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Biomechanical Analysis of Impact Absorption and Traction on Third-Generation Artificial Turf

Thesis for the degree of Philosophiae Doctor

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SAMMENDRAG

Tredjegenerasjons kunstgress (3G kunstgress) er nå i utstrakt bruk både på breddenivå og profesjonelt nivå, og underlaget nyter status som godkjent for konkurranse av Det internasjonale fotballforbundet (FIFA). Ikke desto mindre, til tross for tilsvarende skadefrekvens som på naturgress, har det opprettholdt et rykte for dårlig støtdemping og utrygt friksjonsnivå. Den største bekymringen er at overdrevent stor, repetert belastning og friksjonskrefter utsetter utøvere for større skaderisiko. Både støtdemping og friksjon påvirkes ikke bare av egenskaper ved 3G kunstgress, men også av egenskaper ved fotballskoene som benyttes, der spesielt avlange knotter antas å forårsake høy friksjon.

De mest brukte testmetodene innebærer bruk av mekaniske apparater som har til hensikt å gjenskape en idrettsspesifikk menneskelig bevegelse med antatt høy skaderisiko, enten gjennom å produsere et isolert sammenstøt eller en rotasjon, selv om utøvelsen av idrettene som oftest foregår på 3G kunstgress hovedsakelig innebærer lineære bevegelser. En følge av dette er at den nåværende kunnskapen om egenskaper ved 3G kunstgress nesten utelukkende er basert på tester med mekaniske apparater som, delvis grunnet en manglende evne til å tilpasse seg kontinuerlig, ikke betraktes som nøyaktige for å framstille interaksjonen mellom sko og underlag ved menneskelig bevegelse.

Det overordnede målet med dette arbeidet var å tilføre utøver-basert biomekanisk data gjennom å undersøke støtdemping og lineær friksjon på forskjellige 3G kunstgressystemer (breddenivå, profesjonelt nivå med og uten underliggende støtdempingssjikt) og med vanlige fotballsko med forskjellige typer knotter (kunstgressknotter, tradisjonelle runde knotter, avlange knotter) ved standardisert menneskelig bevegelse.

Sammenlignet med de to kunstgressystemene for profesjonelt nivå var støtdemping dårligere på kunstgressystemet for breddenivå. Generelt sett ble støtdemping påvirket i positiv forstand av både et underliggende støtdempingssjikt og en større mengde fyll i underlaget, men tilsynelatende i høyere grad av førstnevnte. Dette gjenspeilet seg i at kunstgressknotter ga mest støtdemping blant forskjellige typer knotter, muligens grunnet en større mengde sålemateriale.

Friksjonskraft var størst på kunstgressystemet for profesjonelt nivå med underliggende støtdempingssjikt og med kunstgressknotter. Til tross for enkelte forskjeller i friksjonskraft forble imidlertid friksjonskoeffisienten tilnærmet identisk på tvers av alle kombinasjoner av sko og underlag, noe som antyder at forsøkspersonene justerte for uønskede friksjonsbetingelser. Det var ingen tegn på at avlange knotter produserte unormalt høy friksjon. Et positivt li-

neært forhold mellom friksjonskoeffisient og medial rotasjon av skoen i transversalplanet (i forhold til bevegelsesretning på underlaget) fantes, men den begrensede forskyvingen av knotter som forekommer under kontakt med underlaget gjør at bakgrunnen fortsatt er uklar.

Selv om enkelte forskjeller mellom kunstgressystemer ble avdekket, antyder verken størrelsen på sammenstøt eller friksjon at ordentlig vedlikeholdt 3G kunstgress kan betraktes som et spesielt risikabelt underlag. Denne forestillingen styrkes av en skadefrekvens lik den som finnes på naturgress.

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Cynthia, for keeping me going, for turning bad days into good days with a simple smile, and for giving my mind a rest from the project

Until man duplicates a blade of grass, nature can laugh at his so-called scientific knowledge.

– Thomas Edison

TABLE OF CONTENTS

LIST OF PUBLICATIONS

This thesis is based on the following papers and manuscripts, referred to by their Roman numerals in the text. The papers are reprinted with kind permission from the publishers (SAGE, Springer Science and Business Media). Note that this thesis also includes unpublished results.

I. McGhie D, Ettema G. Biomechanical analysis of surface-athlete impacts on third-generation artificial turf. *The American Journal of Sports Medicine*. 2013;41(1):177-185.

II. McGhie D, Ettema G. Biomechanical analysis of traction at the shoe-surface interface on third-generation artificial turf. *Sports Engineering*. 2013;16(2):71-80.

III. McGhie D, Ettema G. On the "trench effect" theory: A biomechanical analysis of the relationship between traction and shoe angle on third-generation artificial turf. *Footwear Science*. In revision.*

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ABBREVIATIONS AND FREQUENTLY USED PHRASES

1G turf	First-generation artificial turf
2G turf	Second-generation artificial turf
3G turf	Third-generation artificial turf
α	Transverse plane shoe angle relative to angle of sliding (degrees)
Bladed cleats	Long, irregular cleats placed primarily around the edges of the sole
Cut sprint	Sprint with a 90° cut to the left
Δl_{slide}	Displacement of shoe during full sole-surface contact (cm)
Δv_{cut}	Total change in velocity during impact in cutting direction ($m \cdot s^{-1}$)
Δv_{run}	Total change in velocity during impact in initial running direction ($m \cdot s^{-1}$)
DU42	Duraspine Ultra 42 (turf system with 42 mm fiber height)
DU50	Duraspine Ultra 50 (turf system with 50 mm fiber height)
DU60	Duraspine Ultra 60 (turf system with 60 mm fiber height)
FIFA	Fédération Internationale de Football Association (i.e., The International Soccer Association)
f_{timp}	Peak total (vector sum of vertical and horizontal) force relative to body weight
f_{trac}	Peak horizontal force relative to body weight
f_{vimp}	Peak vertical force relative to body weight
In vivo (lat.)	Within the living (i.e., occurring within a living organism)
In situ (lat.)	In position (i.e., an object in its natural or original position)
μ	Mean traction coefficient for duration of full sole-surface contact
SBR	Styrene-butadiene rubber (turf system infill from recycled car tires)
Stop sprint	Straight sprint with a rapid deceleration
t_{con}	Duration of surface contact time (ms)
TPE	Extruded thermoplastic elastomer (synthetically manufactured turf system infill)
Traditional round cleats	Long, conical cleats placed around the edges of the sole and in the center of the forefoot
Turf cleats	Dense pattern of short cleats covering most of the sole
v_{app}	Approach velocity ($m \cdot s^{-1}$)
v_{slide}	Sliding velocity ($cm \cdot s^{-1}$)

ABSTRACT

Third-generation artificial turf (3G turf) is currently in widespread use at both the recreational and professional level, enjoying status as a Fédération Internationale de Football Association (FIFA) approved surface for competitive play. Nevertheless, despite the overall injury rate being similar to that of natural grass, it has maintained a reputation for poor impact absorption and an unsafe level of traction, the main concerns being that excessive repetitive loads and traction forces expose athletes to a greater risk of injury. Both impact absorption and traction are affected not only by 3G turf properties but also by shoe properties, with bladed cleats in particular presumably causing high traction.

The most commonly employed test methods involve the use of mechanical devices intended to replicate a sports specific human movement with an assumed high injury risk, either producing an isolated impact or a loaded rotation on the surface, even though performance of the sports which are most frequently played on 3G turf mostly involve translational movements. Hence, the current knowledge of 3G turf properties is almost exclusively based on mechanical devices, which, in part due to their lack of ability to continuously adapt, are not considered accurate representations of the shoe-surface interaction during human movement.

The overall aim of the current work was to provide athlete-based biomechanical data on 3G turf, investigating impact absorption and translational traction properties of various turf systems (recreational-level, professional-level with and without underlying shock pad) and typical cleat configurations (turf cleats, traditional round cleats, bladed cleats) during standardized human movement.

Compared to the two professional-level turf systems, impact absorption was worse on the recreational-level turf system. In general, impact absorption was positively affected by both an underlying shock pad and a greater infill amount, but seemingly more so by the former. This was reflected in turf cleats providing the most impact absorption among cleat configurations, possibly due to a greater amount of sole material.

Traction force was greatest on the professional-level turf system with an underlying shock pad and with turf cleats. However, despite certain differences in traction force, the traction coefficient remained almost identical across all shoe-surface combinations, indicating that the subjects adjusted for undesirable traction conditions. There was nothing to suggest that bladed cleats produced excessive traction. A positive linear relationship between traction coefficient and transverse plane medial shoe rotation (relative to direction of movement on the

surface) existed, but the limited cleat displacement occurring during surface contact leaves the reason unclear.

Regardless of the differences discovered between turf systems, the magnitudes of neither impact nor traction indicate that properly maintained 3G turf can be considered a particularly hazardous surface, a notion which is only strengthened by its injury rate being similar to that of natural grass.

1. INTRODUCTION

Seizing the opportunity to compile and communicate objective research results on a topic riddled with myths and anecdotal evidence, an approach much broader than what the experiment performed would dictate has been taken in the introduction.

The majority of artificial turf research has been done on two sports both primarily known as football where they, respectively, enjoy widespread popularity. Note that, in the current thesis, to avoid confusion, the terms soccer (football) and football (American football) are used to differentiate the two, with the exception of proper names.

1.1. The modern stadium

When evaluating a sports stadium as a whole, both the actual construction and the installed surface must be considered. Modern sport stadiums constructed primarily for soccer and football are designed not only to be able to host games of the respective sports but also to deliver an improved spectator experience. The spectators are an important source of revenue – an investment that must be protected – so much so that they are even referenced in the Fédération Internationale de Football Association's (FIFA) document on stadium requirements with regard to the importance of maintaining a quality surface for game play to remain enjoyable (FIFA 2011b). A consequence of this is the increased use of roofing, shielding spectators from rain and sun alike. Unfortunately, it has been stated (Ekstrand et al. 2006; FIFA 2009a; FIFA 2011b; Fuller et al. 2007a), the lack of direct sunlight adversely affects the growth conditions for natural grass (grass), causing uneven growth or, at worst, inhibiting growth altogether. In addition, in certain parts of the world, geographical constraints such as land fertility and climatic conditions can prove to be an obstacle when trying to maintain adequate surface conditions for game play on grass, regardless of stadium design.

Factors extending beyond sports also come into play when piecing together the specifics of a stadium. With their spectator focused designs, modern sport stadiums are not limited to hosting sporting events, as they are also becoming increasingly common venues for events such as concerts and trade shows. These types of events draw large crowds, exposing the surface to a great amount of wear through the combination of temporary flooring solutions and continuous movement of people. A desire to better meet the expected demands for a sustainable, even profitable, stadium, with the ability to host a multitude of events, can lead to the decision to invest in artificial turf.

While artificial turf fails to provide the natural feel many athletes covet (NISO 2007a), it does have the advantage of providing an even and predictable surface if properly maintained. Despite seemingly being a widespread notion, most likely a relic from its earlier days, artificial turf is not maintenance free nor should it be considered low maintenance; it requires specific preparation, which may be just as time-consuming (a maintenance time of one hour per ten hours of use has been suggested) as for grass (Fleming 2011b), but potentially less expensive (FIFA 2011b). However, its major selling point is that it can provide the users with an increased number of playing hours, up to ten times that of grass (Fleming 2011b). In addition, it provides the opportunity to schedule practices or games immediately following preceding use. This is in stark contrast to grass, which must be repaired after each training or match (FIFA 2011b). Hence, the cost per hour of use is much lower than for grass. Even though it offers high usability, artificial turf does not function as a year-round surface in northern climates without adequate heating – an additional expense of a magnitude that cannot be ignored. Naturally, the total cost of an artificial turf field will be affected by its effective life, which has been suggested to be dependent on initial material and installation quality, intensity of use, and maintenance (FIFA 2011b; Fleming 2011b).

1.2. Generations of artificial turf: a brief history

There is no shortage of consistent information on the development of artificial turf, from its inception to what is in use today, but actual verifiable sources are scarce. This becomes evident when even information gathered from review papers published in international, peer-reviewed journals lacks secondary sources. The first recorded instance of a major artificial turf surface installation at the professional level appears to have occurred in 1966, when ChemGrass (retroactively named AstroTurf) was installed at the Houston Astrodome in Houston, Texas (AstroTurf 2012b), home field of the Houston Astros baseball club (Figure 1). In fact, this new development came about because of problems with maintenance of grass growth within the roofed stadium (AstroTurf 2012b). This type of artificial turf, known today as first-generation artificial turf (1G turf), consisted of a dense artificial turf carpet (a backing material with yarn either woven or tufted into it) with 10-12 mm long fibers (individual strands of yarn) usually of nylon (Fleming 2011a). However, it was not the unequivocal success which may have been envisioned (Glauber 1991). Probably among the main factors leading to the demise of 1G turf was its penchant for skin abrasion (Fleming 2011a; Frederick 1993) and its perceived hardness.

In the 1970s, roughly a decade later, what is now known as second-generation artificial turf (2G turf) was introduced. It proved to be a much more sustainable alternative to grass than its predecessor, which is evident by the fact that it is still in use today. The fibers of 2G turf are generally 20-25 mm long and made of polyethylene, making it softer than the nylon fibers of 1G turf (Fleming 2011a). Increased spacing between tufts of fibers in the carpet allows for sand infill, providing stability while simultaneously aiding performance related qualities such as traction, impact absorption, and ball behavior. After making its way into top-level soccer in the United Kingdom, 2G turf enjoyed a brief period of limited acceptance before being officially banned around 1990 by the English Football Association due to the quality of play on the surface and complaints of injuries (Fletcher 2012; The Football League 2012).

Figure 1. The Houston Astrodome with artificial turf on April 18, 1966 (AstroTurf 2012b).

Just before the turn of the millennium third-generation artificial turf (3G turf) entered the market. It was specifically developed in an effort to replicate grass (FieldTurf Tarkett 2012; FIFA 2011b), with 40-65 mm long fibers (Fleming 2011a), and holds a sizeable amount of infill for impact absorption purposes. The spacing between tufts of fibers in the carpet on 3G turf is adequate to accommodate – compared to 2G turf – large quantities of both sand and rubber infill, with the former acting as a base layer for stability and the latter chiefly acting as an impact absorber and performance facilitator. Due to its multitude of components, 3G turf is often considered as a system. A turf system is defined as the synthetic surface and its infill, shock pad if applicable, and all the supporting layers that influence the biomechanical response and sports performance of the surface (FIFA 2009b). However, the final supporting layer is normally a fairly hard leveling course of gravel or even asphalt, effectively limiting the influence on surface properties to turf system variations above the leveling layer.

