, a phenomenon known as "footlock" can take place, which causes the foot to be dug into the playing surface causing it to stick, which could ultimately lead to injuries[3, 6]. In addition, for sports that take place on turf surfaces, sliding movements can be a desirable action[6, 8]. Athletes who participate in sports such as American football, soccer, and field hockey benefit from playing surfaces that allow an element of sliding, or traction release. By allowing a sliding movement, the cleated athletic shoe is able to release the build-up of forces, thus minimizing potential loads the lower extremity structures would otherwise have to experience[8].

The need for high static traction to maximize acceleration, and low traction for injury reduction poses a unique problem. The elements necessary for maximum athletic performance ultimately present contradicting requirements and complicate the development of equipment and playing surfaces. The problem biomechanists encounter is devising a valid measurement technique which can be used to quantify traction coefficient ranges that maximize performance, yet limit risk of injury[12].

Industry Standards

An important issue involving turf interaction studies is the method of data collection[14]. Internationally recognized, the American Society of Testing and Material (ASTM) provides standards in material testing, which includes shoe-sports surface interfaces. In a statement published in 2004, the ASTM clearly stated that they do not "require a specific device or mechanism to be used" during shoe-turf interaction studies[1]. The ASTM standards do set guidelines for the use of the device collecting traction data. They provide standards for appropriate load conditions for both rotational and linear translational testing. The load conditions are based on field studies of athletes performing specific tasks. For example, the load conditions of tennis players cutting were gathered from actual athletes performing cutting maneuvers on a tennis court over a force plate. Not establishing set complete guidelines for testing devices poses a particularly difficult problem when attempting to compare traction data between research groups.

Translational Traction Studies

There are a number of research group who have collected data on traction characteristics of artificial turf[3, 14, 28]. Many of them study rotational forces affecting traction characteristics[5, 6, 14, 19, 20, 28]. Typically, they use manual torque wrenches during their collection[5, 6, 19, 28]. From a performance and research standpoint both rotational and translational forces occur during athletic performances. They are both of great significance in truly understanding the interactions between the shoe and turf. Canaway (1975) states that there are principal reasons why there is an obvious imbalance in the research conducted between rotational and translational forces interacting with the turf[5]. The first reason is that large linear forces are difficult to produce and required costly equipment. The second reason is that the use and reproduction of real rotational forces is much easier[5].

There are a few groups that have studied translational traction coefficients on artificial turf. In 1975, Bowers and Martin studied translational traction differences between three different styles of cleated athletic shoes on new and old Astroturf[3]. They also examined the difference in traction with and against the grain on wet and dry turf surfaces[3]. The cleated athletic shoes seemed to vary rather dramatically across the different conditions. When looking at the average across the dry conditions the traction coefficients range from 0.63 -2.25 (Table 2)[3]. The authors conclude that one particular cleated athletic shoe satisfied performance needs and reduced the risk of injury[3]. Almost two decades later, Heidt et al. investigated shoe-turf interactions on Astroturf as well[14]. They examined 15 different cleated athletic shoes from 3 different manufacturers[14]. The shoes varied between traditional cleats, turf shoes, court shoes, and molded-rubber cleats. The authors were interested in differences between Astroturf and natural grass fields, as well as dry and wet conditions[14]. They found the traditional cleats and the molded-rubber cleats, on dry Astroturf, had an average traction coefficient of 0.53±0.044 and 0.81±0.054, respectively (Table 2)[14]. The authors conclude that proper shoe selection for an athlete is paramount[14]. They go on to state that the proper athletic shoe worn has an effect on their level of safety[14]. They also recommend that shoe manufactures indicate the conditions in which a particular shoe was designed to be used in[14].

In 2003, Shorten, Hudson, and Himmelsbach studied the traction needs of high school football players while comparing differences between natural turf, synthetic turf, and in-filled synthetic turf surfaces[28]. They used 6 different shoes during testing[28].

Translational traction coefficient values ranged 0.54 – 1.45 (Table 2)[28]. These values were found to be statistically significant. The authors discuss the difficulty in quantifying acceptable traction ranges. They point out the numerous factors influencing this interaction, which reveals the true complexity of the problem[28].

Table 2. Previous Studies Investigating Traction Coefficients Between Cleated Athletic Shoes and Artificial Turf

Author	Year	Number of Shoes	Types of Turf	Vertical Compressive Load	Traction Coefficient Range
Bowers, et al.	1975	3	Astroturf	444.8 N	0.63 - 2.25
Heidt, et al.	1996	15	Astroturf	111.2 N	0.53 - 0.81
Shorten, et al.	2003	6	Astroturf, AstroPlay, Fieldturf	529 N	0.54 - 1.45

Implications for Injury

As increases in athletic participation occur a concurrent rise in injuries takes place, and so too an increase in the need for injury prevention[6, 9, 11, 21, 22, 27]. There are both intrinsic and extrinsic factors that contribute to an athlete's susceptibility to injury. The intrinsic factors could be musculoskeletal or physiological. Extrinsic factors include the athlete's environment such as equipment and playing surface[6]. Cawley et al. (2003) stated that the two most important factors influencing an athlete's safety are the type of athletic shoe worn and the playing surface in which the sport is being played[6]. "The most common factor associated with accidental injuries on artificial playing surfaces is the level of friction between the sports shoe and the playing surface"[8]. This increased level of friction is attributed to foot fixation or footlock, which is known to cause anterior cruciate ligament (ACL) injuries[18]. With the foot fixed, any forces applied to an abnormal joint motion exceeding the elastic capabilities of that structure will result in an injury[21].

Summary

All of the previous research may be summarized as follows:

- Understanding shoe design parameters can help researchers approach the problem of shoe-turf interaction with a greater perception of the problems.
- There are many parameters surrounding artificial turf testing. Understanding the factors that affect performance and injury risk can provide the most ideal environment for the athletes playing on the surface.
- When studying shoe-turf interactions the classical laws of friction don’t always apply. Traction helps to characterize the inconsistencies that traditional ideas of friction may present.
- ASTM is internationally recognized for their contributions to materials testing standards. Though there is an established framework for shoe-surface interaction testing, addition guidelines need to be put in place for easier comparison between research groups.
- Athletes risk accidental injuries at both “impact” of the foot making contact with the ground, and during foot fixation.
- The process of quantifying traction coefficients ranges is a complex problem. Thus research needs to be done investigating shoe-turf interaction from various perspectives and testing conditions.

CHAPTER 3

METHODS AND PROCEDURES

Purpose

The purpose of this study was to investigate whether traction characteristics vary based on a particular cleated athletic shoe style on artificial turf at various angles of internal rotation during a simulated deceleration motion.

Cleated Athletic Shoes

Four cleated athletic shoes were utilized for the purpose of this study. Specifically, the *Reebok 4 NFL Speed III Low* with detachable studs, the *Nike Super Speed D3/4* with detachable studs, the *Nike Air Zoom Super Bad* with molded studs, and the *Adidas Scorch 7 Fly Low* with molded studs. All athletic shoes used were US men's size 12. The cleated athletic shoes selected generally spanned the spectrum of cleated athletic shoe styles used by "skills" position players in youth, collegiate, and professional American football. "Skills" position players are widely known in American football as the individuals that receive the ball once the ball is snapped at the line of scrimmage. These individuals are responsible for advancing the ball from the line of scrimmage.

Reebok 4 NFL Speed III Low

The 4 NFL Speed III Low features a synthetic leather upper and a molded TPU plate. The 4 NFL Speed III Low has a seven-cleat detachable pattern with additional molded studs (Figure 3).

Figure 3. Reebok 4 NFL Speed III Low

Nike Super Speed D3/4

The Super Speed features a synthetic leather upper with a TPU and Pebax® seven-stud detachable cleat pattern (Figure 4).

Figure 4. Nike Super Speed D3/4

Nike Air Zoom Super Bad

The Super Bad features a synthetic leather upper, Zoom Air™, and molded TPU/Pebax® cleats with new high abrasion TPU tips. The Super Bad has a molded five-cleat forefoot with a hind foot blade traction pattern (Figure 5).

Figure 5. Nike Air Zoom Super Bad

Adidas Scorch 7 Fly Low

The Scorch features a synthetic leather upper with a molded EVA insole and a TPU plate outsole. The Scorch has a molded 13-cleat pattern with 9 cleats on the forefoot (Figure 6).

Figure 6. Adidas Scorch 7 Fly Low

The surface area of each cleated athletic shoe was calculated. The diameter of each stud was measured using Mitutoyo® calipers. The area of the stud was calculated using the following equation:

Equation 2. Calculation of the Area of the Cleated Athletic Shoe Stud

$$A = \pi r^2$$

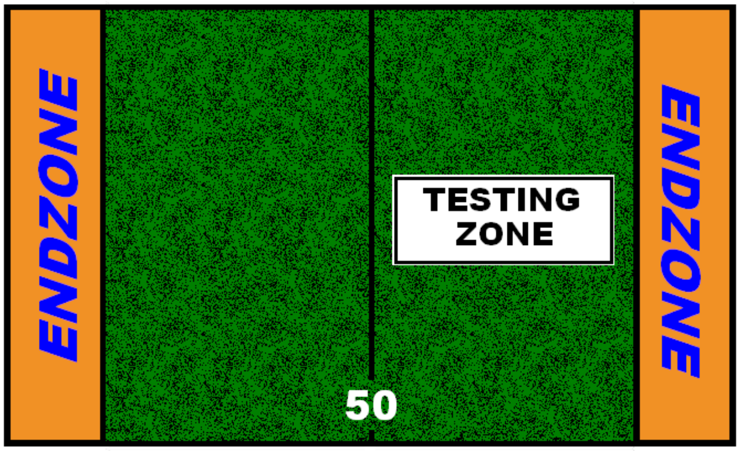
A = Area of a circle
r = Radius of a circle

Only the bottom surface area of the stud was calculated. It is assumed that the bottoms of the studs are the only parts of the shoe engaged with the turf surface throughout the entire test trial.

Artificial Turf

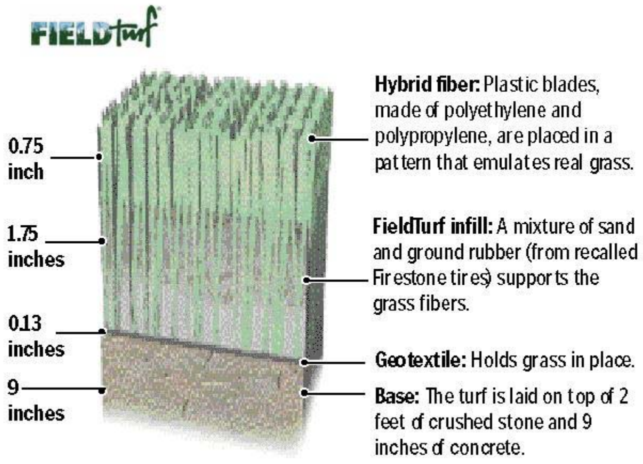
FieldTurf (FieldTurf™ Tarkett, Peachtree City, GA) brand synthetic turf was used as the testing surface in this study. The testing zone on the turf surface took place between the 50-yardline and end zone, and roughly equidistant from either sideline on the playing surface of an American football field (Figure 7).