Although they may often look identical to the naked eye, the modern artificial turf systems consist of various component parts (fiber, stabilizing infill, shock absorbing infill, underlying shock pad), each of which may vary in material, size, shape, and/or amount (Figure 2). Adding to this, variations in the foundation may also occur, but they should, as mentioned, have little effect on surface properties. The shape of the individual turf fibers has been developed toward imitating grass, with the monofilament fiber (single blade, as found in nature) seemingly having solidified its position as the market leader going forward, likely leaving slitfilm fibers (wide, rectangular blades that by design fibrillate during installation) as a thing of the past. The most modern monofilament fibers often approximate a v-shape, albeit more open, with a "spine" running up the center, the purpose being to increase resilience, improving their ability to regain standing posture after being temporarily compressed. The number of shock absorbing infill types on the market is ever-growing, with both recycled and specifically manufactured products available. Infill types produced specifically for sports application are generally more expensive (due to the cost of raw materials and production methods), and are hence often viewed as an option for professional sports more so than for recreational sports. Among these, common infill types include extruded thermoplastic elastomer (TPE) and ethylene propylene diene monomer (EPDM). The infill type in most widespread use to date, presumably in part affected by financial reasons, is styrene-butadiene rubber (SBR), commonly known as recycled tires (Unisport Scandinavia, personal communication, October 11, 2011). The industry distinguishes ambient ground SBR from cryogenically processed SBR, the latter resulting in a finer particle. A necessary consequence of its primary area of application, namely tires, SBR rubber has stronger abrasive properties than its sports-specific counterparts. However, the weaker abrasive properties of TPE and EPDM only hold true if production methods and materials are of high quality.

Figure 2. Left: surface view of a 3G turf system. Right: cross-section illustration of a 3G turf system (FIFA 2011a). From the bottom: foundation, leveling layer, carpet with turf fibers, sand infill, rubber infill.

1.3. The current status of artificial turf

Despite its less than stellar reputation after eventual failures in professional sports (Fletcher 2012; Glauber 1991; The Football League 2012), artificial turf has not always been described in negative terms. As a play on words from the famous Ringling Bros. and Barnum & Bailey Circus slogan "The Greatest Show on Earth", the American football team the St. Louis Rams fielded a high-scoring offense so potent from 1999-2001 that the team was dubbed "The Greatest Show on Turf" after their artificial turf home field which seemingly magnified their speed oriented offense. Today, however, even though its reputation for being a faster surface appears to have persisted (AstroTurf 2012a; Meyers & Barnhill 2004), artificial turf is yet again largely subject to preconceived notions of a negative disposition. Based on questionnaire data it can be seen that professional soccer players attribute injuries to artificial turf without anything to substantiate their claim (NISO 2007b) and subjectively characterize playing on artificial turf as being physically more demanding than playing on grass (Andersson et al. 2008), with the latter opinion existing despite a lack of difference in objectively measured movement characteristics between the two surfaces (Andersson et al. 2008).

The continued poor reputation is likely to be caused, at least in some part, by the problems related to 1G and 2G turf. In fact, just a few years prior to the introduction of 3G turf, artificial turf was reported to be a key contributor to a significant increase in injuries (Árnason et al. 1996; Gorse et al. 1997). However, the development of artificial turf has come a long way (in a short time) since these experiments were conducted, hence their results should be interpreted with caution concerning their relevance today. Regardless of what previous research shows, a lingering problem in the soccer community with regard to artificial turf is still the apparent penchant for relying heavily on anecdotal evidence.

On a detailed level, the chief complaints of artificial turf have been its purportedly poor impact absorption and unsafe frictional properties, the main concerns being that it puts athletes at risk for overuse injuries as a result of excessive repeated impact forces (Bentley et al. 2011; Cole et al. 1996; Eils et al. 2004; Meijer et al. 2006; Queen et al. 2008) and torsion-related injuries as a result of excessive frictional forces between the surface and the shoe (Bonstingl et al. 1975; Shorten et al. 2003). Interestingly enough, an actual cause-effect relationship between impacts and injuries has still not been established (Derrick 2004; Frederick 1986; Nigg & Yeadon 1987; Smith et al. 2004; Stiles & Dixon 2007), yet it remains a widely held belief, likely due to the apparently obvious connection between the two factors.

Naturally, a certain amount of frictional force is necessary for athletes to be able to adequately perform accelerations, decelerations, rapid directional changes, and other movements inherent to most sports that are played on grass or artificial turf. Similarly, impact absorption can only reach a certain level before it becomes counterproductive, serving only as energy draining and not allowing for rapid movements. Achieving the optimal balance between performance and safety is a challenge that has yet to be resolved.

1.3.1. A note on friction and traction

For most people, “friction” is a more familiar term than “traction”. In the literature, both friction and traction are used to describe the resistive forces acting between a surface and the sole of a shoe. According to the classic Coulomb laws of friction, relative motion is determined by the friction coefficient, which is the relationship of horizontal force to vertical force (or friction force to normal force). Friction coefficients are traditionally regarded as material-dependent constants (Shorten et al. 2003; Torg et al. 1974), unaffected by variables such as sliding velocity and pressure. The friction present immediately prior to initiation of motion is referred to as “static friction” while the friction present during constant sliding motion is referred to as “dynamic friction”, with the static friction coefficient being greater than the dynamic friction coefficient. However, the classic laws of friction generally describe interactions between rigid, uniform surfaces, and are thus not suitable to adequately depict the complex interactions that occur between the compliant, non-uniform surfaces of artificial turf with particulate infill and various cleated sports shoes (Nigg & Segesser 1988; Shorten et al. 2003).

The solution has been to use the term traction to indicate shoe-surface interactions, with their accompanying friction-like forces, where the classic laws of friction are deemed not to apply (Shorten et al. 2003; Villwock et al. 2009a). Hence, the traction coefficient describes the relationship of traction force to normal force as the friction coefficient describes the relationship of friction force to normal force (Shorten et al. 2003). Not bound by the classic laws of friction, the traction coefficient is susceptible to be affected by various factors such as load (Cawley et al. 2003; Kuhlman et al. 2009; Nigg & Segesser 1988) and cleat material (Bowers & Martin 1975), and allows for the dynamic traction coefficient to be greater than the static traction coefficient (Kuhlman et al. 2009).

For the remainder of the current thesis, the resistive forces acting at the shoe-surface interface on 3G turf will exclusively be referred to using the term traction.

1.3.2. Population-based studies

As mentioned, throughout its life, artificial turf has been blamed for its perceived contribution to injuries, encompassing both acute injuries and overuse injuries. Attributing overuse injuries to a specific surface is problematic, since the onset of overuse injuries per definition is gradual (Soligard et al. 2012; Steffen et al. 2007). Hence, most of the research on 3G turf is focused on acute injuries, attempting to quantify the incidence of such injuries compared to that on grass.

Varying injury definitions has been the main culprit in preventing valid inter-study comparisons. To counteract this problem, a consensus statement has been drafted (Fuller et al. 2006) in order to improve the uniformity of data collection across studies. Using this as a methodological foundation, a majority of population-based studies fail to uncover a significant difference in overall injury rate between 3G turf and grass (Aoki et al. 2010; Bjørneboe et al. 2010; Ekstrand et al. 2006; Ekstrand et al. 2011; Fuller et al. 2007a; Fuller et al. 2007b; Fuller et al. 2010; Soligard et al. 2012; Steffen et al. 2007). However, 3G turf has shown a tendency for an increased rate of injury in certain sub-categories, with potentially traction-related knee sprains (Bjørneboe et al. 2010; Fuller et al. 2010; Steffen et al. 2007) and non-bone joint injuries (Fuller et al. 2007b) chief among them, as well as skin injuries (Fuller et al. 2007a). Although indisputably uncomfortable, whether or not abrasions should be considered injuries is a matter of opinion; athletes rarely appear to suffer abrasions excessive enough to cause them to miss practice or games and the problem can, to a certain degree, be remedied through equipment use. That being said, grass has shown a tendency for an increased rate of muscle strains (Ekstrand et al. 2006; Ekstrand et al. 2011a) and tears (Meyers 2010). In a sense, this makes the choice of surface type analogous to which type of injury it is preferable to risk incurring.

While the consensus statement solved many problems, two important factors are still largely overlooked; the degree of detail included when describing the surfaces and the cleat configurations employed by the athletes. Rather than provide information about the density, hardness, or other potentially influential characteristics of the grass fields or the composition of turf systems, surfaces are often simply labeled grass or artificial turf. The entire topic of cleat configurations, on the other hand, is generally avoided, despite existing research showing possible effects on both impact absorption and traction (see chapters 1.3.4.2 and 1.3.5.1).

1.3.3. Standardized testing

To remove the subjective component from the evaluation of artificial turf, FIFA, being the governing body, sought to develop set standards. In 2001 they launched the Quality Concept test program (FIFA 2009b) in an effort to ensure that the newly developed playing surfaces would replicate the play-related properties of grass (FIFA 2009a), placing special emphasis on avoiding an increased risk of injury. The test program incorporates both laboratory testing and *in situ* field testing and entails the temporary certification of a specific field after its completion; contrary to how it can often be construed from producers' own product descriptions (i.e., "This turf system meets the demands for FIFA approval"), it is not a universal approval of the product offered by the particular producer (FIFA 2009a). All artificial turf fields intended for use in FIFA governed competition of a certain level are subject to approval by FIFA at regular intervals to gain and maintain certified status. The Quality Concept test program consists of various mechanical device tests (Figure 3), which were initially derived from existing test programs for, among other applications, road works and athletic tracks and subsequently adapted for artificial turf. The current benchmark values for artificial turf are based on tests done on grass fields subjectively deemed to be in good condition (FIFA 2011b).

Among the most fundamental factors influencing surface-athlete interactions are impact-related properties and traction-related properties at the shoe-surface interface. The basic principle behind the test intended to measure impact absorption on artificial turf is a mass allowed to fall uninhibited onto a spring resting on a load cell over a metal test foot (FIFA 2009b). This particular mechanical device is commonly known as the Artificial Athlete. The maximum force is recorded and force reduction is compared to the corresponding value recorded on concrete. For traction, the test battery distinguishes between rotational and translational traction. Despite the desire to remove the subjective component, the rotational traction test actually has a human element to it, with a loaded, cleated test foot manually rotated on the surface (FIFA 2009b). The maximum torque during rotation is recorded. The translational traction test consists of a cleated test foot striking the surface in a semi-circular motion by means of a pendulum (FIFA 2009b). The deceleration from sliding across the surface is recorded, as well as a unitless sliding value. Where applicable, all tests are carried out with a standardized cleat configuration corresponding to that of traditional round cleats (long, conical cleats placed around the edges of the sole and in the center of the forefoot). However, although a consistent cleat configuration for standardized testing is an understandable necessity, the multitude of cleat configurations available and in use today makes it difficult to consider the traditional round cleat as the standard it once was. Hence, the procedures determining if a surface meets the demands for what is by FIFA considered a safe playing environment do not take into consideration the corresponding results when using more aggressive cleat configurations.

Traction appears to be the more challenging variable to quantify, as evidenced by FIFA removing the translational traction test from the official field test battery, after roughly a decade of use, on the grounds that it seemingly had no effect on field performance (FIFA 2012a). It does, however, remain in the laboratory requirements. Interestingly, the Quality Concept test program includes no tests aimed at measuring the traction coefficient, the main determinant of relative motion, except with regard to skin friction (FIFA 2009b). Another test, measuring the material components of the infill, has recently been added to protect the buyers, ensuring that the infill used for field installation matches that from the laboratory tests (FIFA 2012a). A peculiar aside is the fact that the laboratory benchmarks and field test benchmarks are not identical (FIFA 2009b). Considering purely economic reasons, this poses the question of what incentive producers have to install a field with the appropriate amount of infill, as used in the laboratory tests, when less may be needed in order to gain the desired FIFA certification.

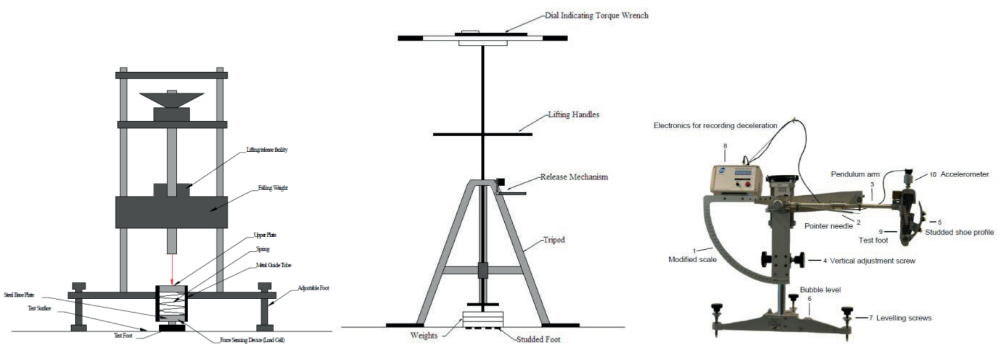


Figure 3. A selection of the mechanical test devices in the FIFA Quality Concept test program. From left to right: impact absorption, rotational traction (FIFA 2009b), translational traction (FIFA 2012d).

After roughly 40 years of being officially deemed inferior to grass – with a few temporary exceptions – it is no exaggeration to say that the 2004 inclusion (FIFA 2009a) of artificial turf in FIFA's "Laws of the Game" (FIFA 2012c) represented a revolution of the game in terms of surface standards. After years of development toward a product specifically designed for soccer (FIFA 2011b), it was finally considered acceptable. By making it an approved surface for FIFA sanctioned international competition, it has become, for all theoretical intents and purposes, the equal of grass. It is worth noting that some exceptions exist, such as the Union of European Football Associations (UEFA) Champions League finals, which is still exclusively played on grass.

1.3.4. Impact absorption

The most common test methods employed for investigating impact absorption on artificial turf involve the use of various mechanical devices producing an isolated impact, often of a fairly rigid nature (McNitt et al. 2004; Naunheim et al. 2004). The devices are intended to represent the very basics of human movement in the form of a typical situation with an assumed high injury risk, such as a hard landing.

A surface's ability to undergo some form of displacement is assumed to be directly related to its impact absorption properties (Shorten & Himmelsbach 2002; Stiles & Dixon 2007). In theory, the greater the thickness of a surface is, the greater its potential for displacement should be, extending the time of contact and hence distributing the impact force. In line with this, the main factors determining the level of impact absorption of 3G turf are thought to be the thickness of a shock pad (or lack thereof) and the amount of infill (Alcántara et al. 2009; McNitt et al. 2004). Possibly a function of a decreased potential for displacement, compaction of the infill through use is considered to have a negative effect on impact absorption (Alcántara et al. 2009; Meijer et al. 2006; Naunheim et al. 2004).

Naturally, shoe properties are also able to affect the impact absorption occurring at the shoe-surface interface. These are commonly expressed through cleat configurations, being the most visible component of the shoe. Serving as the primary link between the surface and the athlete during athletic movements, shoes are designated as an important contributor to impact absorption since the forces acting on the athlete by necessity are transferred through them (Bentley et al. 2011; Smith et al. 2004).

1.3.4.1. Mechanical devices

Following the theory that surface thickness is an important determinant of impact absorption, both the presence of an underlying shock pad (McNitt et al. 2004) and an increased amount of infill (Alcántara et al. 2009) have resulted in greater impact absorption on 3G turf when measured with mechanical devices. However, infill amount does not always dictate impact absorption (McNitt et al. 2004), which makes the relationship seem less obvious than initially assumed. Infill properties beyond mere amounts, such as infill morphology, have also shown an ability to influence impact absorption (Alcántara et al. 2009), with changes in physical deformation (i.e., displacement of infill) being uncovered as well.

In addition, a decrease in both impact absorption and physical deformation of the surface with an increase in simulated use has been demonstrated (Alcántara et al. 2009). Coupled with the previous discovery of varying impact absorption at different sites of a 3G turf field (Naunheim et al. 2004), where decreased impact absorption occurred in conjunction with infill compaction, this lends credence to the notion that infill compaction and the accompanying decreased surface thickness can be a precursor for greater impact forces.

1.3.4.2. Biomechanics

Although mechanical devices enjoy the benefits of reproducibility and practicality in a way *in vivo* measurements never will, they are nevertheless limited to mimicking human movement. This often leads to a severe simplification of the actions taking place, lacking the constant adaptation present in human movement, hence they are not considered to accurately represent impact absorption during athletic movements (Dixon & Stiles 2003; Nigg & Yeadon 1987). In addition, mechanical devices have been deemed invalid for impact testing on point elastic surfaces such as 3G turf, on which the surface material is only deformed at the point where force is applied (Nigg & Yeadon 1987). This highlights the need for biomechanical measurements to gain results reflecting genuine movement.

Still far from being considered the standard, investigations of the impact absorbing qualities of 3G turf by means of *in vivo* experiments are not uncommon, in no small part due to the possibility of using pressure insoles (Bentley et al. 2011; Ford et al. 2006; Queen et al. 2008; Wong et al. 2007). However, more often than not, these experiments focus on the pressure distribution over the foot rather than attempt to interpret the results in light of general impact absorption. A reason for this might be that the forces registered with pressure insoles are lower than those registered with force plates (Barnett et al. 2001), indicating that it might be wise to practice caution when interpreting results from pressure insoles with respect to the magnitude of impact absorption. Nevertheless, pressure insoles still serve a purpose in evaluating impact absorption on 3G turf. Their consistent decrease in impact force across cleat configurations (Barnett et al. 2001) means they should maintain the ability to detect differences, where present, to the same degree a force plate is able to. Biomechanical experiments on 3G turf incorporating a force plate do exist, but, despite their advantage of providing accurate force measurements, remain rare. Unfortunately, to date, they have either demonstrated a neglect of cleat configurations (Meijer et al. 2006) or limited the surface scope to a singular turf system (Müller et al. 2010). This makes it difficult to interpret the results in the context of shoe-surface interactions across different turf systems and cleat configurations, both of which may affect impact absorption simultaneously.

Impact forces in running typically reach magnitudes of approximately 2-3 times body weight (Frederick 1986; Nigg & Wakeling 2001), with sports specific movements producing similar results (Stiles & Dixon 2006). Impact forces on 3G turf from *in vivo* experiments correspond well with these values, generally comprising a range of 2.3-2.6 times body weight for running (Meijer et al. 2006; Müller et al. 2010) and rapid changes of direction (Müller et al. 2010; Queen et al. 2008), suggesting that the impressions ingrained by earlier generations of artificial turf do not do 3G turf justice. Further strengthening the case of 3G turf, impact absorption does not appear to be affected in a meaningful way by infill type (Meijer et al. 2006), meaning that a variety of turf system configurations might prove adequate in providing the desired level of impact absorption.

Experiments based on pressure insoles or force plates also tend to place greater emphasis on the shoes, something which is often lacking in the mechanical devices. It appears as though an important distinction may exist between turf cleats (a dense pattern of short cleats covering most of the sole) and cleat configurations with fewer, longer cleats; turf cleats demonstrate increased impact absorption (Queen et al. 2008), while it remains difficult to distinguish more aggressive cleat configurations from each other (Müller et al. 2010; Queen et al. 2008). There are even instances of aluminum screw-in cleats, likely considered the most aggressive cleat configuration available to date, being used in *in vivo* investigations of impact absorption on 3G turf (Bentley et al. 2011; Müller et al. 2010). However, the specific parts of these experiments pertaining to the screw-in cleats would do well to be disregarded, as this cleat configuration traditionally is reserved for a soft ground with wet grass, making it a strange choice for 3G turf testing (not to mention a wholly unrealistic choice from an athlete's point of view).

1.3.5. Traction

The most common test methods employed for investigating traction on artificial turf involve the use of mechanical devices designed to replicate a sports specific movement. Seemingly based on the FIFA standardized tests, the mechanical devices are often adapted versions of the rotational traction test (Figure 3), seeking to increase the degree to which it corresponds to genuine athletic movement, typically with regard to magnitude of force or velocity of movement. The mechanically replicated movement is usually assumed to represent situations involving a high risk of injury, such as a sudden rotation. These types of movements have traditionally been considered potentially less harmful when performed on grass due to the surface's inherent ability to allow permanent deformation, whereas artificial turf (regardless of generation) offers more resistance, being confined to an elastic response to excessive forces.

The brunt of the attention has been afforded rotational traction, presumably because of its apparent link to torsion-related injuries. The result is a dearth of knowledge concerning translational traction. Although it might seem counter-intuitive, the shoe does not (or to a very small degree) rotate on the surface when a player is performing accelerations, decelerations, and rapid directional changes, as the main requirement is translational traction sufficient enough to avoid slipping (Frederick 1993). Hence, these movements, commonly assumed to cause injuries (Alentorn-Geli et al. 2009), are predominantly translational in their nature (Frederick 1993; Sabick et al. 2009). If isolated rotation of the shoe on the surface occurs, which is what most of the mechanical devices attempt to replicate, the movement is already inappropriate and high traction accompanied by an elevated risk of injury should not come as a surprise. What is most interesting from the point of view of evaluating the properties of 3G turf is whether or not the traction during appropriate movements is so high that it predisposes athletes for injuries, making the surface itself more harmful than its natural counterpart. Translational traction is a necessity for performance, allowing athletes to make sudden movements without slipping, while rotational traction is generally linked to injuries, making the combination of high translational traction and low rotational traction the desired one for sports surfaces (Frederick 1993; Shorten et al. 2003; Villwock et al. 2009b). Directly contradictory to this, 1G turf had high rotational traction and low translational traction (Shorten et al. 2003), basically meaning that by today's standards it was made for injuries, not performance.

As is the case for impact absorption, cleat configuration has the potential to be an important factor for traction at the shoe-surface interface. The modern bladed cleats (long, irregular cleats placed primarily around the edges of the sole) earned a reputation for high traction quickly after their introduction (Lambson et al. 1996), the property unequivocally attributed to cleat shape. For better or worse, this reputation remains today (Taylor 2010), perhaps aided by soccer shoe producers' penchant for continually advertising traction as an exclusively positive property.

1.3.5.1. Mechanical devices

Similar to earlier generations of artificial turf (Bonstingl et al. 1975; Bowers & Martin 1975; Heidt et al. 1996; Lambson et al. 1996; Torg et al. 1974; Torg et al. 1996), what is currently known regarding 3G turf, shoe-surface interactions, and traction is mostly reliant upon mechanical device data (Cawley et al. 2003; Kuhlman et al. 2009; Livesay et al. 2006; Sabick et al. 2009; Severn et al. 2010; Severn et al. 2011; Shorten et al. 2003; Villwock et al. 2009a; Villwock et al. 2009b; Wannop et al. 2012). However, despite the advantages mechanical devices hold regarding factors such as reproducibility, it has not translated to unambiguous results, possibly due to the many different adaptations that exist. This becomes apparent when rotational traction varies between mechanical devices that are tested directly against each other (Severn et al. 2011).

When compared to both grass and 1G turf, the previously mentioned desired combination of low rotational traction and high translational traction has been identified on 3G turf (Shorten et al. 2003). Still, contradictory discoveries, showing 3G turf to display greater rotational traction than grass at both lower (Livesay et al. 2006) and higher (Villwock et al. 2009a) loads, leave its safety and performance shrouded in questions while failing to reveal a consistent pattern with regard to load. Further complicating the interpretation of load is the bidirectional manner in which it appears to influence traction on 3G turf when increased, with rotational traction increasing (Severn et al. 2010) and translational traction decreasing (Kuhlman et al. 2009). The differences uncovered are not caused by the mechanical devices alone, though, as rotational traction also varies between 3G turf systems (Severn et al. 2011), with greater traction suggested to coincide with increased fiber heights and higher infill densities. Whereas clear tendencies of how most turf system components affect traction are difficult to see, infill density appears to be a turf system property with a rare consistency to it. Rotational traction decreases with a base layer of simulated thatch (a so-called "root zone") and increases with the finer cryogenically processed SBR infill (Villwock et al. 2009b), turf system components reducing and facilitating infill compaction, respectively. Translational traction, in the form of traction coefficients, also increases with greater infill density (Severn et al. 2011), a discovery that is consistent across turf systems.

Despite the reputedly high traction design of bladed cleats, the available literature indicates that much is yet to be resolved. Although bladed cleats have been discovered to produce higher traction coefficients than traditional round cleats (Kuhlman et al. 2009), the two cleat types have also yielded traction coefficients that are comparable at both low (Shorten et al. 2003; Wannop et al. 2012) and high (Sabick et al. 2009) loads. Across these experiments, greater traction coefficients generally coincide with higher loads, but possible exceptions to this tendency are also present (Shorten et al. 2003). A further increase in traction coefficients with an even greater load (Kuhlman et al. 2009) provides additional evidence for a potential load-dependency.

Interestingly, turf cleats, with a far less aggressive cleat configuration, can provide traction coefficients similar to both bladed cleats and traditional round cleats (Shorten et al. 2003). Turf cleats may even produce traction force of a greater magnitude than more pronounced cleat configurations (Cawley et al. 2003). Perhaps more surprisingly, in some instances the similarity between all three cleat configurations holds true for rotational traction (Livesay et al. 2006; Shorten et al. 2003; Villwock et al. 2009a). However, the results are not consistent; rotational traction is lower with turf cleats when compared to traditional round cleats at low loads (Livesay et al. 2006) and both traditional round cleats and bladed cleats at high loads (Villwock et al. 2009a; Villwock et al. 2009b).

The differing results due to the various adaptations employed indicate that, instead of attempting to reproduce a realistic load situation mechanically, it might be wise to conduct experiments with genuine athletic movement to ensure that realistic load conditions and hence meaningful results are obtained.

1.3.5.2. Biomechanics

Studies on traction fully embracing the biological aspect have been few and far between, despite being advocated for approximately two decades (Frederick 1993; Heidt et al. 1996; Sabick et al. 2009). This is somewhat confusing considering the general desire to be able to form a conclusive opinion on the extent to which athletes are affected by artificial turf, whether it be in combination with a specific cleat configuration or not. Most likely this is a result of the lack of absolute control that is introduced when including humans as opposed to mechanical devices. However, as is the case for mechanical devices intended for measuring impact absorption, what they gain in control they lack in accurate representation of the true dynamics of shoe-surface interactions.

An attempt has been made to employ high-speed video analysis of genuine athletic movements on 3G turf with the intent to provide a better framework for mechanical devices (Kirk et al. 2007), though it remains unsure whether or not the results are suitable for improving what is currently in use. As for the immediate results, high-speed video analysis proved ineffective in detecting any differences between traditional round cleats and bladed cleats with regard to traction properties (Kirk et al. 2007). Echoing this is the discovery of similar traction coefficients on 3G turf, derived from force plate data, between the two cleat configurations during both running and rapid changes of direction (Sterzing et al. 2010). This last experiment is based on the same forces as one presented previously concerning impact absorption (Müller et al. 2010) and hence is essentially the same one, further illustrating the scarceness of *in vivo* experiments on 3G turf in general.

1.4. Aims

In short, the main objections to the advance of artificial turf with regard to game play remain the supposed poor impact absorption and excessive traction, both of which may be influenced by surface and shoe properties. The overall aim of the work included in the current thesis was to provide the rapidly growing field of artificial turf research with objective, athlete-based data at a detailed level, of which there is a surprising lack in the literature, covering these issues. This should help to establish a proper baseline for further *in vivo* study, encouraging its use as mechanical devices do not accurately depict the shoe-surface interactions taking place during genuine athletic movement.

More specifically, the aim was to investigate whether or not differences exist between various turf systems and commonly used cleat configurations with regard to impact absorption and translational traction, including the effect of independently chosen cleat orientation on traction, when measured *in vivo* during genuine, albeit standardized, athletic movements with corresponding forces. Further, the aim was to quantify the *in vivo* magnitudes of impact and traction.

2. METHODS

Permission to conduct the experiment was given by the Regional Ethical Committee and it was conducted in accordance with the Declaration of Helsinki. Although not all parts of the experiment and calculated variables were utilized for each paper, they are presented as a whole in the current thesis.

2.1. Subjects

Twenty-two male soccer players (mean ± standard deviation (SD) age 23.1 ± 2.8 years, height 1.81 ± 0.06 m, and body mass 77.5 ± 6.0 kg) were recruited for the experiment. Playing level ranged from professional to recreational, encompassing the entire organized division structure in Norway. To ensure homogeneity of the group, the following criteria for participation were enforced: male, age 18-30 years, right leg dominant (not tested explicitly as part of the experiment), playing at an organized level, a minimum of two years' experience with 3G turf, free of major injuries to the lower extremities for the past six months, no known diagnoses or conditions that could influence the ability to participate (e.g., heart condition), and shoe size from 42 to 44 (US size 8½ to 9½). All subjects signed an informed consent form prior to participation and were made aware that they could withdraw from the experiment at any point without providing an explanation.

2.2. Laboratory setup: equipment and data collection

Due to the confines of the laboratory situation, the effort to recreate an environment that was as realistic as possible was limited to turf-covered wooden running tracks, as opposed to a larger general area, constructed around a BP6001200 AMTI 3D force plate (Advanced Medical Technology Inc., Watertown, MA, USA), on which three FieldTurf (FieldTurf Tarkett, Calhoun, GA, USA) 3G turf systems were alternately fastened. To withstand movement, the turf systems (0.6 x 1.2 m) were held in place by means of 3M Dual Lock reclosable fasteners (3M Norway AS, Skjetten, Norway). They were equipped with hard rubber borders to ensure they could be placed isolated on the force plate, complete with infill, without touching the adjacent running tracks (Figure 4). All running tracks were secured to the floor with a ~0.5 cm gap to the force plate to avoid signal distortion resulting from impacts occurring prior to contact with the force plate. A designated contact area of 0.6 x 0.6 m was marked on the turf systems fastened to the force plate.