Figure 7. Location of the Testing Zone on the Playing Surface of an American Football Field



FieldTurf® synthetic turf combines a washed silica sand and cryogenic rubber infill with polyethylene and polyproylene fiber blades (Figure 8). The hybrid fiber blades are approximately 2.5 inches in length. The FieldTurf infill mixture fills 1.75 inches of the total length of the hybrid fiber blades. The geotextile acts an anchoring device for the hybrid fiber blades, and is 0.13 inches thick. Finally, the base is comprised of a 9 inch layer of crushed stone and concrete.

Figure 8. FieldTurf System



Hybrid fiber: Plastic blades, made of polyethylene and polypropylene, are placed in a pattern that emulates real grass.

FieldTurf infill: A mixture of sand and ground rubber (from recalled Firestone tires) supports the grass fibers.

Geotextile: Holds grass in place.

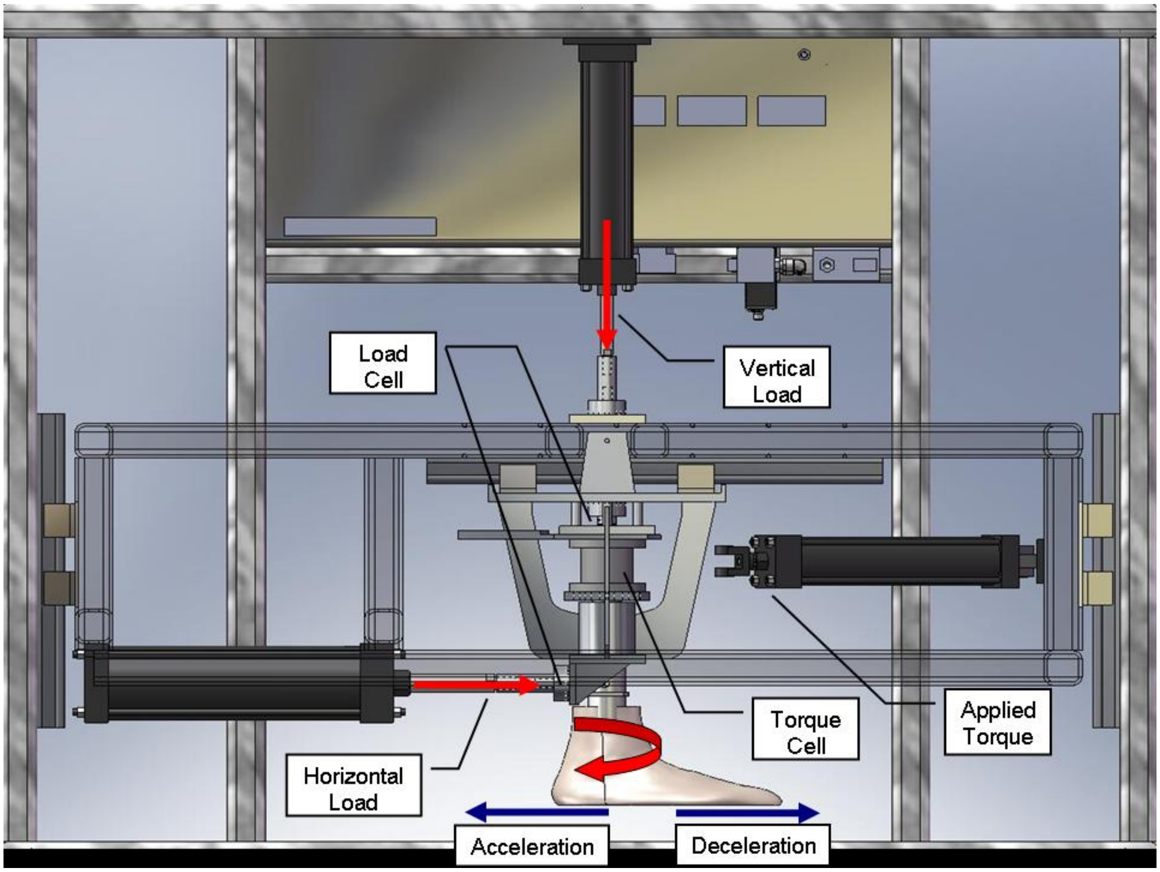
Base: The turf is laid on top of 2 feet of crushed stone and 9 inches of concrete.

Source: FieldTurf

Instruments and Apparatus

This study utilized a computerized and pneumatic device that simulates the motion of a foot decelerating across the surface of a specified area of artificial turf. The motion of the foot is repeatable and restricted to a defined path. This unique device, the Boise State TurfBuster, was design and developed at the Intermountain Orthopaedics Sports Medicine & Biomechanics Research Laboratory at Boise State University in Boise, Idaho (Figure 9).

Figure 9. Functioning Diagram of the Boise State TurfBuster



The vertical load was applied via a pneumatic cylinder capable of producing up to 3500 N of force. This force is synonymous to the reaction force seen between an athlete's shoe and the playing surface. A load cell mounted directly to the ankle shaft measures the actual load that was applied by the vertical actuator. To create translational motion for the deceleration test, the entire shoe and ankle shaft assembly is mounted to a cradle which moves horizontally through low friction bearings. The motion was controlled using a pneumatic actuator connected to the ankle shaft just above the ankle joint. The ankle shaft and cradle is supported in such a way so that the horizontal actuator does not apply any form of moment to the shoe. The horizontal actuator is capable of applying up to 8900 N of horizontal load to the shoe. The actuator is capable of a velocity up to 1 m/s depending on the vertical load condition over a distance of 30 cm of translation. Linear speed and motion is measured by a linear transducer attached to the actuator. The degree of internal rotation was set using a pin system located in the inner frame of the device. All angles set were checked using a manual goniometer instrument.

To acquire meaningful results, each of the three load cells mounted to the Boise State TurfBuster had to be calibrated against a known standard. This standard is the Kistler force platform located in the Intermountain Orthopaedics Sports Medicine & Biomechanics Research Laboratory at Boise State University. By calibrating the load cells to the ground reaction force readings from the force platform, most of the force caused by friction in the bearings is negated. The final calibration of the horizontal and torque load cells was done at the same vertical load that was used during in-field testing to insure that the calibration was accurate.

Temperature and humidity of the turf's surface was collected using a hand-held thermometer and hygrometer.

All data was collected at 250 Hz using a National Instruments DAQPad card and LabVIEW software. The sample rate was set based on previous data collected at Boise State University which resulted in ample signal resolution for the variables of interest[17].

Dependent Variables

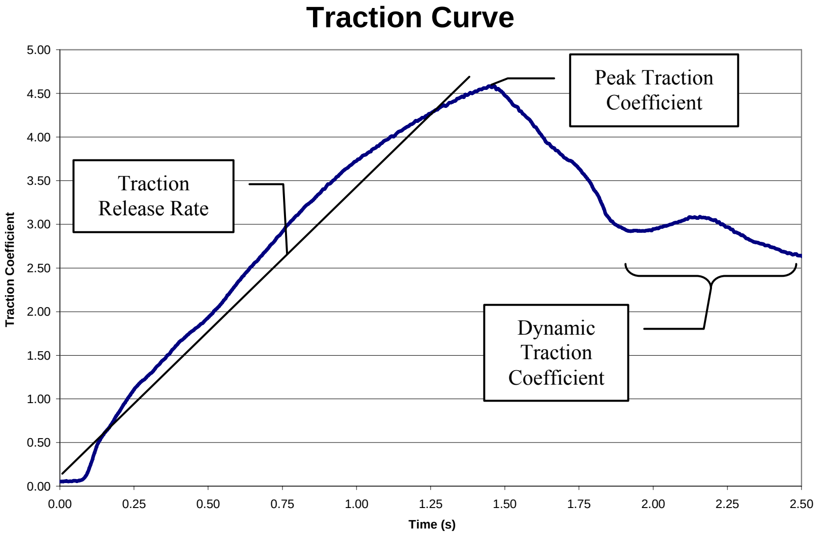
The following four pieces of data were collected for each shoe on the turf surface:

1. Traction Release Rate – The slope of the traction coefficient vs. time curve between the point where the traction coefficient first exceeds zero and the instant

at which the peak traction coefficient occurs. This represents the rate of increase of the traction coefficient to the peak value (Figure 10).

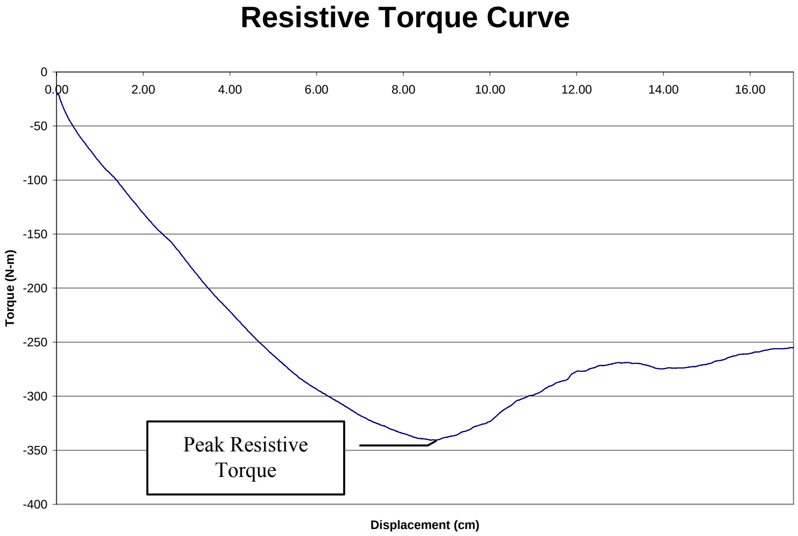
2. Peak Traction Coefficient– The peak value of the ratio of horizontal to vertical forces throughout the translation of the shoe. The horizontal force is somewhat a reaction to the amount of resistance experienced during translation. Ultimately, this value represents the greatest traction coefficient experienced during the shoe's translation (Figure 10).
3. Dynamic Traction Coefficient– The mean value of the ratio of horizontal to vertical force after the peak (the final 2 cm of the trial were used to calculate the coefficient). This represents the traction coefficient between the turf and shoe when the shoe is moving relative to the turf (Figure 10).

Figure 10. Traction Curve



4. Peak Resistive Torque – The peak value of torque resisted by the ankle. This represents the shoe's tendency to rotate internally or externally during translation, even though the shoe is only being driven forward (Figure 11).

Figure 11. Resistive Torque Curve



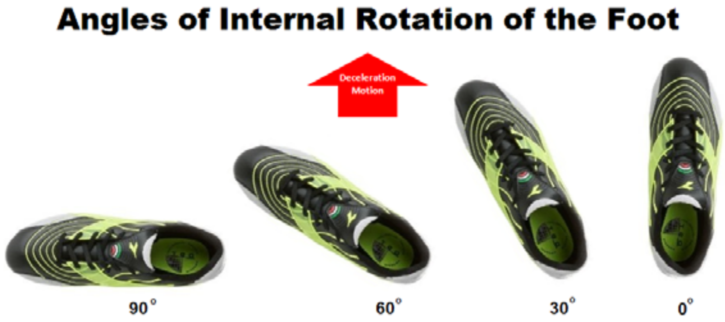
Procedures

Data collection took place on one day at the Caven-Williams Sports Complex at Boise State University in Boise, Idaho. Prior to testing information was gathered about the installation process, maintenance, and current conditions of the synthetic turf (Appendix A).

The dependent variables were collected for each of the cleated athletic shoes on the turf surface. Each shoe underwent the following:

- 5 trials of deceleration at each test angle of internal rotation. The deceleration was be used to simulate a "braking" or "hard stopping" situation. In this condition the shoe was vertically loaded with 900 N and pushed at the heel through the turf with no ankle rotation. The shoe was oriented at the appropriate testing angle relative to the ground for a flat-footed position, so all cleats were engaged with the turf. The shoe experienced 20 cm of translation at a rate of 10 cm/second.
- This test was repeated for each of the desired angles of internal rotation (0°, 30°, 60°, and 90°) (Figure 12).

Figure 12. Angles of Internal Rotation of the Foot



After each trial the device was lifted and moved approximately two feet within the testing zone to ensure an undisturbed portion of the artificial turf was tested on. The device was also secured to an immovable object to prevent any relative movement between the turf surface and the device. To ensure this, a chain was attached to the device and secured to the wall of the facility. Any slack in the chain was removed with a winch system which created constant tension in the line.

Data Analysis

Microsoft® Office Excel 2003 was used to process all of the data. The data was analyzed to determine differences among the cleated athletic shoe styles and various angles of internal rotation of the shoes on the artificial turf. Each of the variables were averaged over all 5 trials of each of the test conditions.

Experimental Design

This study utilized a repeated measures design. The independent variables are the cleated athletic shoes and angles of internal rotation. The dependent variables are traction release rate, peak traction coefficient, dynamic traction coefficient, and peak resistive torque.

Statistical Analysis

SPSS Version 17.0 for Windows was used to process all the statistics. Repeated measures univariate analysis of variances (ANOVAs) was used to compare the means of the dependents variable between each angle of internal rotation across the shoes and within each individual shoe. A Holm's Sequential Selective Bonferroni Method post-hoc was performed on significant values.

CHAPTER 4

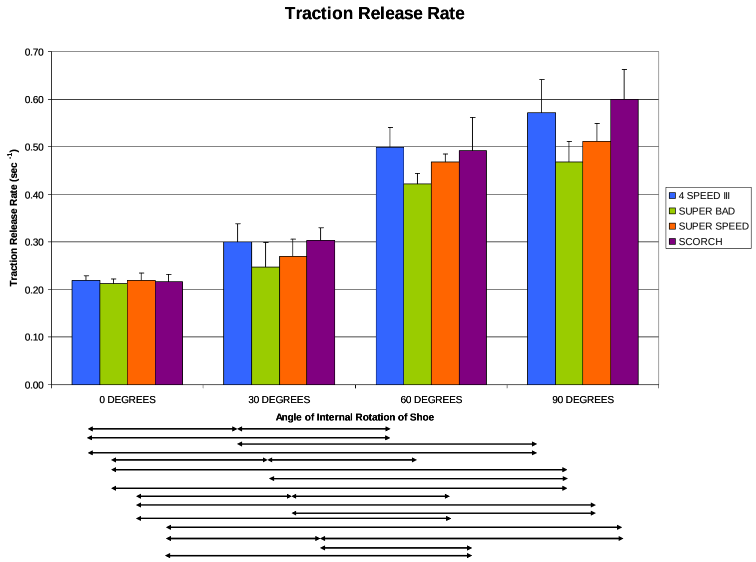
RESULTS

The largest mean traction release rate value (mean±SD) was 0.60±0.06 $\sec^{-1}$ at 90º of internal rotation (IR) for the Scorch shoe. The lowest mean traction release rate value was 0.21±0.01 $\sec^{-1}$ at 0º of IR for the Super Bad shoe (Figure 13) (Appendix C). The largest mean peak traction coefficient was 5.28±0.53 at 60º of IR for the Scorch shoe. The lowest mean peak traction coefficient was 1.74±0.17 at 0º of IR for the Super Speed shoe (Figure 14) (Appendix C). The largest mean dynamic traction coefficient was 4.34±1.56 at 60º of IR for the Scorch shoe. The largest mean dynamic traction coefficient was 1.05±0.08 at 0º of IR for the Super Speed shoe (Figure 15) (Appendix C). The largest mean peak resistive torque value was -373.75±15.80 N-m at 60º of IR for the Scorch shoe. The minimum mean peak resistive torque value was -4.08±0.59 N-m at 0º of IR for the Scorch shoe (Figure 16) (Appendix C). Appendix B can be referenced for a complete table of results.

A repeated measures univariate analysis of variance (ANOVA) revealed there were significant differences within all cleated athletic shoes across the angles of IR (p=0.00) (Appendix D).

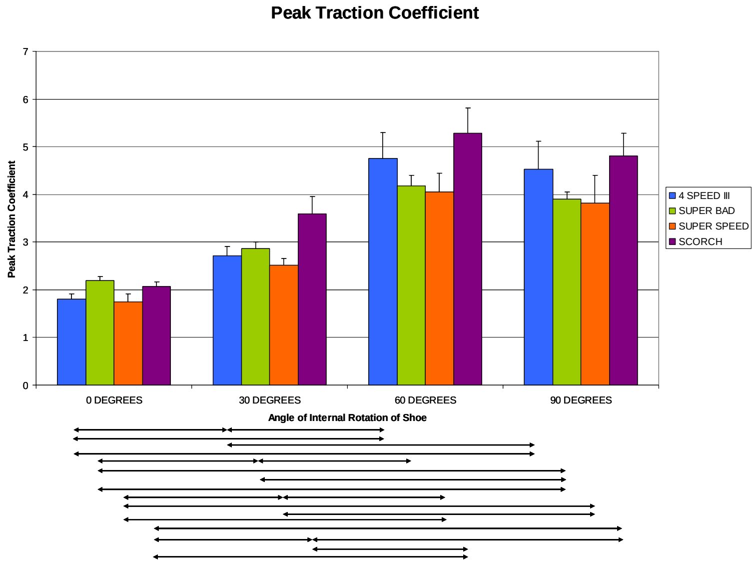
Pair-wise comparisons of traction release rates between angles of IR within cleated athletic shoes determined that there were significantly differences (Figure 13) (Appendix E).

Figure 13. Comparisons of Traction Release Rates between Angles of Internal Rotation within Cleated Athletic Shoes



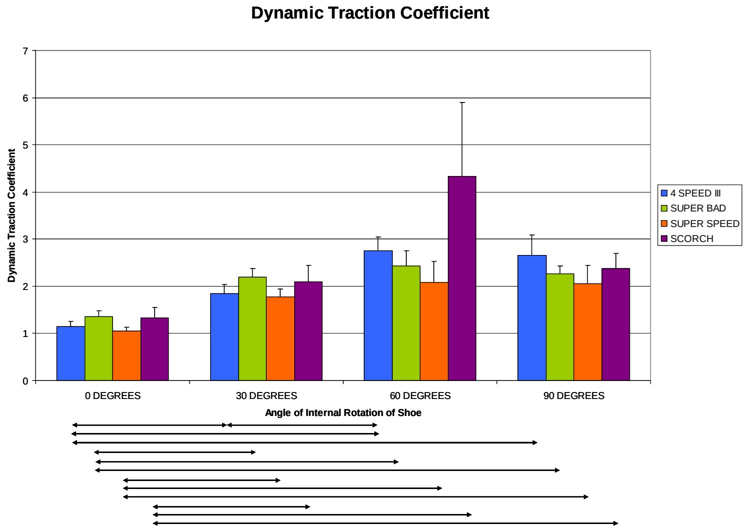
Pair-wise comparisons of peak traction coefficients between angles of IR within cleated athletic shoes determined that there were significant differences (Figure 14) (Appendix E).

Figure 14. Comparisons of Peak Traction Coefficients between Angles of Internal Rotation within Cleated Athletic Shoes



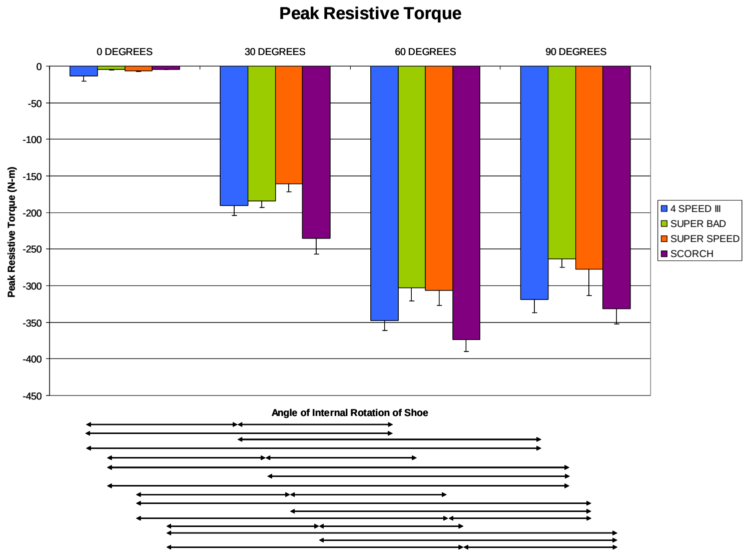
Pair-wise comparisons of dynamic traction coefficients between angles of IR within cleated athletic shoes determined that there were significant differences (Figure 15) (Appendix E).

Figure 15. Comparisons of Dynamic Traction Coefficients between Angles of Internal Rotation within Cleated Athletic Shoes



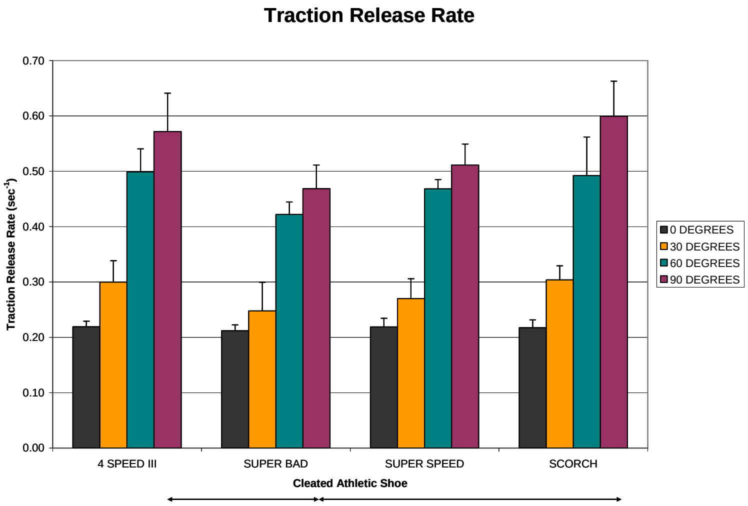
Pair-wise comparisons of peak resistive torques between angles of IR within cleated athletic shoes determined that were significant differences (Figure 16) (Appendix E).