Around the force plate, six ProReflex motion capture cameras (Qualisys, Gothenburg, Sweden) were placed, providing a 360° view. In addition, three pairs of photo cells (TC-PhotoGate A&B, Brower Timing Systems, Draper, UT, USA) were placed along the in-run at a height of ~1 m above the running track. Data from the photo cells were transmitted wirelessly to a handheld receiver (TC-Timer, Brower Timing Systems). The laboratory setup, with complete dimensions, can be seen in Figure 5.

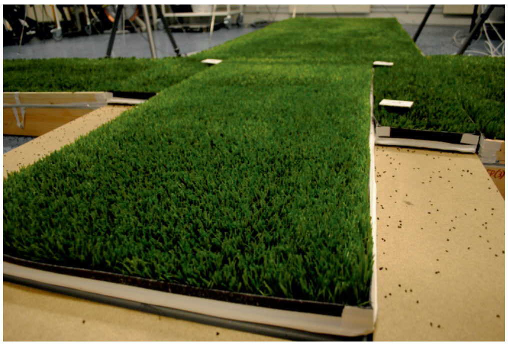


Figure 4. Hard rubber borders ensured that the infill was kept in place with the turf systems isolated on the force plate. Temporary markers indicated the designated contact area (one marker not visible in photograph).

Force and position data were recorded using Qualisys Track Manager 2.5.595 (Qualisys) and processed in Matlab 7.9.0.529 (Mathworks, Natick, MA, USA). Dynamic signals (force), acquired via a DSA-6 digital strain gage amplifier (Advanced Medical Technology Inc.), were recorded at a sample rate of 1000 Hz. Kinematic signals (position) were recorded at a sample rate of 500 Hz, obtaining a spatial resolution of 0.3 mm.

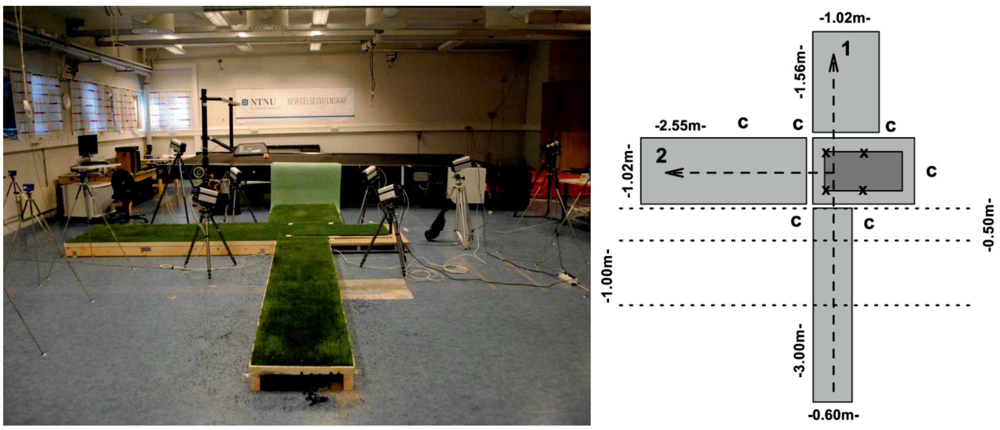


Figure 5. Left: picture of the laboratory setup. Right: schematic of the dimensions of the laboratory setup. The force plate (dark gray, 0.6 x 1.2 m) is surrounded by running tracks (light gray), with six cameras (c) angled toward the designated contact area (x). Horizontal dotted lines represent photo cell trigger beams. Dashed line arrows represent movement directions of running tasks: a straight sprint with a sudden stop (1) and a sprint with a 90° cut to the left (2).

Ambient temperature in the laboratory was ~20 °C with a relative humidity of ~40 % throughout the data collection period, as measured by a La Crosse Technology WS-868025 weather station (La Crosse Technology, La Crosse, WI, USA). This is approximately consistent with the guidelines for laboratory environments provided by FIFA, specifying that tests should be conducted at an ambient temperature of 23 ± 2 °C (FIFA 2009b).

Table 1. Detailed specifications of the turf systems.

	Turf system producer	Duraspine Ultra 42 FieldTurf Tarkett	Duraspine Ultra 50 FieldTurf Tarkett	Duraspine Ultra 60 FieldTurf Tarkett
FIBER	type	monofilament	monofilament	monofilament
	material	polyethylene	polyethylene	polyethylene
	height (mm)	42	50	60
	weight (dtex)	11500	11500	11500
	thickness (micron)	80 – 240	80 – 240	80 – 240
	tufts/m^2	9450	8820	8190
	strands/tuft	6	6	6
	tuft pattern	straight	straight	straight
	height above infill (mm)	15	15	15
	total weight/m^2 (kg)	0.956	1.101	1.217
STABILIZATION INFILL	material	Quartz sand	Quartz sand	Quartz sand
	infill thickness (mm)	5	8	13
	weight/m^2 (kg)	8	12	18
	particle size (mm)	0.4 – 0.8	0.4 – 0.8	0.4 – 0.8
	particle shape	round	round	round
SHOCK ABSORBING INFILL	material	SBR	SBR	SBR
	manufacturing process	ambient ground	ambient ground	ambient ground
	infill thickness (mm)	20	27	32
	weight/m^2* (kg)	7.5	10.5	12
	particle size (mm)	1 – 3.15	1 – 3.15	1 – 3.15
	particle shape	angular	angular	angular
SHOCK PAD	type	Recticel Rebound	--	--
	material	composite foam	--	--
	thickness (mm)	12	--	--
	weight/m^2 (kg)	3.1	--	--

* ~75 % of amount detailed in producers specifications, as described in the text.

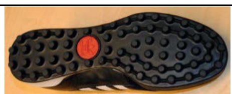
2.2.1. *Turf systems*

Three different 3G turf systems from FieldTurf were included in the experiment: Duraspine ULTRA 42 (DU42), a professional-level turf system with an underlying shock pad; Duraspine ULTRA 50 (DU50), a recreational-level turf system without an underlying shock pad; Duraspine ULTRA 60 (DU60), a professional-level turf system without an underlying shock pad (Unisport Scandinavia AS, Drammen, Norway).

Figure 6. Soccer shoe models included in the experiment. From top to bottom: adidas Mundial Team TF, adidas Copa Mundial FG, adidas adiPURE 3 TRX FG.

In accordance with the instructions provided by the producer, upon initial installation in the laboratory the amount of ambient ground SBR infill was decreased to ~75 % of what was detailed in the product specifications. This was done to ensure ~1.5 cm of free fiber above the infill. Rather opting for additional infill at a later point if necessary, this method is customary to avoid excess infill at installation. The running tracks surrounding the force plate were covered with DU50 for all three turf system conditions on the force plate, making the average difference in height from in-run to force plate as small as possible. Complete turf system details are presented in Table 1.

Table 2. Cleat configuration details.

	Cleat type	Surface	Number of cleats (heel/forefoot)	Cleat height range (mm)
	Turf	Turf/gravel	20/45	6-9
	Traditional round	Firm grass	4/8	9-11
	Bladed	Firm grass	4/9	11-13

2.2.2. Cleat configurations

Three different soccer shoe models manufactured by adidas (adidas, Beaverton, OR, USA) were included in the experiment, each representing a typical cleat configuration (Figure 6): adidas Mundial Team TF (turf cleats); adidas Copa Mundial FG (traditional round cleats); adidas adiPURE TRX FG (bladed cleats). All the shoes were from size 42 to 44 (US size 8½ to 9½). Further cleat configuration details are provided in Table 2. The right shoe of each pair was fitted with six semi-spherical reflective markers, providing the ability to define the orientation of the shoe in space. The markers, one each at the heel and toe and the remaining four bilaterally 6 cm in from the heel and toe, respectively, were placed at a height of 5 cm from the bottom of the shoe, cleats included (Figure 7).

Figure 7. Placement of reflective markers on shoe (pictured: adidas adiPURE 3 TRX FG).

2.3. Experimental protocol

Testing was carried out over a period of approximately two months, in which every subject completed three separate days of testing; one for each turf system. Each day of testing consisted of a self-regulated warm-up of ten minutes running on a treadmill (Woodway, Waukesha, WI, USA), a weight measurement, and 30 sprints with maximum effort, for a total of 1980 sprints across all subjects, turf systems, and cleat configurations. The sprints were divided evenly among two separate running tasks (Figure 5) performed alternately: a straight sprint with a rapid deceleration (termed "stop sprint"), in which the subjects were instructed to come to a complete stop within two steps after striking the designated contact area with their right foot; a sprint with a 90° cut to the left (termed "cut sprint"), in which the subjects were instructed to plant their right foot in the designated contact area and perform the aforementioned change of direction while maintaining velocity.

The subjects were allowed to familiarize themselves with both tasks before data collection commenced. Sprints were performed in groups of ten for each cleat configuration, comprising five for each running task. Rest periods of 30-45 s between each sprint and >2 min between groups of ten sprints were included to minimize fatigue. The sequences of turf systems, cleat configurations, and running tasks were all counterbalanced to avoid systematic order effects.

At the end of each day of testing, the subjects were asked to rank the shoes from 1 to 3 (1 being the best) with regard to performance, comfort, and personal preference. If unable to distinguish two shoes from each other, they were both given the same rank at the opposite end of the scale of the one which could be distinguished from the others.

2.4. Data analysis

Both dynamic and kinematic signals were low-pass filtered at 100 Hz using an 8^{th} order Butterworth filter. If present, any offsets in the force data were adjusted. Gaps caused by missing kinematic data were interpolated. Body mass was determined as the mean of the three weight measurements. In an effort to diminish the effect of triggering the photo cells prematurely with an outstretched arm when running, approach velocity (v_{app}) was calculated from the final 1.5 m of the in-run rather than the final 0.5 m ($m \cdot s^{-1}$). Across all subjects, 137 of 990 (13.8 %) stop sprint velocity files and 31 of 990 (3.1 %) cut sprint velocity files were discarded due to equipment error, evenly distributed among all shoe-surface combinations (mean number of files discarded was 15.2, range 9-20, and 3.4, range 1-6, respectively).

Impact was determined to occur when vertical force exceeded 2 SDs above the mean of baseline force (i.e., unloaded force plate). Impact absorption of turf systems and cleat configurations was indicated by peak total impact (f_{timp}) relative to subject body weight (W), calculated as

$$f_{timp} = \frac{F_{peak}}{W} \quad [1]$$

where F_{peak} is the peak of the vector sum of vertical and horizontal force during impact. Time of contact (t_{con}) was defined as the duration of the impact period. Peak vertical impact (f_{vimp}) and traction (f_{trac}) force during impact were also determined relative to subject body weight (W), as

$$f_{vimp} = \frac{F_{vpeak}}{W} \quad [2]$$

and

$$f_{trac} = \frac{F_{hpeak}}{W} \quad [3]$$

respectively, where F_{vpeak} is peak vertical force and F_{hpeak} is peak horizontal force. The total change in velocity ($m \cdot s^{-1}$) during impact was calculated for both the initial running direction (Δv_{run}) and the cutting direction (Δv_{cut}), as

$$\Delta v = \sum_{i=1}^{N} \left(\frac{F_{hi} \times \Delta t}{m} \right) \quad [4]$$

where F_h is horizontal force in the corresponding direction, Δt is sample time, m is subject mass, and N is number of samples. In the initial running direction, a negative change in velocity is indicative of braking. In the cutting direction, a positive change in velocity is indicative of acceleration.

Within the impact period, a 2 SD threshold (corresponding to the one used to determine the impact period) above toe and heel vertical position baselines was used to determine the temporal occurrence of full sole-surface contact (see paper II). The vertical position baselines were isolated to a period during which it could be assumed that the entire sole contacted the surface (25-60 % of impact time). The presence or absence of sliding of the shoe over the surface during full sole-surface contact was determined through linear regression, and, if present, the angle of movement was determined. The entire coordinate system was then rotated a corresponding angle, redistributing the proportions of x and y component forces, such that the new x axis and sliding direction coincided. Traction coefficient (μ) was calculated during full sole-surface contact, as

$$\mu = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{F_h}{F_v} \right)_i \quad [5]$$

where F_h is horizontal force in sliding direction, F_v is vertical force, and N is number of samples. Sliding velocity (v_{slide}) during full sole-surface contact was calculated as the mean velocity ($\text{cm}\cdot\text{s}^{-1}$). Both μ and v_{slide} were deemed invalid if sliding of at least 3 mm (ten times the resolution) could not be demonstrated or if 90 % of the sliding movement present occurred prior to 40 % of full sole-surface contact time (thresholds determined through visual inspection). Across all subjects, 258 of 990 (26.0 %, mean number of files discarded across all shoe-surface combinations was 28.7, range 16-44) cut sprint files were unable to provide a valid μ.

Transverse plane shoe angle (α) during full sole-surface contact was calculated as the mean angle of shoe orientation relative to the angle of sliding. Shoe angle magnitude indicates the degrees of medial rotation relative to sliding direction. From positional data, displacement of the shoe during full sole-surface contact (Δl_{slide}) was determined as the displacement in cm in sliding direction. Across all subjects, 304 of 990 cut sprint files (30.7 %), evenly distributed among all shoe-surface combinations (mean number of files discarded was 33.8, range 21-46), either were unable to provide a valid μ or could not provide a suitable basis for determining shoe angle or shoe displacement due to missing data.

2.5. Force magnitude test

To validate the experimental method chosen with regard to magnitude of force when placing a surface on top of the force plate, simultaneous measurements were conducted with the force plate under the surface and an Artificial Athlete device (FIFA 2009b) over the surface. For each turf system, five impacts were recorded, each at a different area of the turf system. For this purpose, data from both devices were low-pass filtered at 120 Hz using a 2nd order Butterworth filter, in compliance with FIFA standards (FIFA 2009b).

2.6. Statistical analysis

All statistical analyses were performed in PASW Statistics 18 (SPSS, Inc., an IBM Company, Chicago, IL, USA), release 18.0.0. Statistical significance was set at $p < .05$. Where applicable, data are presented as mean ± SD. Note that although several of the statistical analyses utilize estimated marginal means, arithmetic means are presented for ease of understanding, as they are close to identical.

The effects of turf system and cleat configuration on f_{timp}, t_{con}, f_{vimp}, f_{trac}, Δv_{run}, and Δv_{cut} were assessed using two-way analyses of variance (ANOVA) for repeated measures, corrected for between-subject effects. Degrees of freedom were adjusted using the Huynh-Feldt correction if sphericity could not be assumed. Where significant F-values were present, a post hoc LSD correction was applied.

The effects of turf system and cleat configuration on v_{app}, μ, v_{slide}, and Δl_{slide} were assessed using linear mixed models, with turf system and cleat configuration set as fixed effects and accounting for intra-individual variance as a random effect, due to random missing values resulting from either equipment error (v_{app}) or a strict calculation process (μ, v_{slide}, Δl_{slide}). To better assess the main effects, non-significant interaction effects were removed from the analyses where applicable.