Figure 16. Comparisons of Peak Resistive Torques between Angles of Internal Rotation within Cleated Athletic Shoes



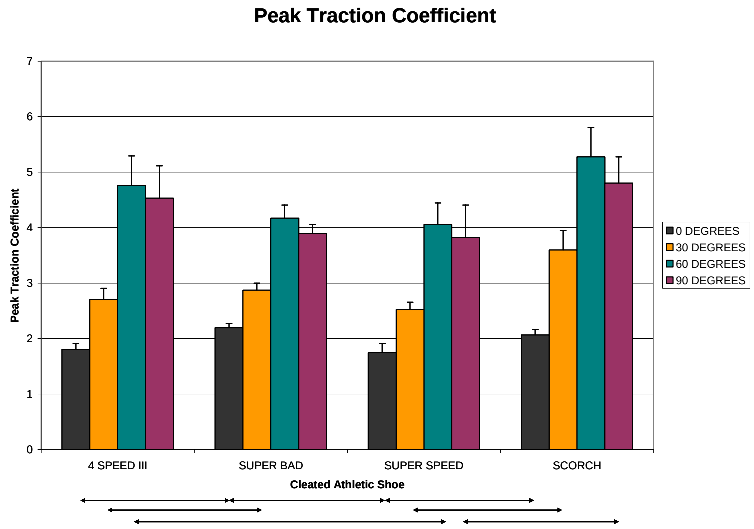
A repeated measures univariate ANOVA revealed that the traction release rates at 90º (p=0.002) of IR were significantly different among cleated athletic shoes (Appendix C). Post-hoc pair-wise comparisons of traction release rates within the angle of IR between the cleated athletic shoes determined no significance (Figure 17) (Appendix F).

Figure 17. Comparisons of Traction Release Rates between Cleated Athletics Shoes across Various Angles of Internal Rotation



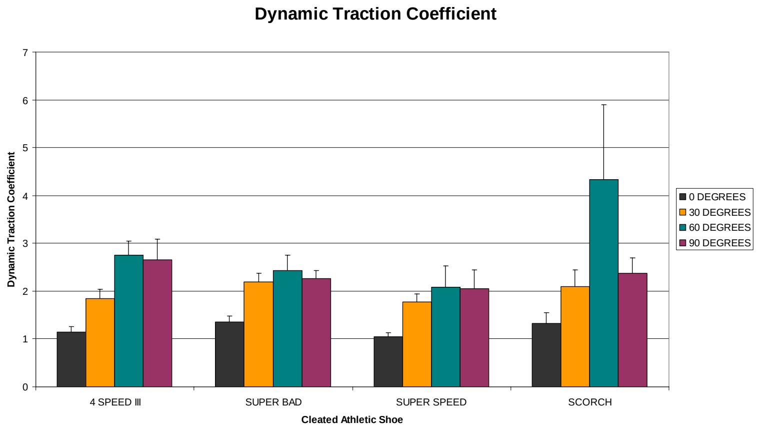
A repeated measures univariate ANOVA revealed that the peak traction coefficients at angles 0º (p=0.000), 30º (p=0.000), 60º (p=0.003), and 90º (p=0.003) of IR between cleated athletic shoes were significant (Appendix C). Pair-wise comparisons of peak traction coefficients within angles of IR determined that Super Speed differed from Scorch at 0º, 30º, and 90º, that 4 Speed III and Super Bad were significantly different at 0º and 30º, that Super Bad differed from Super Speed at 0º, and that 4 Speed III was significantly different than Super Speed at 60º (Figure 18) (Appendix F).

Figure 18. Comparisons of Peak Traction Coefficients between Cleated Athletics Shoes across Various Angles of Internal Rotation



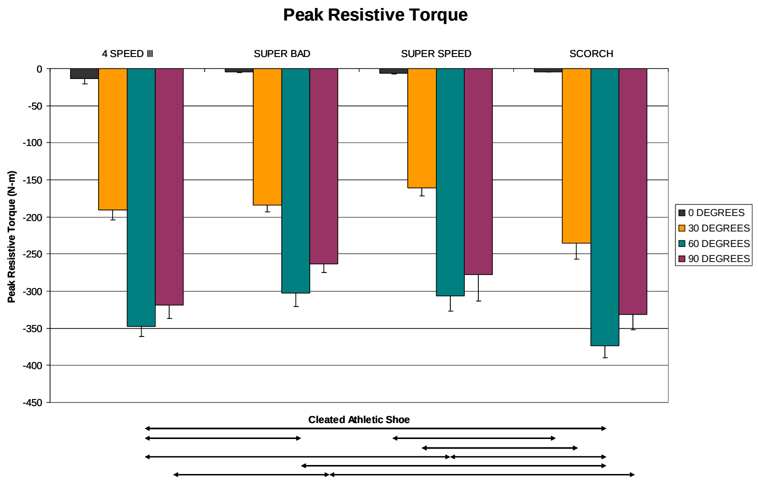
A repeated measures univariate ANOVA revealed that the dynamic traction coefficients at angles 0º (p=0.013) and 60º (p=0.006) of IR between cleated athletic shoes were significantly different (Appendix C). Pair-wise comparisons of dynamic traction coefficients within angles of IR between the cleated athletic shoes were not significant (Figure 19) (Appendix F.)

Figure 19. Comparisons of Dynamic Traction Coefficients between Cleated Athletic Shoes across Various Angles of Internal Rotation



A repeated measures univariate ANOVA revealed that the peak resistive torques at angles 0º (p=0.008), 30º (p=0.000), 60º (p=0.000), and 90º (p=0.000) of IR were significantly different among cleated athletic shoes (Appendix C). Pair-wise comparisons of peak resistive torques within angles of IR identified similar differences between Super Speed and Scorch at 0º, 30º, and 60º, between 4 Speed III and Super Bad at 60º and 90º, between Super Bad and Scorch at 60º and 90º, between 4 Speed III and Super Speed at 60º, and between 4 Speed III and Scorch at 60º (Figure 20) (Appendix F).

Figure 20. Comparisons of Peak Resistive Torques between Cleated Athletic Shoes across Various Angles of Internal Rotation



Compliance of Hypothesis

The hypothesis that a variety of cleated athletic shoe styles at various angles of internal rotation would not exhibit different traction characteristics was accepted. The second hypothesis that there would no difference in traction characteristics within cleated athletic shoes at the various angles of internal rotation was rejected.

Results Summary

All of the study’s results can be summarized as follows:

- There was very little inter-trial variability within a particular test condition.
- All ANOVAs between angles of internal rotation within a cleated athletic shoe, for all dependent variables, were found to be significant (p=0.000).

- A considerable number of pair-wise comparisons between angles of internal rotation within a cleated athletic shoe, for the dependent variables, were found to be significant.
- Most of the ANOVAs between cleated athletic shoes across various angles of internal rotation, for the dependent variables, were found to be significant ($p \leq 0.05$)
- Pair-wise comparisons between cleated athletic shoes across various angles of internal rotation, for the dependent variables, revealed few significant differences.
- Pair-wise comparisons between cleated athletic shoes across various angles of internal rotation during dynamic traction were not significant.
- The research hypothesis that a variety of cleated athletic shoe styles at various angles of internal rotations would not exhibit different traction characteristics was accepted.
- The research hypothesis that there would no difference in traction characteristics within cleated athletic shoes at the various angles of internal rotation was rejected.

CHAPTER 5

DISCUSSION

Limitations of the Testing Protocol

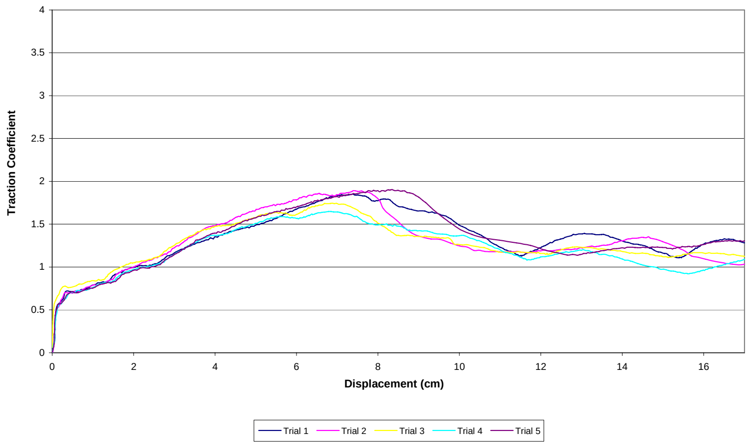
This study relied on a pneumatic and computerized traction testing device for all the data collection. This provided a very reliable system of data collection. The limitations of the device include the assumption the shoe/footform was a rigid body, the relative location of the vertical load cell, the calibration method of the device and the observed movement of the entire device at the initiation of the testing trial. After further inspection of the cleated athletic shoe post-testing, there were no visible changes to the shape, firmness, or integrity of the shoe or concrete-epoxy in-fill, thus maintaining the assumption the cleated athletic shoe was a rigid body.

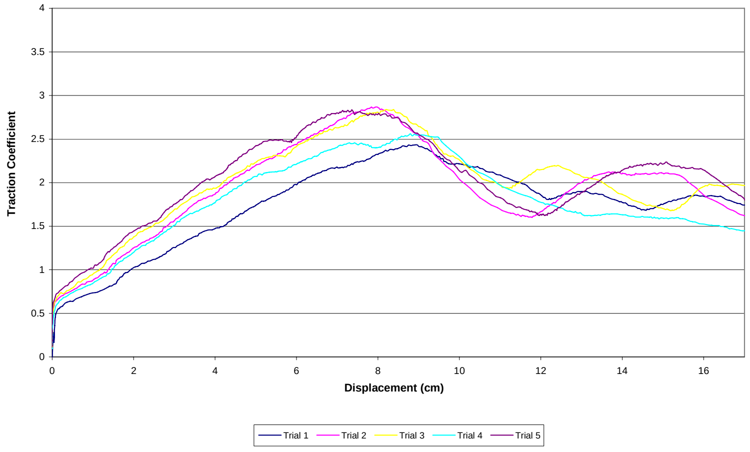
The precision of the vertical, horizontal and torque loads being applied were checked pre- and post-testing using a Kistler force platform during the calibration process. Outputs from the device fell within 1.5% of the force platform output. Since the device does not have an internal calibration system, all calibrations needed to be conducted in the laboratory prior to testing. When the calibration was conducted, all the load cells (vertical, horizontal, and torque) fell within the predetermined 1.5% range when compared between pre- and post-testing. Finally, as the cleated athletic shoes were engaged with the artificial turf and the trial commenced, there was some relative movement of the entire device in the opposing direction of the shoe. Essentially the horizontal force being applied became greater than the frictional force between the device and the turf. Measures were taken to prevent the translational motion of the device by securing it to an immovable object, and thus preventing most of the undesired movement.

Reliability of the Methods & Test Device

The traction curve trials within a particular cleated athletic shoe and across angles of internal rotation were consistent. This reinforces the reliability of the testing methods and of the results. Figure 21 shows two plots that are representative of the traction curves seen throughout the results. The traction curves tend to be very consistent and vary in amplitude as a function of the angle of internal rotation of the shoe.

Figure 21. Representative Traction Curves

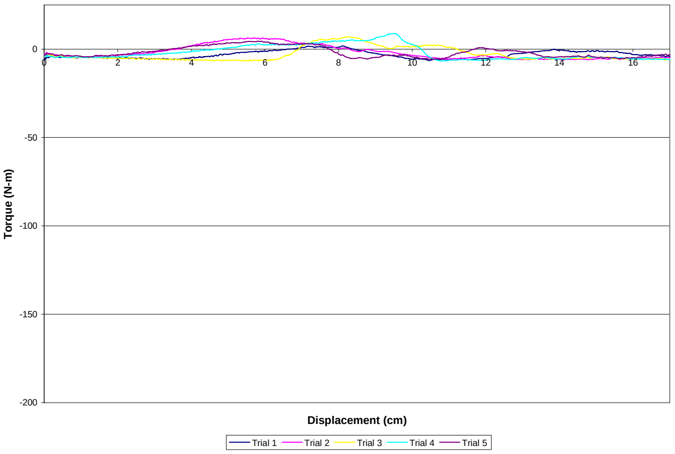

Traction Curve - 4 Speed III 0 degrees


Traction Curve - 4 Speed III 30 degrees

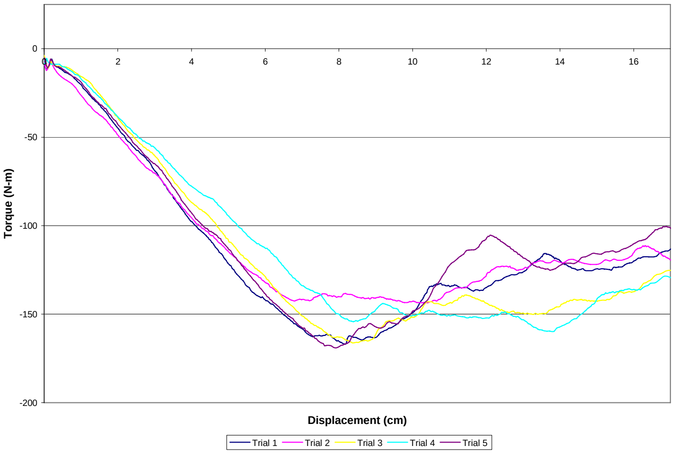
Similarly, the resistive torque curves were consistent throughout the results, and vary based on the angle of the shoe relative to the direction of the force being applied (Figure 22).

Figure 22. Representative Resistive Torque Curves

Resistive Torque - Super Speed 0 degrees



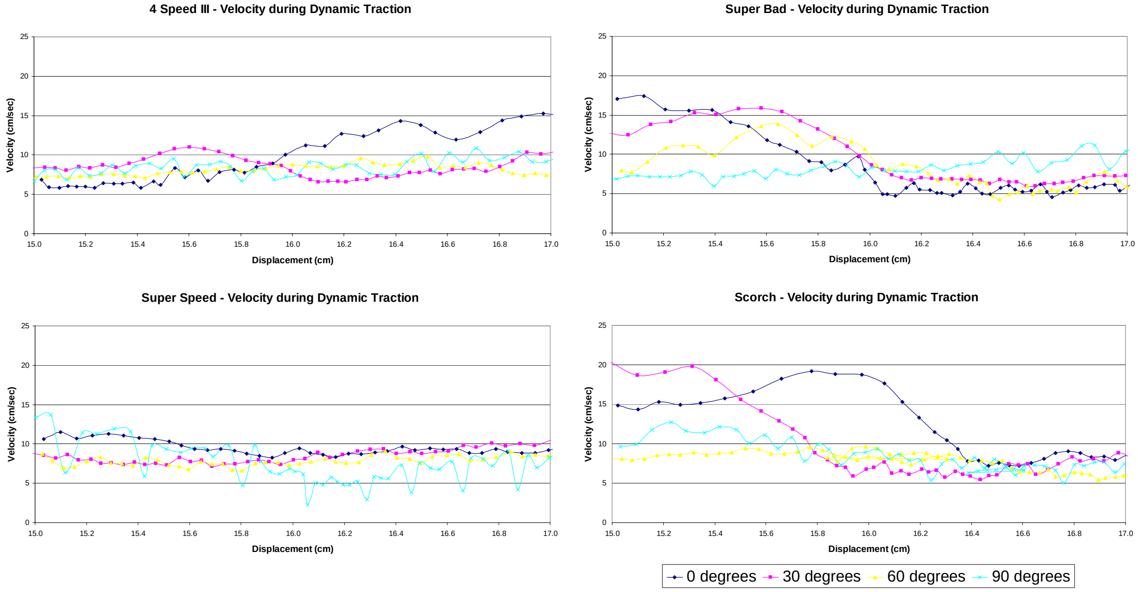
Resistive Torque - Super Speed 30 degrees



An interesting observation was made across all the cleated athletic shoes at 0º. The torque amplitudes for all the shoes at 0º were low, but oscillated around zero, meaning the shoe had a tendency to both rotate internally and externally at different instances throughout the trial.. Essentially, this means that the shoe's behavior is somewhat unpredictable during linear translation at 0º. This tendency for randomness maybe attributed to the stud pattern on the shoe, the material of the shoe and studs, the material and lay of the artificial turf, as well as minute movements in the device mounting.

Since the traction coefficient may be dependent on the testing velocity, consistency of the velocities is critical when interpreting dynamic traction. Therefore, velocities during dynamic traction were evaluated. Although test velocities do vary somewhat from the expected 10 cm/s, they were fairly consistent, especially within a particular shoe and across the various angles of internal rotation. In fact, there were no significant differences between velocities within a cleated athletic shoe (p=0.396) or across the various angles (p=0.108) (Figure 23) during the two seconds during which the dynamic traction was recorded.

Figure 23. Velocity of the Cleated Athletic Shoes During Dynamic Traction


4 Speed III - Velocity during Dynamic Traction

Super Bad - Velocity during Dynamic Traction

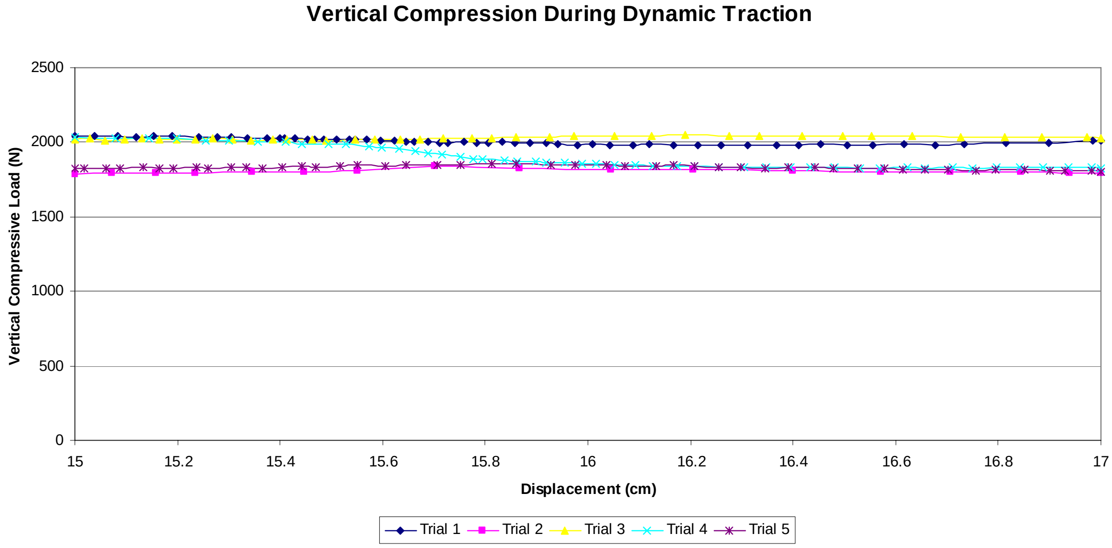
Super Speed - Velocity during Dynamic Traction

Scorch - Velocity during Dynamic Traction

Another important factor to consider when interpreting dynamic traction is the compressive loads during that period. The vertical compressive loads should be rather consistent since the traction coefficient is known to vary with compressive load. Figure

24 is representative of the actual vertical compressive loads observed during the two seconds of the trial during which dynamic traction coefficient was computed. The vertical compressive loads varied only 4.2±3.5% during this period.

Figure 24. Variation in Vertical Compressive Load During Dynamic Traction



Observations of Results

An unpublished study by Kuhlman et al. revealed interesting findings when compared to the current study[17]. The same cleated athletic shoes, artificial turf, and device were used for both studies. The vertical compressive load differed by 12 N. Kuhlman et al. observed peak traction coefficients in the range of 2.18 – 3.20±0.45, and the current study observed peak traction coefficients in the range of 1.74 – 2.19±0.21 (Table 3).

Table 3. Comparison Between Similar Traction Studies

Study	Year	Number of Shoes	Type of Turf	Angle of Internal Rotation	Vertical Compressive Load	Peak Traction Coefficient Range
Kuhlman, S. et al. (unpublished)	2009	4	FieldTurf	0º	888 N	2.18 -3.20 ± 0.45
Current Study	2009	4			900 N	1.74 - 2.19 ± 0.21

The calibration of the device was within acceptable ranges pre- and post-testing for both sessions. Therefore the differences in observed traction coefficients can only be attributed to differences in the artificial turf itself. Through visual inspection of the field, differences in the in-fill level were obvious. In some areas of the field the in-fill mix was visible, and in others it wasn't. Theses inconsistencies in the volume of in-fill in a given area might explain the differences in observed peak traction coefficients between the two studies. This reinforces the fact that it is of the utmost importance that maintenance and grooming take place on the artificial turf on a regular basis. Proper maintenance and grooming with help aid in the consistency of the artificial turf's behavior.