The relationships between μ and α across cleat configurations and turf systems, respectively, were assessed using an analysis of covariance (ANCOVA), with α as the covariate, cleat configuration and turf system as factors, and μ as the dependent variable. Linearity of the data was determined through ordinary least squares regression, while, due to the large sample size, normality was assumed if both kurtosis and skewness fell between -1 and 1. Levene's test for equality of error variances supported homogeneity of variance ($F_{8,677} = 1.08$, $p = .372$). Any interaction term was removed and the model re-run if the factor-covariate interaction was non-significant. Trials were treated as independent due to the within-subject variation in α and since neither exhaustion nor learning effects were expected between the first and last repetition within a specific combination of cleat configuration and turf system. Hence, subject and repetition were not included as fixed factors in the model. Missing data were deleted list-wise.

The subjective ranking of shoes was assessed using separate Friedman's ANOVAs for performance, comfort, and personal preference, respectively. Where significant, Wilcoxon's signed-ranks tests were performed post hoc to assess differences between shoes.

3. SUMMARY OF RESULTS

Table 3 shows mean ± SD of all impact and traction variables across turf systems and cleat configurations, with the exception of the $\mu - \alpha$ relationship. Traction results are reported for cut sprints only. Across all cleat configurations, the mean v_{app} was 3.50 $m \cdot s^{-1}$ for stop sprints and 2.93 $m \cdot s^{-1}$ for cut sprints. In cut sprints, bladed cleats produced a marginally, but significantly, slower v_{app} than both turf cleats and traditional round cleats.

3.1. Paper I: Impact absorption

For stop sprints, the f_{timp} range was 2.94-3.18 W and the t_{con} range 170-194 ms across all shoe-surface combinations. For cut sprints, the f_{timp} range was 2.77-3.01 W and the t_{con} range 326-341 ms across all shoe-surface combinations. Mean ± SD f_{timp} and t_{con} for all shoe-surface combinations for both running tasks are presented in Figure 8.

Among turf systems, inferior impact absorption was demonstrated consistently on DU50, with a greater f_{timp} and a shorter t_{con} in stop sprints and a shorter t_{con} in cut sprints compared to both DU42 and DU60, between which the only difference was a longer t_{con} on DU42 in stop sprints.

Among cleat configurations, a more ambiguous response was elicited. Traditional round cleats demonstrated a greater f_{timp} than turf cleats and bladed cleats in cut sprints, while bladed cleats demonstrated a shorter t_{con} in stop sprints, increasing progressively with traditional round cleats and turf cleats, respectively. In general, superior impact absorption was demonstrated with turf cleats.

Significant interactions were present only for t_{con}: the effect of cleat configuration was greater on DU60 in stop sprints and greater on DU42 in cut sprints; the effect of turf system was greater when using turf cleats in stop sprints and when using traditional round cleats in cut sprints.

Table 3. Impact and traction variables across turf systems and cleat configurations (mean ± SD). Note that variables exclusive to traction are presented for cut sprints only.

	Running task	Turf system (T) Cleat configuration (C)	DU42 Turf cleats	DU50 Round cleats	DU60 Bladed cleats
v_{app} ($m \cdot s^{-1}$)	Stop	T	3.46 ± 0.52	3.50 ± 0.49	3.53 ± 0.58
		C	3.51 ± 0.55	3.47 ± 0.52	3.50 ± 0.52
	Cut	T	2.92 ± 0.36	2.93 ± 0.34	2.94 ± 0.37
		C *	2.97 ± 0.35 ^{b}	2.94 ± 0.35 ^{b}	2.89 ± 0.37
t_{con} (ms)	Stop	T ***	191 ± 45 $^{a\,b}$	175 ± 36 ^{b}	185 ± 46 ^{a}
		C ***	189 ± 47 $^{a\,b}$	183 ± 44 ^{b}	179 ± 36 ^{a}
	Cut	T **	337 ± 74 ^{a}	328 ± 76	335 ± 73 ^{a}
		C	333 ± 76	333 ± 73	333 ± 75
f_{timp} (*W*)	Stop	T **	3.01 ± 0.74 ^{a}	3.12 ± 0.81	3.02 ± 0.75 ^{a}
		C	3.01 ± 0.76	3.06 ± 0.77	3.08 ± 0.77
	Cut	T	2.89 ± 0.60	2.93 ± 0.64	2.88 ± 0.60
		C ***	2.84 ± 0.54 ^{a}	2.99 ± 0.68	2.87 ± 0.61 ^{a}
f_{vimp} (*W*)	Stop	T **	2.88 ± 0.66 ^{a}	3.01 ± 0.76	2.91 ± 0.70 ^{a}
		C *	2.87 ± 0.69 $^{a\,b}$	2.96 ± 0.72	2.97 ± 0.72
	Cut	T	2.49 ± 0.54	2.54 ± 0.59	2.51 ± 0.55
		C ***	2.42 ± 0.48 $^{a\,b}$	2.62 ± 0.62 ^{b}	2.51 ± 0.56 ^{a}
f_{trac} (*W*)	Cut	T *	1.61 ± 0.38 ^{b}	1.61 ± 0.35 ^{b}	1.57 ± 0.34
		C ***	1.63 ± 0.38 ^{b}	1.60 ± 0.36 ^{b}	1.56 ± 0.33
μ (-)	Cut	T	0.65 ± 0.07	0.65 ± 0.07	0.65 ± 0.07
		C	0.66 ± 0.07	0.65 ± 0.07	0.65 ± 0.07
Δv_{run} ($m \cdot s^{-1}$)	Cut	T **	-1.98 ± 0.36 ^{a}	-1.94 ± 0.30	-1.98 ± 0.36 ^{a}
		C *	-1.98 ± 0.34 ^{b}	-1.97 ± 0.34 ^{b}	-1.95 ± 0.35
Δv_{cut} ($m \cdot s^{-1}$)	Cut	T ***	1.90 ± 0.37 $^{a\,b}$	1.84 ± 0.34	1.83 ± 0.34
		C **	1.88 ± 0.34 ^{b}	1.86 ± 0.37	1.84 ± 0.34
v_{slide} ($cm \cdot s^{-1}$)	Cut	T	6.69 ± 4.21	7.56 ± 5.03	7.02 ± 4.25
		C ***	6.69 ± 3.95 ^{a}	7.66 ± 5.05	6.77 ± 4.30 ^{a}
Δl_{slide} (cm)	Cut	T	1.34 ± 0.59	1.34 ± 0.64	1.33 ± 0.59
		C ***	1.29 ± 0.56 ^{a}	1.46 ± 0.65	1.24 ± 0.58 ^{a}

* Significant differences between turf systems/cleat configurations (* p < .05; ** p < .01; *** p < .001).

[a] Significantly different from DU50/round cleats.

[b] Significantly different from DU60/bladed cleats.

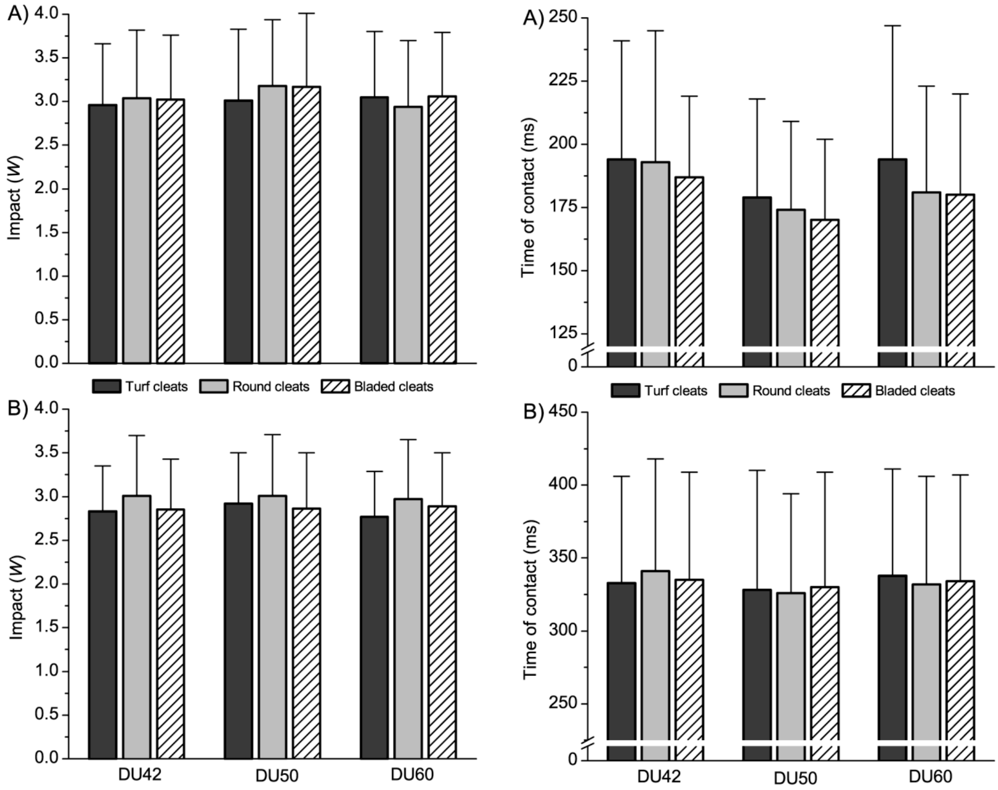


Figure 8. Left: mean ± SD peak total impact (*W*) for all shoe-surface combinations for stop sprints (A) and cut sprints (B). Impacts were significantly greater on DU50 in stop sprints and with traditional round cleats in cut sprints. Right: mean ± SD contact time (ms) for all shoe-surface combinations for stop sprints (A) and cut sprints (B). Contact time differed between all turf systems and cleat configurations in stop sprints and was shorter with traditional round cleats in cut sprints.

3.2. Paper II: Traction

Across all shoe-surface combinations, the f_{trac} range was 1.55-1.68 *W* and the μ range 0.64-0.66. Mean ± SD f_{trac} and time normalized traction coefficient traces for all shoe-surface combinations are presented in Figure 9 and Figure 10.

Among turf systems, DU42 consistently demonstrated higher traction, with greater f_{trac} than DU60, greater Δv_{run} than DU50, and greater Δv_{cut} than both DU50 and DU60. For v_{slide}, f_{vimp}, and μ, no significant differences between the three turf systems were discovered.

Among cleat configurations, turf cleats consistently demonstrated higher traction, with greater f_{trac}, Δv_{run}, and Δv_{cut} than bladed cleats and slower v_{slide} than traditional round cleats. Bladed cleats consistently demonstrated the opposite effect, with lesser f_{trac} and Δv_{run} than turf cleats and traditional round cleats and lesser Δv_{cut} than turf cleats, the lone exception being

v_{slide}. Traditional round cleats produced the greatest f_{vimp}, decreasing progressively with bladed cleats and turf cleats, respectively. Only μ remained unaffected by cleat configuration, although a tendency was observed for greater μ with turf cleats.

For v_{slide} and f_{trac}, significant interactions were also present: the effect of cleat configuration on v_{slide} was lesser on DU42 and the effect of turf system on v_{slide} was greater when using traditional round cleats; the effect of cleat configuration on f_{trac} was lesser on DU60 and the effect of turf system on f_{trac} was lesser when using bladed cleats.

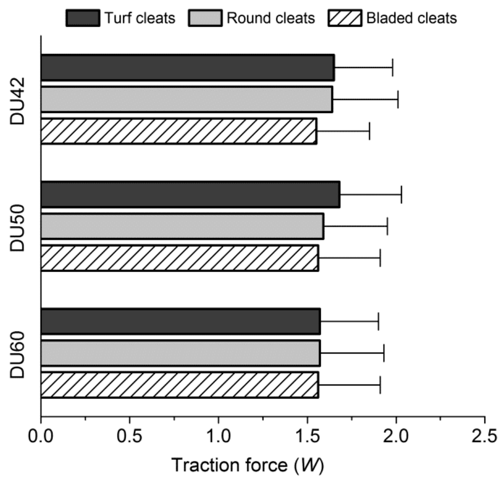


Figure 9. Mean ± SD traction force (W) for all shoe-surface combinations for cut sprints. Traction force was significantly lesser on DU60 and with bladed cleats.

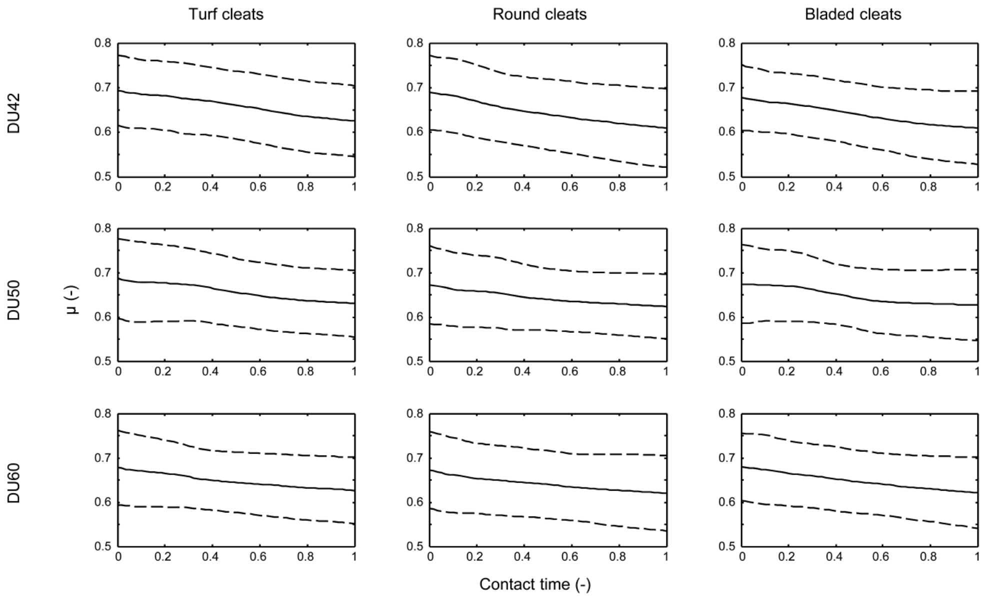


Figure 10. Mean ± SD time normalized traction coefficient traces for all shoe-surface combinations. No significant differences in mean traction coefficients between turf systems or cleat configurations were present.

3.3. Paper III: The relationship between traction and shoe angle

A significant positive $\mu - \alpha$ relationship was discovered ($F_{1,680} = 57.46$, $p < .001$), with a predicted increase in μ of .0017 per degree of α (medial rotation). The relationship, presented in Figure 11, did not differ across cleat configurations ($F_{2,680} = 1.29$, $p = .277$) or turf systems ($F_{2,680} = 0.05$, $p = .950$). The Δl_{slide} range was 1.24-1.46 cm across cleat configurations and 1.33-1.34 cm across turf systems. Traditional round cleats produced a greater Δl_{slide} than turf cleats and bladed cleats, but no differences between turf systems were found. Across all shoe-surface combinations, mean ± SD Δl_{slide} was 1.33 ± 0.60 cm.