Although there have been several studies investigating translational traction characteristics in the past, this is the first to investigate traction characteristics at various angles of internal rotation. When observing the plots of the traction characteristics (peak traction coefficients, dynamic traction coefficients, and peak resistive torques) a pattern emerges across them. All the values increased from 0º – 60º and then decreased from 60º – 90º. Statistically, there was no difference found from 60º – 90º on any traction characteristics across the cleated athlete shoes, except Super Speed and Scorch at peak resistive torque (Appendix E).

Another important result is the comparisons between shoes. Based on the results, there is very little difference between the cleated athletic shoes' behavior. The traction release rates, or the slope of the line from the initiation of movement to peak traction, were not significantly different. There were only two comparisons (4 Speed III – Super Bad and Super Bad– Scorch) that yielded significant results. This means that the four cleated athletic shoes "load" at a similar rates. None of the dynamic traction coefficients were significantly different. It can therefore be inferred that the all four cleated athletic shoes have similar steady state actions after they are in relative motion at a constant speed. This is an interesting finding, because it suggests that the athlete's choice of footwear is not particularly important in terms of the load he or she will experience when stopping or cutting.

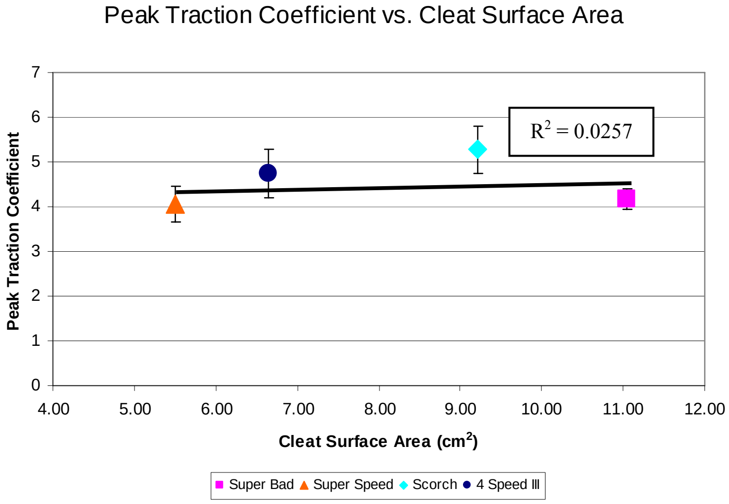
Cleat Surface Area and the "Trench Effect"

To determine whether traction was related to the cleat surface area, analysis of the bottom surface area of the studs was performed on the cleated athletic shoes. The bottom surface area of each stud was calculated and summed to compute the cleat bottom surface area for each shoe. This was representative of total surface area of the cleats. We then compared peak traction coefficients of each shoe to the representative surface area of each shoe and found that there was no linear relationship between the two factors (Table 4) (Figure 25). Therefore, traction coefficients are not simply related to the amount of cleat surface area.

Table 4. Cleat Specifications

Cleat Specifications				
Shoe Name	# of Cleats: Front	Rear	Total	Stud Area (cm^2)
4 Speed III	5	2	7	6.65
Super Bad	5	4	9	11.05
Super Speed	5	2	7	5.50
Scorch	9	4	13	9.22

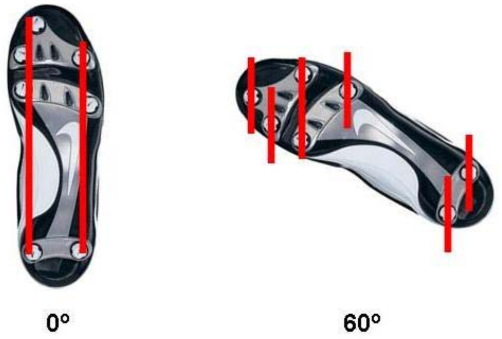
Figure 25. Peak Traction Coefficient vs. Cleat Surface Area



Only the bottoms of the studs were factored in the calculation of the surface area. The volume, shape, and material were not considered, and need to be for this analysis to have more validity. Certainly these findings in themselves are interesting because previous literature has stated that the number of cleats do affect the level of traction[29]. Additionally, more research needs to be conducted in the area of cleat orientation and patterns. These elements may be greater determinants of shoe behavior than simply the number of cleats.

If traction coefficients were solely based on cleat surface area, there would be no reason for peak traction coefficients to increase with increases in the angle of internal rotation. However, our results consistently demonstrated increasing traction coefficients up to 60º of internal rotation. One explanation for this could be related to the number of the cleats exposed to the turf material in the direction of the applied force. A “trench effect” occurs when the studs from the shoe dig into the turf surface and create small canals in the material. As other studs pass through the previous studs’ path in the turf material there is less resistance, thus making multiple studs along the same path less effective. Changes in internal rotation angle for a particular shoe will affect the number of cleats that are aligned in columns along the direction of motion (Figure 26).

Figure 26. Trench Effect



In the example above, we see that as the shoe rotates from 0º – 60º, more studs are exposed and open to create unique paths in the turf material. This should increase the resistance, and ultimately the horizontal force necessary for linear translation.

Athlete-Shoe-Turf Interactions

From an applied standpoint, shoe-turf interaction studies are not sufficient. In essence, pure shoe-turf interactions studies are essentially mechanical/material engineering problems[8]. Conclusions cannot be directly made that the forces seen at the shoe-turf interface are the same forces being transferred through the athlete's entire musculoskeletal system. In real life, there are a myriad of factors affecting the outcome and transfer of forces, for example kinematic considerations. Van Gheluwe and Deporte speculated, in a study examining shoe-surface interactions on tennis surfaces, that kinematics may play a role in the outcome of frictional forces[30]. The authors suggest that athletes may react to the varying surface conditions by performing "alternative kinematic sequence(s)" [30]. The lack of kinematic considerations exposes a weakness in current laboratory traction testing[8, 23]. Kinematic considerations, in this study were limited to just two-planes (saggital and frontal). Movements in these planes were constrained, and interaction between the two was limited.

Inter-Study Comparisons

ASTM provides a starting point for those interested in researching shoe-surface interaction, but additional guidelines for testing need to be established. Comparisons between research groups are nearly impossible without greater device specifications. In a review published by Bell et al., they stated that "due to the nature of the experiments and in particular the use of different equipment to measure friction, the results cannot always be compared or easily reproduced"[2]. Even comparisons between similar test conditions become difficult because of the variations in vertical compressive loads[3, 14, 28], size of cleated athletic shoes tested[3, 14, 28], and acceleration rate of the shoe[28]. The ASTM does provide guidelines for vertical compressive loads and acceleration rates, but at the time of this study we were unaware of many studies within the current guidelines.

Evaluating Shoe-Turf Interaction

As stated by Shorten, traction testing is a stochastic process[28]. There are seemingly countless factors affecting the traction coefficients observed between the shoe and turf interface. There are numerous variables to account for and try and control. The turf surface alone has many different variables. The surface geometry, thermal stability, stiffness, material fatigue, material strength, and environmental resistance all have an effect on the behavior of that surface[4]. These are just a few of the parameters to consider when studying artificial turf[4]. The shoe contributes a great deal of variability as well. The number of cleats, the material of the shoe and cleat, the shape of the shoe and cleat, the pattern of the cleat, and size of the shoe all play important roles in its behavior[12]. Once again, these are just a fraction of the factors that may affect the behavior of the cleated athletic shoe. The final element necessary to apply the information to athletic performance is the athlete. This narrows the scope of application even more. The athlete's anthropometric measurements, kinematics, and skill level all play significant roles in considering appropriate traction coefficient ranges[2, 8, 14, 21, 23, 28]. When conducting tests the shoe, turf, and athlete need to be considered in order to make it applicable to sports performance. Even then, the scope becomes extremely narrow, and recommendations can only be applicable to that specific population under the exact same test conditions.

The shoe-turf interaction is not simple. Even greater complexity is shoe-turf-athlete interaction. These interactions cannot be trivialized, but this is not to say the information gathered from such studies is not useful. Information gathered needs to be approached with the mind set that it is a piece of the puzzle.

Conclusion

The athlete's performance and safety are the two most important factors in sport. Maintaining the optimal level of performance without compromising the safety is the balancing act coaches, turf managers, and researchers struggle with daily. Determining the most favorable traction coefficient ranges is a complex task.

In this study, we wanted to investigate the traction characteristics of cleated athletic shoes at various angles of internal rotation. We compared the various angles of internal rotation within a cleated athletic shoe, as well as cleated athletic shoes across the angles of internal rotation. Based on the results from this study, we found that the type of cleated athletic shoe does not significantly affect the traction characteristics. This contradicts some of the previous studies investigating differences in traction characteristics between cleated athletic shoes[18, 29]. Another important finding was that the angle of internal rotation of the shoe had an affect on traction characteristics. A plausible explanation for this is the trench effect. The significance of this finding is that orientation of the foot, relative to the applied force, has an effect on an athlete's performance. As an athlete plants their foot on the artificial turf surface while performing a cutting maneuver, the orientation will certainly have an effect on the amount of force being applied to the playing surface as well as the musculoskeletal system. This then will have implications for both performance and risk of injury. Future research should investigate the significance of cleat pattern on athletic shoes. Variations in cleat patterns may have the greatest impact on athletic performance.

With so few studies investigating linear translational traction and not enough consistency in the test methods, comparing results between research groups becomes nearly impossible. On the basis of this study we urge research groups to use similar testing devices when studying traction characteristics. Furthermore, the ultimate goal is to determine acceptable traction coefficient ranges for a particular athlete wearing a particular shoe while playing on artificial turf, and additional studies will need to be conducted to reach this ultimate goal.

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APPENDIX A

Boise State University Turf Traction Testing Conditions Information Sheet

Boise State University Turf Traction Testing Conditions Information Sheet

Testing Conditions

Type of Turf/Grass (e.g. make of turf, type of grass): ___________________

Current Conditions of Turf (e.g. age, game ready):______________________

____

____

Future Changes to Turf (e.g. frequency of refilling infill):________________

____

____

Installation of Turf (e.g. crown):_____________________________________

____

____

Maintenance of Turf: ____

____

Moisture Content (e.g. ideal, detection device): ________________________

____

Suggestions and Future Considerations: _______________________________

____

____

APPENDIX B

Complete Table of Means and Standard Deviations of the Dependent Variables

Table B1. Complete Table of Means and Standard Deviations of the Dependent Variables

4 SPEED III

	0 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2169	1.8485	1.2106	-6.5968
Trial 2	0.2355	1.8893	1.1375	-19.1285
Trial 3	0.2114	1.7448	1.1420	-10.3873
Trial 4	0.2210	1.6484	0.9828	-6.8255
Trial 5	0.2115	1.9037	1.2630	-22.5922
Mean	**0.2193**	**1.8070**	**1.1472**	**-13.1061**
St. Dev	**0.0099**	**0.1083**	**0.1056**	**7.3393**

	30 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2526	2.4334	1.8078	-196.2713
Trial 2	0.3317	2.8692	1.9408	-203.7708
Trial 3	0.3053	2.8371	1.8275	-198.0849
Trial 4	0.2678	2.5601	1.5311	-183.3311
Trial 5	0.3415	2.8343	2.0861	-169.6230
Mean	**0.2998**	**2.7068**	**1.8387**	**-190.2162**
St. Dev	**0.0389**	**0.1974**	**0.2045**	**13.7276**

	60 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.5188	5.4263	3.0914	-359.6586
Trial 2	0.5266	4.8645	2.5878	-363.1388
Trial 3	0.4612	4.2779	2.5166	-336.1961
Trial 4	0.4468	4.1429	2.5545	-335.5752
Trial 5	0.5401	5.0594	3.0466	-344.0224
Mean	**0.4987**	**4.7542**	**2.7594**	**-347.7182**
St. Dev	**0.0418**	**0.5380**	**0.2842**	**12.9830**

	90 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.6024	5.3153	3.0621	-322.7493
Trial 2	0.4871	3.7858	2.1315	-294.6793
Trial 3	0.5178	4.4390	3.0382	-306.7209
Trial 4	0.6594	4.2792	2.7848	-334.0884
Trial 5	0.5931	4.8427	2.2538	-336.3921
Mean	**0.5720**	**4.5324**	**2.6541**	**-318.9260**
St. Dev	**0.0692**	**0.5787**	**0.4372**	**17.9335**

SUPER BAD

	0 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2034	2.1069	1.2142	-5.8779
Trial 2	0.2141	2.1929	1.2855	-5.0446
Trial 3	0.2025	2.2098	1.4107	-4.7342
Trial 4	0.2112	2.3148	1.3692	-4.0807
Trial 5	0.2286	2.1433	1.5239	-4.2767
Mean	**0.2120**	**2.1936**	**1.3607**	**-4.8028**
St. Dev	**0.0105**	**0.0791**	**0.1187**	**0.7102**

	30 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2592	2.7130	1.9772	-188.7556
Trial 2	0.2654	2.9523	2.0804	-190.0627
Trial 3	0.2882	2.9884	2.3970	-168.8551
Trial 4	0.1566	2.7516	2.3594	-189.5071
Trial 5	0.2684	2.9504	2.1553	-184.3768
Mean	**0.2476**	**2.8711**	**2.1939**	**-184.3115**
St. Dev	**0.0520**	**0.1284**	**0.1803**	**8.9264**

	60 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.4155	4.2434	2.3578	-292.0324
Trial 2	0.4064	3.8967	2.1524	-307.8156
Trial 3	0.4516	4.4310	2.9556	-330.8206
Trial 4	0.3981	3.9563	2.4653	-299.6299
Trial 5	0.4385	4.3275	2.2594	-284.0754
Mean	**0.4220**	**4.1710**	**2.4381**	**-302.8748**
St. Dev	**0.0224**	**0.2338**	**0.3117**	**17.9366**

	90 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.4890	3.8316	2.1864	-271.4946
Trial 2	0.4316	3.8903	2.2591	-259.0445
Trial 3	0.4144	3.6714	2.0612	-246.2677
Trial 4	0.4981	4.0863	2.3253	-275.7917
Trial 5	0.5102	3.9984	2.5067	-263.1946
Mean	**0.4687**	**3.8956**	**2.2677**	**-263.1586**
St. Dev	**0.0428**	**0.1592**	**0.1656**	**11.5251**

SUPER SPEED

	0 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2093	1.6708	1.1430	-6.4334
Trial 2	0.2131	1.6398	1.0593	-6.0413
Trial 3	0.2458	1.6768	0.9587	-6.6295
Trial 4	0.2185	2.0412	1.1049	-6.4824
Trial 5	0.2082	1.6937	0.9831	-7.5771
Mean	**0.2190**	**1.7445**	**1.0498**	**-6.6327**
St. Dev	**0.0155**	**0.1670**	**0.0784**	**0.5710**

	30 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2881	2.7337	1.8301	-166.7311
Trial 2	0.2101	2.3730	1.6295	-143.5793
Trial 3	0.2840	2.5343	1.8874	-166.1919
Trial 4	0.2646	2.4467	1.9552	-159.8035
Trial 5	0.3025	2.5175	1.5632	-169.0512
Mean	**0.2699**	**2.5211**	**1.7731**	**-161.0714**
St. Dev	**0.0360**	**0.1350**	**0.1689**	**10.3623**

	60 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.4973	4.5755	2.8687	-335.8856
Trial 2	0.4670	4.2294	1.7138	-316.7529
Trial 3	0.4601	3.5376	2.0077	-279.7130
Trial 4	0.4591	3.8636	1.9044	-294.8590
Trial 5	0.4580	4.0736	1.8963	-302.6526
Mean	**0.4683**	**4.0560**	**2.0782**	**-305.9726**
St. Dev	**0.0166**	**0.3892**	**0.4544**	**21.4191**

	90 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.5436	4.7976	2.7141	-320.6089
Trial 2	0.4481	3.7949	1.8302	-284.2061
Trial 3	0.5191	3.2364	1.6764	-222.8053
Trial 4	0.5099	3.6300	2.0351	-279.6313
Trial 5	0.5366	3.6410	1.9838	-282.5886
Mean	**0.5115**	**3.8200**	**2.0479**	**-277.9680**
St. Dev	**0.0379**	**0.5842**	**0.3979**	**35.0863**

SCORCH

	0 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2048	1.9851	1.6267	-3.6885
Trial 2	0.2236	1.9901	1.2864	-3.5415
Trial 3	0.2168	2.0128	1.0173	-4.2604
Trial 4	0.2378	2.1223	1.3613	-3.9009
Trial 5	0.2033	2.2157	1.3648	-5.0283
Mean	**0.2173**	**2.0652**	**1.3313**	**-4.0839**
St. Dev	**0.0143**	**0.1009**	**0.2179**	**0.5931**

	30 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.2759	3.9667	2.6270	-248.2120
Trial 2	0.2831	3.1412	1.9260	-201.4670
Trial 3	0.3068	3.9104	2.0045	-247.9015
Trial 4	0.3116	3.6063	2.2171	-251.3653
Trial 5	0.3404	3.3637	1.6720	-229.8963
Mean	**0.3036**	**3.5977**	**2.0893**	**-235.7684**
St. Dev	**0.0256**	**0.3526**	**0.3583**	**20.9546**

	60 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.3974	5.2094	4.9927	-379.3306
Trial 2	0.4892	5.6486	5.5051	-387.5817
Trial 3	0.4617	4.9340	2.9183	-356.4235
Trial 4	0.5814	5.9491	5.8378	-388.0882
Trial 5	0.5316	4.6342	2.4315	-357.3058
Mean	**0.4923**	**5.2751**	**4.3371**	**-373.7460**
St. Dev	**0.0697**	**0.5304**	**1.5565**	**15.8008**

	90 DEGREES			
	Release Rate (sec^{-1})	Peak	Dynamic	R Torque (N-m)
Trial 1	0.6788	5.4304	2.3988	-362.1584
Trial 2	0.6121	4.9160	2.8861	-335.3138
Trial 3	0.5324	4.3748	1.9939	-331.0494
Trial 4	0.5377	4.2829	2.2194	-321.4258
Trial 5	0.6361	5.0017	2.3673	-307.2111
Mean	**0.5994**	**4.8012**	**2.3731**	**-331.4317**
St. Dev	**0.0635**	**0.4743**	**0.3283**	**20.2861**

APPENDIX C

Means and Standard Deviations of the Dependent Variables

Table C1. Mean and Standard Deviation of Traction Release Rate Values (sec^{-1})

Shoe	**Degree of Internal Rotation**			
	0	30	60	90
4 Speed III	0.22 ± 0.01	0.30 ± 0.04	0.50 ± 0.04	0.57 ± 0.07
Super Bad	**0.21 ± 0.01**	0.25 ± 0.05	0.42 ± 0.02	0.47 ± 0.04
Super Speed	0.22 ± 0.02	0.27 ± 0.04	0.47 ± 0.02	0.51 ± 0.04
Scorch	0.22 ± 0.01	0.30 ± 0.03	0.49 ± 0.07	**0.60 ± 0.06**

Table C2. Mean and Standard Deviation of Peak Traction Coefficients

Shoe	**Degree of Internal Rotation**			
	0	30	60	90
4 Speed III	1.81 ± 0.11	2.71 ± 0.20	4.75 ± 0.54	4.53 ± 0.58
Super Bad	2.19 ± 0.08	2.87 ± 0.13	4.17 ± 0.23	3.90 ± 0.16
Super Speed	**1.74 ± 0.17**	2.52 ± 0.13	4.06 ± 0.39	3.82 ± 0.58
Scorch	2.07 ± 0.10	3.60 ± 0.35	**5.28 ± 0.53**	4.80 ± 0.47

Table C3. Mean and Standard Deviation of Dynamic Traction Coefficients

Shoe	**Degree of Internal Rotation**			
	0	30	60	90
4 Speed III	1.15 ± 0.11	1.84 ± 0.20	2.76 ± 0.28	2.65 ± 0.44
Super Bad	1.36 ± 0.12	2.19 ± 0.18	2.44 ± 0.31	2.27 ± 0.17
Super Speed	**1.05 ± 0.08**	1.77 ± 0.17	2.08 ± 0.45	2.05 ± 0.40
Scorch	1.33 ± 0.22	2.09 ± 0.36	**4.34 ± 1.56**	2.37 ± 0.33

Table C4. Mean and Standard Deviation of Peak Resistive Torque Values (N-m)

Shoe	**Degree of Internal Rotation**			
	0	30	60	90
4 Speed III	-13.11 ± 7.34	-190.22 ± 13.73	-347.72 ± 12.98	-318.93 ± 17.93
Super Bad	-4.80 ± 0.71	-184.31 ± 8.93	-302.87 ± 17.94	-263.16 ± 11.53
Super Speed	-6.63 ± 0.57	-161.07 ± 10.36	-305.97 ± 21.42	-277.97 ± 35.09
Scorch	**-4.08 ± 0.59**	-235.77 ± 20.95	**-373.75 ± 15.80**	-331.43 ± 20.29

Minimum Value **Maximum Value**

APPENDIX D

Repeated Measures Univariate Analysis of Variances (ANOVAs) within the Cleated Athletic Shoes and across the Various Angles of Internal Rotation

Table D1. ANOVAs Within Shoes and Across Angles

Within Shoe (0, 30, 60, 90 degrees)

4 Speed III	Significance
Release Slope	0.000
Peak Traction	0.000
Dynamic Traction	0.000
Resistive Torque	0.000

Super Bad	Significance
Release Slope	0.000
Peak Traction	0.000
Dynamic Traction	0.000
Resistive Torque	0.000

Super Speed	Significance
Release Slope	0.000
Peak Traction	0.000
Dynamic Traction	0.000
Resistive Torque	0.000

Scorch	Significance
Release Slope	0.000
Peak Traction	0.000
Dynamic Traction	0.000
Resistive Torque	0.000

p -value set at 0.05

Across Angle (4 Speed III, Super Bad, Super Speed, Scorch)