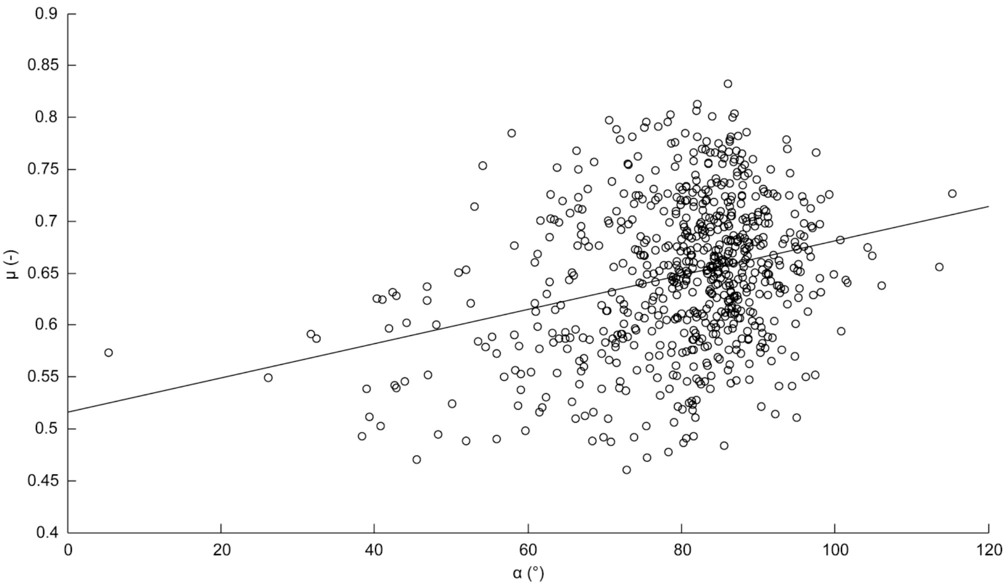


Figure 11. Significant relationship between traction coefficient (μ) and shoe angle (α) for all turf systems and cleat configurations. The slope of the regression line is .0017.

3.4. Subjective ranking of shoes

Table 4 shows mean ± SD subjective ranking of shoes for performance, comfort, and personal preference across cleat configurations (unpublished). Bladed cleats were ranked significantly higher than turf cleats for performance ($z = -2.83$, p = 0.005) and personal preference ($z = -2.95$, p = 0.003). There was a tendency for bladed cleats to rank higher than traditional round cleats as well for both performance ($z = -1.92$, p = 0.055) and personal preference ($z = -1.90$, p = 0.058). No significant differences in ranking of shoes with regard to comfort were discovered.

Table 4. Subjective ranking (1-3) of shoes (mean ± SD).

	Turf cleats	Round cleats	Bladed cleats	df	X^2	*P* value
Performance	2.34 ± 0.78	2.09 ± 0.84	1.65 ± 0.74*	2	6.49	0.038
Comfort	1.73 ± 0.85	2.26 ± 0.77	2.03 ± 0.78	2	4.49	0.105
Personal preference	2.36 ± 0.74	2.15 ± 0.85	1.62 ± 0.78*	2	8.58	0.012

* Significantly different from turf cleats.

4. DISCUSSION

Detailed discussions on the degree to which impact and traction are affected by turf systems, cleat configurations, and – in the case of traction – shoe angles are presented in papers I-III. Hence, the following discussion is rather focused on providing a "big picture" view, highlighting how the variables are connected and what the possible implications of the results are when placed in a larger framework, as well as a broader perspective on methodological considerations when conducting experiments on 3G turf.

4.1. Methodological considerations

Although the element of striving to conduct the perfect experiment is ever-present in research, it is rarely, if ever, feasible. Quite often, time constraints or financial constraints – or a combination of the two – force the necessity of making certain choices potentially narrowing the scope or basis of comparison of the research (even with unlimited resources it is debatable whether or not a perfect experiment is achievable).

4.1.1. Man versus machine

In essence, the methods employed in artificial turf research boils down to the age-old argument of man versus machine. As previously mentioned, new adaptations of mechanical testing devices are seemingly continually developed with the purpose of reproducing human movement more accurately than their predecessors. A major limitation of most current mechanical devices is the application of a constant, static load. Considering the innate ability of humans to adjust loading conditions, these fixed energy devices are contended to represent an insufficient replication of actual surface-athlete loading conditions and may produce invalid interpretations (Fleming 2011a).

In an effort to solve one of the main problems encountered by purely translational or rotational mechanical devices when attempting to replicate realistic movements and corresponding loads occurring at the shoe-surface interface, a device capable of executing a combined drop and translational movement has recently been developed (Kent et al. 2012). Its intention is to mimic a landing with a subsequent cutting move. Mechanical devices such as this have to be viewed as a step in the right direction with regard to replicating genuine athletic movement. However, despite managing to incorporate vertical and horizontal velocity simultaneously, some problems persist with the suggested method of combined movement. In a drop, the mass is subject only to gravitational forces, meaning there is no active adjustment of force during impact; it is completely passive. During impact, horizontal force is only arrested by the shoe-surface interaction, meaning there is no active force working in the direction of movement after impact; it too is passive. These factors make it difficult to consider the device representative of dynamic movement.

The device uses a mass of 42 kg and a horizontal velocity 1.5 $m \cdot s^{-1}$, achieving a target peak impact force of approximately three times body weight (~3000 N, target athlete mass 95 kg). This adheres to the American Society for Testing and Materials (ASTM) standard F2333-04, "Standard test method for traction characteristics of the athletic shoe-sports surface interface", which specifies a normal load of 3000 N for replicating stopping movements and 2200 N for replicating cutting movements, along with a minimum sliding velocity of 30 $cm \cdot s^{-1}$ for reporting traction coefficients (Kuhlman et al. 2009). Results from paper II show that, using human subjects, relative impacts of a similar magnitude (i.e., three times body weight) were obtained with a mean mass of 77.5 kg and mean horizontal velocities of 3.50 $m \cdot s^{-1}$ and 2.93 $m \cdot s^{-1}$. The fact that approximately twice the mass and horizontal velocity uncovered similar relative impacts indicates that athletes actively affect the forces in genuine movement. This is an important factor which seemingly cannot, at least to date, be replicated with mechanical devices.

Even with the constant development of mechanical devices, paramount to large-scale testing, there is still a long way to go toward reaching the ideal of accurately reproducing surface-athlete interactions under realistic, dynamic load conditions. In fact, this might not even be attainable considering the uncertainty regarding the specifics of the dynamic behavior exhibited by athletes.

4.1.2. Disregarding grass

Lying at the heart of almost every topic related to artificial turf is the conflict of how it measures up to grass. For laboratory experiments concerned with mechanical surface characteristics, a range of 3G turfs would ideally be compared against a range of grass fields, allowing for a direct comparison of the two surface types. However, while a turf system can be separated by layers (Figure 2) there is no standard for, e.g., the amount of soil that should be included under the surface when performing experiments on grass. This is not to say that the task is impossible. Instances of grass being successfully introduced in a laboratory setting do exist (Smith et al. 2004; Stiles et al. 2006), but it is difficult to ascertain their validity with regard to *in situ* conditions. Regardless, the concept of using grass as a benchmark for comparison appears somewhat flawed, as the characteristics of different species vary widely (Orchard & Powell 2003) and it is highly variable between different climates and regions, even to the point of inconsistencies between different parts of the same field (Ekstrand & Nigg 1989; Stanitski et al. 1974; Theobald et al. 2010). This forces the issue of basically being limited to comparisons between different turf systems.

4.1.3. Surface-covered force plate

The setup employed in the current experiment, affixing a surface (such as 3G turf) to a force plate, has been criticized for its alleged inaccuracy, as it purportedly alters the data registered by the force plate (Pedroza et al. 2010). Synchronous measurements with the force plate and an Artificial Athlete device (FIFA 2009b) revealed that, across all turf systems, the mean peak force registered by the force plate (underneath the surface) was 98.7 ± 1.2 % (range 98.0-99.8 %) of that registered by the Artificial Athlete (above the surface). In addition, force profiles failed to display signs of being distorted with regard to shape for any of the turf systems. Concerning the validity of the general magnitude of force registered, the experimental conditions are similar to what athletes are subjected to on regular 3G turf fields, where the turf system is installed over a number of fairly hard base layers with purposes such as drainage and leveling.

4.1.4. Turf systems

The three turf systems used in this experiment only represent a segment of what is obtainable on the market since they all come from the same manufacturer. Nevertheless, they do largely cover what is in extensive use across manufacturers today, both at the professional (DU42 and DU60) and the recreational (DU50) level.

Perhaps due to the industry being comparatively smaller and hence the alternatives fewer, research done on 1G and 2G turf rarely emphasized the particular surface employed. Unfortunately, the problem of insufficient surface specifics, previously mentioned with regard to population-based studies, was apparently carried over into both mechanical device studies and biomechanical studies on 3G turf. This has yet to be fully resolved, as there is still research being published where the surface in question is simply referred to as “3G turf” or by brand name alone without any further specification (Cawley et al. 2003; Kuhlman et al. 2009). Although the level of detail tends to be much greater than the gross label of “artificial turf” commonly employed in population-based studies, the information provided on the turf systems tested often leaves a lot to be desired, in some cases possibly caused by manufacturers’ unwillingness to divulge this information (Theobald et al. 2010). This is especially devastating in such a, relatively speaking, small field of research, as it leaves few direct comparisons between studies. To counteract this problem and make future comparisons easier, a conscious effort was made in the current work to present turf system specifications as detailed as possible.

4.1.5. Cleat configurations

Since the cleat variations in existence today can appear almost limitless, a deliberate choice was made to exclude any cleat configuration which, at the time of the experiment, could be considered a potential novelty. Hence, the cleat configurations that were included represent the major categories in most common use, with a seemingly secure position in the market. Despite the existence of inter-brand variations (e.g., bladed cleats from one brand do not necessarily have the exact same shape as bladed cleats from another brand), the cleat configurations of the shoe models chosen provide a good baseline for comparison due to their classic cleat shapes within their respective categories.

In the current experiment, adidas Copa Mundial FG was initially chosen as it is, where applicable, the market-available shoe of choice for FIFA testing (FIFA 2012b). To ensure the shoes were as similar as possible with the exception of their cleat configurations, its artificial turf-counterpart, adidas Mundial Team TF, was a natural choice. Unfortunately, a corresponding version of the shoe with bladed cleats does not exist, forcing the need to settle for the next best thing in adidas adiPURE TRX FG, being the shoe model with bladed cleats closest to the general make-up of adidas Copa Mundial FG as per adidas Norway (personal communication, September 3, 2010).

4.1.6. Determining impact force

Although the standard for describing surface-athlete impacts has generally been vertical force, total impact force (i.e., vector sum of vertical and horizontal force) is rather reported from the current experiment in an effort to more completely reflect the load imposed on the athlete. However, vertical impact is presented in paper II as it may aid in the interpretation of the traction coefficient. Note that peak vertical impact can only be used indirectly to understand the traction coefficient, considering the latter is not derived directly from peak values of vertical and horizontal force. Across turf systems and cleat configurations, relative impacts increased by 3.7 % (range 3.4-4.9 %) in stop sprints and 15.5 % (14.1-17.4 %) in cut sprints with the inclusion of horizontal force.

4.1.7. Determining traction coefficient

Contrary to the FIFA standardized tests, the traction coefficient has not been an uncommon measure from various adapted mechanical devices, recognizing its importance for describing functional traction. However, although the general calculation of the traction coefficient (the ratio of horizontal force to vertical force) is devoid of controversy, a variety of methods for reaching a single value to denote it can be found in the literature, some complicating interpretation more than others. Examples of determining the traction coefficient at peak traction force (Newton et al. 2002), at peak vertical force (Lloyd & Stevenson 1990), as the peak static coefficient (Wannop et al. 2012), as the peak coefficient found (Wannop et al. 2010), as the mean coefficient during initial motion (Shorten et al. 2003), and as the mean coefficient during constant velocity (Kuhlman et al. 2009; Sabick et al. 2009) all exist, whereas others simply omit further details altogether (Andréasson et al. 1986; Bowers & Martin 1975; Severn et al. 2011).

In the current work, a novel method was employed in an effort to quantify the translational traction at the shoe-surface interface, by means of the traction coefficient, as accurately as possible. Since the dynamic traction coefficient is dependent on sliding of the shoe over the surface, this was set as a requirement. Peak vertical force is generally gained later than peak horizontal force, making the traction coefficient, derived from the relationship of horizontal to vertical force, artificially large in the initial stages of shoe-surface contact (Fong et al. 2009). As part of isolating the sliding period, this initial contact was excluded. Traction coefficients calculated from sprints where sliding could not be demonstrated did not appear to differ from the remaining traction coefficients, hence it could probably be argued that these are equally valid, with the problem situated in the method used for determining movement. However, only sprints where sliding of the shoe over the surface could be established with certainty were included in the statistical analysis. Further, only the component of horizontal force working in the same direction as the sliding movement was used, removing the contribution of other forces not providing resistance to the final traction coefficient. Lastly, to quantify the traction coefficient, the mean value during sliding was used. As discussed in paper II, there exists no consensus on how to most accurately report traction coefficients, leaving any method chosen ripe for criticism. Due to the inherent variation present in human-induced force, the traction coefficient over a period of time will necessarily contain fluctuations diminishing the accuracy of selecting a specific point in time to denote the surface-athlete interaction that is occurring (see paper III for graphical presentation). This does not mean that the behavior of the traction coefficient is completely random, but more so it represents a natural limit to the precision with which the traction coefficient can be established. By using the mean value the interaction over the entire period, also accounting for the effect of the peak, is reflected in the traction coefficient.

This could all be considered moot, as the entire premise of utilizing a traction coefficient has been criticized for relying upon a linear relationship between vertical and horizontal force that does not exist (Kent et al. 2012). Based on tests with a mechanical device it is further concluded that the traction coefficient is an unsuitable measure due to its highly transient nature. However, as shown in paper II, the transient nature of the traction coefficient might not always be as pronounced as assumed, indicated by both the magnitude and the stability of SDs over the course of shoe-surface interaction (Figure 10). Hence, as discussed both in the current thesis and in paper III, it is possible to obtain traction coefficients that adequately reflect the shoe-surface interaction occurring. In addition, a separate regression analysis (unpublished) revealed the existence of a linear relationship ($F_{1,988}$ = 460.36, $p < .001$) between relative body weight (vertical force, f_{vimp}) and traction force (horizontal force, f_{trac}).

4.2. Magnitude of force and what it means for injuries

At the core of the alleged greater injury risk on artificial turf is the excessive magnitude of force an athlete will encounter when interacting with the surface. As mentioned earlier, both impact and traction must achieve a balance between being excessive with regard to injuries and being insufficient to the point of being detrimental to performance.