0 Degrees	Significance
Release Slope	0.801
Peak Traction	0.000
Dynamic Traction	0.013
Resistive Torque	0.008

30 Degrees	Significance
Release Slope	0.085
Peak Traction	0.000
Dynamic Traction	0.074
Resistive Torque	0.000

60 Degrees	Significance
Release Slope	0.089
Peak Traction	0.003
Dynamic Traction	0.006
Resistive Torque	0.000

90 Degrees	Significance
Release Slope	0.002
Peak Traction	0.003
Dynamic Traction	0.116
Resistive Torque	0.000

Not Significant

APPENDIX E

Pair-Wise Comparisons between Angles of Internal Rotation within Cleated Athletic Shoes

Table E1. Pair-Wise Comparisons of Traction Release Rates between Angles of Internal Rotation within a Cleated Athletic Shoe

4 Speed III - Traction Release Rate	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
30 - 60 degrees	0.000	0.013
30 - 90 degrees	0.003	0.017
0 - 30 degrees	0.010	0.025
60 - 90 degrees	0.145	0.050

Super Bad - Traction Release Rate	Significance	Cutoff
0 - 30 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
30 - 60 degrees	0.001	0.013
30 - 90 degrees	0.004	0.017
60 - 90 degrees	0.126	0.025
0 - 60 degrees	0.209	0.050

Super Speed - Traction Release Rate	Significance	Cutoff
0 - 30 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
30 - 60 degrees	0.000	0.013
30 - 90 degrees	0.000	0.017
0 - 60 degrees	0.040	0.025
60 - 90 degrees	0.059	0.050

Scorch - Traction Release Rate	Significance	Cutoff
0 - 90 degrees	0.000	0.008
0 - 30 degrees	0.001	0.010
30 - 90 degrees	0.001	0.013
30 - 60 degrees	0.002	0.017
0 - 60 degrees	0.003	0.025
60 - 90 degrees	0.110	0.050

Not Significant

Table E2. Pair-Wise Comparisons of Peak Traction Coefficients between Angles of Internal Rotation within a Cleated Athletic Shoe

4 Speed III - Peak Traction Coefficient	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
0 - 90 degrees	0.000	0.013
30 - 60 degrees	0.002	0.017
30 - 90 degrees	0.005	0.025
60 - 90 degrees	0.382	0.050

Super Bad - Peak Traction Coefficient	Significance	Cutoff
0 - 30 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
30 - 60 degrees	0.000	0.013
0 - 60 degrees	0.001	0.017
30 - 90 degrees	0.001	0.025
60 - 90 degrees	0.154	0.050

Super Speed - Peak Traction Coefficient	Significance	Cutoff
0 - 30 degrees	0.000	0.008
30 - 60 degrees	0.001	0.010
0 - 60 degrees	0.002	0.013
0 - 90 degrees	0.002	0.017
30 - 90 degrees	0.004	0.025
60 - 90 degrees	0.123	0.050

Scorch - Peak Traction Coefficient	Significance	Cutoff
0 - 30 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
0 - 60 degrees	0.001	0.013
30 - 60 degrees	0.006	0.017
30 - 90 degrees	0.011	0.025
60 - 90 degrees	0.266	0.050

Not Significant

Table E3. Pair-Wise Comparisons of Dynamic Traction Coefficients between Angles of Internal Rotation within a Cleated Athletic Shoe

4 Speed III - Dynamic Traction Coefficient	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
30 - 60 degrees	0.001	0.013
0 - 90 degrees	0.002	0.017
30 - 90 degrees	0.035	0.025
60 - 90 degrees	0.678	0.050

Super Bad - Dynamic Traction Coefficient	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 90 degrees	0.000	0.010
0 - 30 degrees	0.001	0.013
30 - 60 degrees	0.064	0.017
60 - 90 degrees	0.436	0.025
30 - 90 degrees	0.570	0.050

Super Speed - Dynamic Traction Coefficient	Significance	Cutoff
0 - 60 degrees	0.001	0.008
0 - 90 degrees	0.003	0.010
0 - 30 degrees	0.005	0.013
30 - 60 degrees	0.190	0.017
30 - 90 degrees	0.208	0.025
60 - 90 degrees	0.757	0.050

Scorch - Dynamic Traction Coefficient	Significance	Cutoff
0 - 90 degrees	0.002	0.008
0 - 60 degrees	0.004	0.010
0 - 30 degrees	0.010	0.013
30 - 60 degrees	0.022	0.017
60 - 90 degrees	0.038	0.025
30 - 90 degrees	0.284	0.050

Not Significant

Table E4. Pair-Wise Comparisons of Peak Resistive Torques between Angles of Internal Rotation within a Cleated Athletic Shoe

4 Speed III - Peak Resistive Torque	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
0 - 90 degrees	0.000	0.013
30 - 60 degrees	0.000	0.017
30 - 90 degrees	0.001	0.025
60 - 90 degrees	0.073	0.050

Super Bad - Peak Resistive Torque	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
0 - 90 degrees	0.000	0.013
30 - 60 degrees	0.000	0.017
30 - 90 degrees	0.000	0.025
60 - 90 degrees	0.033	0.050

Super Speed - Peak Resistive Torque	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
0 - 90 degrees	0.000	0.013
30 - 60 degrees	0.000	0.017
30 - 90 degrees	0.002	0.025
60 - 90 degrees	0.024	0.050

Scorch - Peak Resistive Torque	Significance	Cutoff
0 - 60 degrees	0.000	0.008
0 - 30 degrees	0.000	0.010
0 - 90 degrees	0.000	0.013
30 - 60 degrees	0.000	0.017
30 - 90 degrees	0.001	0.025
60 - 90 degrees	0.010	0.050

Not Significant

APPENDIX F

Pair-Wise Comparisons between Cleated Athletic Shoes across Various Angles of Internal Rotation

Table F1. Pair-Wise Comparisons of Traction Release Rates between Cleated Athletic Shoes across Various Angles of Internal Rotation

0 Degrees - Traction Release Rate	Significance	Cutoff
N/A		

30 Degrees - Traction Release Rate	Significance	Cutoff
N/A		

60 Degrees - Traction Release Rate	Significance	Cutoff
N/A		

90 Degrees - Traction Release Rate	Significance	Cutoff
4 Speed III - Super Bad	0.004	0.008
Super Bad - Scorch	0.008	0.010
Super Speed - Scorch	0.040	0.013
Super Bad - Super Speed	0.067	0.017
4 Speed III - Super Speed	0.071	0.025
4 Speed III - Scorch	0.545	0.050

Not Significant

Table F2. Pair-Wise Comparisons of Peak Traction Coefficients between Cleated Athletic Shoes across Various Angles of Internal Rotation

0 Degrees - Peak Traction Coefficient	Significance	Cutoff
Super Bad - Super Speed	0.001	0.008
4 Speed III - Super Bad	0.009	0.010
Super Speed - Scorch	0.010	0.013
4 Speed III - Scorch	0.018	0.017
Super Bad - Scorch	0.070	0.025
4 Speed III - Super Speed	0.624	0.050

30 Degrees - Peak Traction Coefficient	Significance	Cutoff
Super Speed - Scorch	0.001	0.008
4 Speed III - Super Bad	0.008	0.010
4 Speed III - Scorch	0.016	0.013
Super Bad - Scorch	0.019	0.017
Super Bad - Super Speed	0.027	0.025
4 Speed III - Super Speed	0.243	0.050

60 Degrees - Peak Traction Coefficient	Significance	Cutoff
4 Speed III - Super Speed	0.004	0.008
Super Speed - Scorch	0.013	0.010
Super Bad - Scorch	0.030	0.013
4 Speed III - Super Bad	0.078	0.017
4 Speed III - Scorch	0.261	0.025
Super Bad - Super Speed	0.638	0.050

90 Degrees - Peak Traction Coefficient	Significance	Cutoff
Super Speed - Scorch	0.002	0.008
Super Bad - Scorch	0.017	0.010
4 Speed III - Super Speed	0.035	0.013
4 Speed III - Super Bad	0.082	0.017
4 Speed III - Scorch	0.287	0.025
Super Bad - Super Speed	0.792	0.050

Not Significant

Table F3. Pair-Wise Comparisons of Dynamic Traction Coefficients between Cleated Athletic Shoes across Various Angles of Internal Rotation

0 Degrees - Dynamic Traction Coefficient	Significance	Cutoff
Super Speed - Scorch	0.018	0.008
Super Bad - Super Speed	0.020	0.010
4 Speed III - Super Bad	0.030	0.013
4 Speed III - Scorch	0.136	0.017
4 Speed III - Super Speed	0.220	0.025
Super Bad - Scorch	0.834	0.050

30 Degrees - Dynamic Traction Coefficient	Significance	Cutoff
N/A		

60 Degrees - Dynamic Traction Coefficient	Significance	Cutoff
4 Speed III - Super Speed	0.012	0.008
Super Speed - Scorch	0.033	0.010
Super Bad - Scorch	0.067	0.013
4 Speed III - Scorch	0.101	0.017
Super Bad - Super Speed	0.208	0.025
4 Speed III - Super Bad	0.230	0.050

90 Degrees - Dynamic Traction Coefficient	Significance	Cutoff
N/A		

Not Significant

Table F4. Pair-Wise Comparisons of Peak Resistive Torques between Cleated Athletic Shoes across Various Angles of Internal Rotation

0 Degrees - Peak Resistive Torque	Significance	Cutoff
Super Speed - Scorch	0.000	0.008
Super Bad - Super Speed	0.020	0.010
4 Speed III - Scorch	0.046	0.013
4 Speed III - Super Bad	0.070	0.017
4 Speed III - Super Speed	0.111	0.025
Super Bad - Scorch	0.235	0.050

30 Degrees - Peak Resistive Torque	Significance	Cutoff
Super Speed - Scorch	0.000	0.008
Super Bad - Scorch	0.011	0.010
4 Speed III - Scorch	0.021	0.013
Super Bad - Super Speed	0.034	0.017
4 Speed III - Super Speed	0.038	0.025
4 Speed III - Super Bad	0.485	0.050

60 Degrees - Peak Resistive Torque	Significance	Cutoff
4 Speed III - Super Speed	0.001	0.008
Super Speed - Scorch	0.001	0.010
Super Bad - Scorch	0.004	0.013
4 Speed III - Super Bad	0.016	0.017
4 Speed III - Scorch	0.019	0.025
Super Bad - Super Speed	0.853	0.050

90 Degrees - Peak Resistive Torque	Significance	Cutoff
4 Speed III - Super Bad	0.001	0.008
Super Bad - Scorch	0.002	0.010
Super Speed - Scorch	0.020	0.013
4 Speed III - Super Speed	0.055	0.017
Super Bad - Super Speed	0.285	0.025
4 Speed III - Scorch	0.428	0.050

Not Significant