Excessive impacts, although potentially beneficial for energy reutilization during running, are widely assumed to be related to injuries (Bentley et al. 2011; Cole et al. 1996; Eils et al. 2004; Meijer et al. 2006; Queen et al. 2008) despite the lack of an established cause-effect relationship (Derrick 2004; Frederick 1986; Nigg & Yeadon 1987; Smith et al. 2004; Stiles & Dixon 2007). However, it is important to remember that this assumption has not been refuted either, its persistence likely derived from existing knowledge of the structural limitations of the human body. Albeit outside the scope of the current work, it is worth mentioning that substantially different views also exist, with the proposed paradigm that impact forces are related to muscle tuning rather than being important in an injury perspective (Nigg & Wakeling 2001).

Excessive traction may cause injuries as a result of the shoe being temporarily fixed to the surface. Conversely, insufficient traction will lessen the likelihood of shoe fixation. Granted, insufficient traction may be hazardous in its own right by disposing athletes to injuries caused by slipping, but these will normally be regarded as less severe. Although potentially hazardous, excessive traction can in some instances even be beneficial for performance, making rapid changes of direction easier to accomplish at high speeds. In theory, the main dilemma that presents itself is that athletes are essentially forced to choose between performance and safety. Taking factors beyond the athletes' control into account, such as both home and away game surface and shoe sponsor deals entered into by team management, they may not even be given the choice.

4.2.1. Surface-athlete impact

The impacts presented in paper I, comprising a range of magnitude of approximately 2.8-3.2 W, generally correspond well with typical impact forces of 2-3 times body weight found in both running (Frederick 1986; Nigg & Wakeling 2001) and sports specific movements (Stiles & Dixon 2006). Compared to previous *in vivo* experiments on 3G turf, producing a range of impacts of 2.3-2.6 times body weight for both running (Meijer et al. 2006; Müller et al. 2010) and cutting (Müller et al. 2010; Queen et al. 2008), they are slightly higher, albeit not alarmingly so.

There are several reasons for this apparent increase from previous 3G turf experiments, the most notable of which is the choice to utilize total force rather than just vertical force, which is more common, to denote the impact. Whereas the range of f_{timp} across turf systems and cleat configurations was 2.9-3.2 W for stop sprints and 2.8-3.0 W for cut sprints, the range of f_{vimp} was 2.8-3.1 W for stop sprints (unpublished) and 2.4-2.6 W for cut sprints (paper II). Although stop sprints generally produced impacts of higher magnitudes than cut sprints regardless of calculation method, the difference between the two running tasks was greater when only vertical force was considered. Not surprisingly, the inclusion of horizontal forces had more of an effect on impact force in cut sprints than in stop sprints. A likely reason for the comparatively high impacts in stop sprints with both calculation methods is the nature of the task. It is fair to assume that sudden changes in acceleration, such as a sprint with an abrupt stop – a movement commonly utilized in both soccer and football – will produce impact forces that are not consistent with those achieved during continuous running (Stiles & Dixon 2006). In theory, this should hold true also for cutting movements, which it does when considering f_{timp}. However, the magnitudes of f_{vimp} in cut sprints were similar to those found in previous experiments on both running and cutting. A probable explanation is that the proportion of horizontal force is greater in cut sprints due to the necessity of working akin to centripetal force, leaving a smaller proportion of vertical force. Finally, the equipment used to gather impact forces might also be a factor, since pressure insoles generally register lower forces than force plates (Barnett et al. 2001).

The f_{timp} presented in paper I was slightly higher than what has previously been determined on 3G turf, while the f_{vimp} presented in paper II and in the current thesis was quite similar. Compared to the typical impact of 2-3 times body weight during running, which usually considers vertical force only, there is nothing in the current work to indicate that the 3G turf systems employed expose athletes to any excessive danger with regard to impacts.

4.2.2. Shoe-surface traction

No optimal level of traction for performance or safety has been determined to date, but the μ presented in paper II, approximately 0.65 across turf systems and cleat configurations, correspond to the lower end of the spectrum (0.5-1.2) of what has previously been recommended to ensure the ability to perform athletic movements (Frederick 1993; Lloyd & Stevenson 1990; Nigg & Segesser 1988; Pedroza et al. 2010; Valiant 1993). Traction coefficients beyond the recommended range are generally considered unnecessary at best and hazardous at worst. Interestingly, on 3G turf, results from mechanical device tests are more often than not indicative of theoretically hazardous conditions, producing traction coefficients of 0.6-0.8 (Wannop et al. 2012), 1.2 (Sabick et al. 2009), 0.8-1.3 (Shorten et al. 2003), and 1.3-1.4 (Severn et al. 2011). In contrast, an experimental setup similar to the one employed in the current work yielded lower force ratios (relationship of peak horizontal force and peak vertical force) of 0.56-0.57 (Sterzing et al. 2010).

For the positive relationship that was observed between μ and α, the predicted increase in μ for every degree of medial rotation was .0017. This means that, according to the model, for every 30° of rotation, μ increases by ~.05, in theory corresponding to an additional traction force of .05 times body weight. The majority of measured α spanned a range of ~60°, making the total increase in μ ~.1. When viewed in conjunction with the range of previously recommended traction coefficients, a change of ~.1 does not appear likely to have any meaningful effect on the traction force working against the athlete. This is especially true when the magnitude of μ discovered in the current work is considered, in no way indicating that the 3G turf systems employed expose athletes to any excessive danger with regard to traction.

Unfortunately, there is not a lot of data on 3G turf in the existing literature that allows for direct comparison to the f_{trac} presented in paper II, which was of a magnitude of approximately 1.6 W across both turf systems and cleat configurations. However, taking the typical magnitude of f_{vimp} and the relatively low μ into account, there is nothing to suggest that f_{trac} is particularly high.

4.3. Interpreting the interaction between impact and traction

Whereas the interpretation of impacts can often be considered more or less straightforward, the interpretation of traction is potentially a more difficult task due to the fact that it is inherently influenced by the normal load. This might be more of a clouding issue in mechanical testing; even though the load is not only predetermined but also constant, there is no discernible pattern between load and traction coefficient at loads under 900 N (Sabick et al. 2009; Severn et al. 2011; Shorten et al. 2003; Wannop et al. 2012), while a negative relationship has been identified at loads above 900 N (Kuhlman et al. 2009). For *in vivo* experiments the equivalent to the normal load is the magnitude of impact. As such, for genuine athletic movement, the traction coefficient, comprised of both impact force and traction force, provides possibly the most accurate representation of functional traction.

It has been argued that the traction coefficient fails to provide information on the magnitude of forces involved (Kent et al. 2012). If viewed in isolation, this is true. To relate the traction coefficient to magnitude of force, it should be interpreted in light of the impact occurring. However, for certain movements, such as running, we can generally predict the approximate magnitude of this based on previous research (Frederick 1986; Nigg & Wakeling 2001). Hence, if body mass is included, a traction coefficient can provide useful information on the magnitude of forces as well, on the condition of trust in the linearity between vertical force and horizontal force presented earlier (chapter 4.1.7).

Further, it is important to note that there may be instances where the relationship between forces is of greater interest than the magnitudes. For a given movement, we can assume with a fair degree of confidence that the impact forces involved normally will be within a certain range. Thus, a high traction coefficient will indicate high traction force. This might make the need for a traction coefficient seem counter-intuitive, since traction force is already a part of the traction coefficient and could therefore be presented outright. However, due to their relation, the magnitude of traction force provides information of limited usefulness if we do not know the magnitude of the impact. Hence, the traction coefficient provides a measure of functional traction, accounting for the magnitude of the impact. That is not to say that traction force is not an important determinant of surface or shoe properties, but it does not fully reflect the interaction taking place between surface and athlete. The relationship reflected in traction coefficients also allows for comparisons across different normal loads or impacts, making it a useful tool considering the variety of mechanical devices and their continual development.

Naturally, when utilizing total force to denote the impact experienced by an athlete, this interaction works in the opposite manner as well, with horizontal force inevitably influencing impact force. The effect of traction on impact, although often understated, is deserving of attention, considering the notion that the degree of sliding allowed by a surface during impact is related to its ability to absorb force (Stiles & Dixon 2007). This relationship is not evident from the results presented in paper II, showing f_{vimp} to be similar for all turf systems while f_{trac} is lower on DU60 than the other turf systems. Interestingly, the magnitudes of f_{vimp} and f_{trac} do coincide for traditional round cleats, with both situated at the high end of the comparison, but no pattern is evident for turf cleats and bladed cleats. However, the general theory might not be applicable to cleat configurations as much as it is to surfaces. The possibility exists that these variables must be viewed at trial-by-trial level in order to detect the presence of coinciding relative magnitudes of force, but if there was any consistency, the same pattern should be found at group level. A potential reason for the lack of any consistent pattern is the multitude of factors seemingly able to affect the relationship between traction and impact force; in the literature, normal load (Kuhlman et al. 2009; Lloyd & Stevenson 1990; Valiant 1993), body mass (Pedroza et al. 2010), surface properties (Nigg & Yeadon 1987; Severn et al. 2011; Shorten et al. 2003; Wannop et al. 2012), shoe sole properties (Kuhlman et al. 2009; Nigg & Yeadon 1987; Shorten et al. 2003; Wannop et al. 2010), transverse plane shoe angle (Sabick et al. 2009), shoe-surface contact area (Valiant 1993), and velocity (Andréasson et al. 1986; Lloyd & Stevenson 1990; Nigg & Yeadon 1987) have all been identified to influence the traction coefficient.

4.4. The relative effects of turf system and cleat configuration

Even though the magnitudes of neither impact nor traction appeared to reach presumably hazardous levels in the current work, differences between turf systems and cleat configurations with regard to both impact absorption properties and traction properties were still present.

As detailed in paper I, DU50, the turf system intended for recreational-level use, generally demonstrated less impact absorption than DU42 and DU60, its two professional-level counterparts. While this was not a surprising outcome, it is still, despite the relatively low absolute magnitude also on DU50, an important observation that might be worth keeping an eye on as the development of artificial turf progresses. With media attention often focused on the professional level, it is important to remember the vast number of athletes potentially affected at the recreational level. In the current experiment, all three turf systems had the same infill type, namely ambient ground SBR, effectively removing supposed high-level infill types that are synthetically manufactured with sports application in mind as the cause for greater impact absorption on the professional-level turf systems. Regardless, previous research has shown impact absorption to be unaffected by infill type, with no differences being detected between SBR and TPE (Meijer et al. 2006). The results from the current work, as argued in paper I, indicate that the presence or absence of an underlying shock pad seems likely to be the main determinant of impact absorption, more so even than the height, and corresponding infill amount, of the turf system.

Infill amount might play a more pivotal role in influencing traction, as evidenced by the lower rotational traction found on 3G turf than on 2G turf (Shorten et al. 2003). The infill depth on 3G turf, much greater than that of its predecessor, allows for a greater degree of physical displacement of surface components, not unlike grass where the soil undergoes semi-permanent deformation when subjected to large forces. As detailed in paper II, lower traction measures were consistently found on DU60, the turf system with the greatest infill amount. In theory, a greater infill amount should facilitate compaction, increasing traction (Severn et al. 2010; Severn et al. 2011). However, the current experiment was conducted on newly installed 3G turf, continuously maintained throughout data collection. Hence, the infill was never allowed to compact, resulting in DU60 actually providing the greatest potential for infill displacement. In line with this, DU42, the turf system with the lowest amount of infill to displace, consistently proved to be at the high end of the turf system comparisons across various measures of traction, lending support to the theory that a decreased potential for infill displacement (as is the case with compaction) might increase traction. The consistently loose state of infill across all turf systems could also contribute to the lack of effect on the $\mu - \alpha$ relationship, as discussed in paper III.

The results presented in the current work are all based on ambient ground SBR, which might be an important factor since it has previously been identified to produce lower rotational traction than cryogenically processed SBR (Villwock et al. 2009b). It is unknown whether or not this difference is transferable to translational traction, but the proposed explanation, being that cryogenically processed SBR results in a finer particle which facilitates compaction and increases cleat-surface contact, provides no fundamental reason why it should not be. Due to the continuous turf system maintenance in the current experiment, ensuring similar conditions for all combinations of turf system, cleat configuration, and subject, interpretation of the results in light of turf system compaction is limited to theoretical compaction potential based on what has previously been quantified (Severn et al. 2010; Severn et al. 2011).

The differences between turf systems presented in paper I and paper II clearly illustrate the importance of not reducing the scope of artificial turf research to comparisons with grass. Although seemingly often forgotten, perhaps increasingly so with regard to grass, variations in surface properties exist within both groups. Hence, especially in research, care must be taken not to treat 3G turf (or grass, for that matter) as one uniform group with identical properties. That being said, when selecting the components of a 3G turf system, ambient ground SBR seems to be a perfectly adequate alternative regardless of level of play, providing suitable magnitudes of impact absorption and translational traction with regard to both safety and performance. Note that this does not take into account potential environmental aspects, which are outside the scope of the current work (but should remain an important factor in the decision-making process).

Although undoubtedly a factor, surface properties alone do not dictate impact absorption or traction. Shoes, acting as a necessary link between surface and athlete during competition at all levels, play an important role as well. Results from paper I indicate that turf cleats generally provide greater impact absorption than traditional round cleats and bladed cleats, a discovery which is also present, although only of secondary interest, through f_{vimp} in paper II. It is conceivable that the cause is unrelated to the cleat configuration itself, rather being a result of a more extensive shoe sole construction than what is typically found in shoes with more aggressive cleat configurations (Figure 6), a parallel of sorts to the effect of an underlying shock pad.

Interestingly, as shown in paper II, turf cleats also generally produced higher traction measures than traditional round cleats and bladed cleats. This discovery is strengthened by the tendency for a higher μ with turf cleats. At the other end of the spectrum, bladed cleats consistently produced the lowest values across various measures of traction. This goes against what has come to be regarded as conventional wisdom, only in part aided by objective research (Kuhlman et al. 2009; Villwock et al. 2009b). The expected greater traction with bladed cleats is usually attributed to the relatively sharp cleat shape coupled with a large cleat surface area, which is a potential influence on rotational and translational traction alike. Despite certain traction-related differences between cleat configurations, they all, somewhat surprisingly, responded in similar fashion to varying degrees of transverse plane rotation, as detailed in paper III. A potential clue to why vastly different cleat configurations did not appear to be affected by shoe angle is the low coefficient of determination of the $\mu - \alpha$ relationship

(R^2 = .086, unpublished), a "byproduct" of the ANCOVA model. It indicates that only 8.6 % of the variation in μ can be explained by the variation in α, perhaps signifying that shoe angle, and within it cleat surface area working against the resistance of the turf system, is not as important for traction as theoretically assumed. This could be related to the limited cleat displacement or, as mentioned previously, the loose state of turf system infill. However, a more likely explanation for the low coefficient of determination is simply that it reflects the large number of trials and high level of variation in the data combined with a relatively small slope. This does not compromise statistical inferences, but caution should be practiced when using the model to predict at an individual level.

When considering recommendations for athletes, it is important to recognize that across all shoe-surface combinations, μ, the measure of functional traction, remained almost identical despite differences in several traction-related properties between turf systems (f_{trac}, Δv_{run}, and Δv_{cut}) and between cleat configurations (f_{trac}, f_{vimp}, v_{slide}, Δv_{run}, and Δv_{cut}). As argued in paper II, this does not mean that the differences that were uncovered are not indicative of actual variations between turf systems or cleat configurations, but rather introduces a human element, opening up for the possibility that undesirable traction conditions are adjusted for in an effort to maintain a specific level of performance and/or safety. Athletes have previously been noted to have a notion – nonspecific in nature – of desired traction (Stanitski et al. 1974), supporting the idea that they might subconsciously, based on past experience, alter certain variables to achieve the desired result. Considering the variety of factors previously determined to affect the traction coefficient, it seems logical to assume that it is not determined exclusively by material properties, but rather is dependent on human behavior.

4.4.1. Assumed culprit: surface or shoes?

Based on the current work, it is difficult to discern whether turf system or cleat configuration has a greater potential effect on injuries than the other. As presented in paper I, both turf system and cleat configuration influenced impact absorption. The same was true for traction, presented in paper II, although a greater number of traction variables were affected by cleat configuration than by turf system. The results from paper II also revealed a tendency for cleat configuration to affect μ, whereas no such tendency was present for turf system. However, to counter this, a tendency to affect the $\mu - \alpha$ relationship was present only for turf system in the initial model used in paper III (unpublished), effectively rendering the previous argument moot.

Total injury occurrence is largely similar between 3G turf and grass (Aoki et al. 2010; Bjørneboe et al. 2010; Ekstrand et al. 2006; Ekstrand et al. 2011; Fuller et al. 2007a; Fuller et al. 2007b; Fuller et al. 2010; Soligard et al. 2012; Steffen et al. 2007). Supporting this, results from *in vivo* studies on 3G turf, including those presented in paper II, do not indicate hazardous levels of traction (Sterzing et al. 2010). In fact, research based on mechanical devices is seemingly alone in concluding that 3G turf increases traction and hence the risk of injury (Livesay et al. 2006; Villwock et al. 2009a). Considering the results from the current work, adjustments for desired traction performed by athletes might be an underlying cause of why epidemiological studies fail to detect a difference between the two surface types, further strengthening the notion that mechanical devices are unable to capture the interaction that takes place between surface and athlete. Unfortunately, missing from the literature – disregarding one ultimately failed attempt (Aoki et al. 2010) – are epidemiological studies where cleat configurations are accounted for. Such studies would aid tremendously in shedding light on the role cleat configurations play, both in an isolated manner and in combination with certain surface types, with regard to injuries. Their absence is most likely due to methodological difficulties, since monitoring would have to be done at an individual level as opposed to team level.

Paper I and paper II, respectively, show turf cleats to produce not only greater impact absorption but also greater traction than traditional round cleats and bladed cleats across different 3G turf systems. Such a combination of properties indicate that this cleat configuration should be preferred over the other two, as it does not sacrifice one property for the sake of the other. However, the current experiment was conducted exclusively under dry conditions, making it easier for turf cleats to excel with regard to traction. Under wet conditions, which are routinely found at the professional level where artificial turf fields are watered prior to competition, the need for a certain degree of surface-penetrating cleats to counteract the lower traction may show itself more clearly. Interestingly, due to the interaction between impact and traction (Stiles & Dixon 2007), a wet 3G turf system might in theory also provide improved impact absorption as a consequence of the lower traction.

Observations at all levels of play indicate that turf cleats are often discarded in favor of more aggressive cleat configurations on 3G turf, which may be a reflection of a desire to ensure sufficient traction regardless of playing conditions (disregarding other factors that inevitably influence choice of shoes, at least at the recreational level, such as fashion, advertisements, and finances). Under dry conditions, this may result in choosing a cleat configuration with inferior impact absorption because of a perceived superior traction which in reality is not present. These perceived cleat configuration properties are clearly illustrated in the subjective shoe rankings presented earlier; bladed cleats ranked first for performance despite there being no differences in functional traction. In fact, a recent survey on soccer shoe properties revealed comfort, stability, and traction to be of highest priority while injury protection was deemed far less important (Hennig 2011). This basically indicates that performance takes precedence over safety, coinciding fairly well with the subjective shoe rankings from the current experiment; bladed cleats ranked first for both performance and personal preference, whereas turf cleats generally, although not statistically, received the highest ranking for comfort. It is tempting to suggest the athletes as the main culprits in injury situations on 3G turf by citing their responsibility in selecting an appropriate cleat configuration. In short, the surface should not be blamed for incidences occurring when using cleat configurations designed for another surface. However, the cleat configurations typically used on both 3G turf and grass, namely traditional round cleats and bladed cleats, were originally designed for grass (with the exception of some recently developed cleat configurations). Hence, attributing potentially hazardous conditions simply to the misuse of equipment relative to its intended area of application serves little purpose until sustainable alternatives exist on the market.

There is no apparent difference in the degree to which turf system and cleat configuration affect impact absorption and traction. Rather, the discovery that turf cleats generally produce greater traction than more aggressive cleat configurations under dry conditions points toward the potential effects of a specific combination of turf system and cleat configuration properties. Strengthening this notion is the absence of any effects on the $\mu - \alpha$ relationship; not only must the necessary parameters be provided by both cleat configuration (i.e., cleat surface area) and turf system (i.e., infill density), but the presence of any potential effect might, as argued in paper III, be contingent on certain conditions (i.e., sufficient displacement). Regardless, taking the relatively low overall magnitudes into consideration further diminishes the rationale behind attempting to associate either turf system or cleat configuration, or a specific combination of the two, with a greater injury risk. Nevertheless, the reputations of both 3G turf and bladed cleats will undoubtedly persist beyond the publication of the current work. Changing an attitude that has been ingrained in a vast sports population is not done overnight, but hopefully the current work can be a step toward a more objective view on the advance of artificial turf.

5. CONCLUSIONS

The intention behind the current work was never to analyze athletic movements at an individual level, but rather to employ standardized human movement, with a reasonably homogenous subject group (i.e., homogenous with regard to the movements performed, yet not identical on a trial-by-trial basis), as a method to obtain objective data on *in vivo* shoe-surface interactions, not forced to rely on mechanical devices.

Both an increased amount of infill and the inclusion of an underlying shock pad improved impact absorption on 3G turf, with the latter seemingly being of greater effect. This was paralleled by turf cleats, aided by a greater amount of sole material, providing improved impact absorption relative to traditional round cleats and bladed cleats.

Differences in several traction-related properties were discovered between turf systems and cleat configurations. Still, functional traction remained almost identical across all shoe-surface combinations, suggesting the presence of a human component in acquiring suitable traction conditions, something which has previously been afforded little attention. Notably, this is a factor which cannot be detected by mechanical devices. The magnitude of functional traction was positively related to transverse plane shoe angle (relative to the direction of movement on the surface), but the underlying reason for this relationship remains unclear due to the limited cleat displacement that occurs during surface contact.

Not addressed in the current thesis were potential long-term effects. Even though functional traction was similar across all shoe-surface combinations, the possible adjustments made by the subjects might still be important. If they indeed, whether subconsciously or not, perform some action to obtain the desired traction, the physical cost of doing so could manifest itself over time as being greater on a specific turf system or with a specific cleat configuration.

Relative to existing benchmarks, neither the absolute magnitudes of impact nor the absolute magnitudes of traction, including the increase in traction over a large range of shoe angles, that were discovered for any of the turf systems or cleat configurations can be considered excessive with regard to potential injuries. As yet, taking the similar overall injury rates on 3G turf and grass into consideration, any scientific rationale to support the notion that 3G turf is a particularly hazardous surface with regard to genuine human movement is missing.

5.1. Practical implications and further research

The sheer number of variations – and continual development – of each component of a 3G turf system and the resulting number of possible combinations makes it difficult to obtain a complete overview of surface properties. Hence, the current work does not propose to provide the definitive answers, but is rather a piece of the puzzle, providing knowledge that is currently missing from the literature. Due to the potential effects of infill compaction on both impact absorption and traction, the validity of the results from the current work are contingent on proper maintenance of 3G turf systems. Note that while the results presented in theory should be transferable to a wet surface with regard to safety (not accounting for injuries caused by slipping), the same is not necessarily true for performance.

Further research on 3G turf should make a conscious effort to utilize genuine athletic movement as a test method, as it reveals information that simply cannot be provided by mechanical devices, and focus on turf system characteristics at different levels of maintenance, particularly with regard to infill compaction, as well as financially sustainable improvements of surface conditions at the recreational level. Experiments on rotational traction in human movement would also be of interest, although likely not feasible from an ethical point of view.

Grass has been the preferred surface for sports such as soccer and football for the majority of their history because it was the available surface best suited to their demands. As a result of this, the development of artificial turf has continually worked toward replicating the properties of grass. However, grass is the default surface not because it is necessarily the best possible, but because it is the best available, which begs the question: should the goal be to make a product that is as similar to grass as possible or should it be to make a product that is the best possible for the sport?

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Paper I

Biomechanical Analysis of Surface-Athlete Impacts on Third-Generation Artificial Turf

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Background: Excessive repetitive loads are widely believed to be the cause of overload or overuse injuries. On third-generation artificial turf, impacts have been found to vary with surface and shoe properties. Mechanical devices are considered not representative for measuring impact absorption during athletic movements, and pressure insoles have been shown as inaccurate with regard to magnitude of force.

Purpose: To compare impact properties between different third-generation artificial turf systems in combination with various cleat configurations in vivo using force plate technology.

Study Design: Controlled laboratory study.

Methods: Twenty-two male soccer players (mean ± SD: age, 23.1 ± 2.8 y; height, 1.81 ± 0.1 m; body mass, 77.5 ± 6.0 kg) performed 10 short sprints, 5 straight with a sudden stop and 5 with a 90° cut, over a force plate covered with artificial turf for each combination of 3 turf systems and 3 cleat configurations.

Results: During stop sprints, peak impact was significantly higher on a recreational-level turf system than professional-level turf systems with and without an underlying shock pad (3.12 body weight [*W*] vs 3.01 *W* and 3.02 *W*, respectively). During cut sprints, peak impact was significantly higher with traditional round cleats than with turf cleats and bladed cleats (2.99 *W* vs 2.84 *W* and 2.87 *W*, respectively).

Conclusion: The results indicate that both an increase in assumed impact-absorbing surface properties and a larger distribution of shorter cleats produced lower impacts during standardized athletic movements. Regardless, none of the shoe-surface combinations yielded peak impacts of an assumed hazardous magnitude.

Clinical Relevance: The study provides information on the extent to which various third-generation artificial turf systems and cleat configurations affect impact force, widely believed to be a causative factor for overload and overuse injuries.

Keywords: artificial turf; biomechanics; cleats; impact; soccer

The development of third-generation artificial turf (3G turf) in the late 1990s led to a resurgence of artificial surfaces, now in widespread use at both the recreational and professional level. In 2004, the Fédération Internationale de Football Association (FIFA) allowed 3G turf to be used for official match play,[9] a clear sign of endorsement from the governing body. However, 3G turf still struggles to gain acceptance as a legitimate alternative to natural grass (grass), partly because of its continued reputation, despite the absence of epidemiological evidence,[7] for causing injuries.[24,25] Overload or overuse injuries are widely believed to occur because of excessive repetitive impacts,[3,4,8,19,27] with surface properties,[12,23] shoe properties,[3,29] and movement type[8,32] all having been suggested as important contributors. Although the connection between impacts and injuries seemingly is evident, a clear cause-effect relationship has yet to be confirmed.[5,13,22,29,30] Unfortunately, since overuse injuries per definition cannot be connected to a single, identifiable event,[14] they are difficult to attribute to a specific surface. Consequently, long-term effects of 3G turf play are to date undocumented.

Based mainly on research done before its introduction, 3G turf is thought to provide decreased impact absorption compared with grass.[30,31] Recent research does not support this notion.[12] Impact absorption is assumed to be influenced by the maximum possible displacement of a surface,[28] a property related to surface thickness. Greater surface displacement will typically extend the time of contact, allowing force to be distributed over a larger time frame. Hence, factors such as infill type and amount and the presence or absence of a shock pad underneath the

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surface are thought to be among the determinants of 3G turf impact properties.[1,18] A greater potential for displacement should result in increased impact absorption,[28,30] which has been demonstrated on 3G turf with both an underlying shock pad[18] and an increased amount of rubber infill.[1] Contrary to the latter, impact absorption has also been found to be unaffected by infill depth.[18] In addition, impact absorption has been shown to remain similar between infill types.[19] Compaction of the infill, however, is thought to be detrimental to the impact absorption of 3G turf,[1,19,21] with various sites within a field providing decreased impact absorption as a result of excessive use.[21]

During athletic movements, shoes are considered to play a vital role in the transmission of forces from surface to athlete[3,29] and have been suggested to have a greater influence on impact absorption than the surface.[6] Turf cleats (short cleats covering the entire sole) have been found to display increased impact absorption compared with longer, more aggressive cleats on both 3G turf[27] and grass,[29] whereas a selection of more aggressive cleat configurations have been shown to be unable to affect impact absorption.[20,27] The role of 3G turf components and cleat configurations with regard to impacts has yet to be resolved.

Despite their obvious advantages in practicality and reproducibility, mechanical devices constructed to mimic human movement in a simplified manner are considered not representative in predicting impact absorption during athletic movements,[6,23] in part because they lack the self-regulating component of human movement. In addition, they have been deemed invalid for impact testing on point elastic surfaces (surface material is deformed only at the location of applied force),[23] such as 3G turf. Hence, biomechanical analysis is needed to properly examine the interaction between surface and athlete under conditions reflecting actual human movement. However, existing force plate–based biomechanical studies have either displayed a lack of control over shoes[19] or focused solely on shoes, including only 1 turf system.[20]

The aim of the present study was to compare impact properties between different 3G turf systems with various cleat configurations during standardized athletic movements and quantify the magnitude of impacts during these movements. It was hypothesized that the turf system with an underlying shock pad would provide the most impact absorption and that turf cleats would produce lower impact forces than traditional circular cleats and bladed cleats on all turf systems.

METHODS

Subjects

Twenty-two male soccer players (mean ± SD: age, 23.1 ± 2.8 y; height, 1.81 ± 0.1 m; and body mass, 77.5 ± 6.0 kg) from recreational to professional playing level were recruited for the study. Participation was contingent on the following criteria: male, age 18 to 30 years, playing at an organized level, dominant right leg, a minimum of 2 years' experience with 3G turf, free of major injuries to the lower extremities for the past 6 months, no known diagnoses or conditions that could influence the ability to participate (eg, heart condition), and shoe size between 42 and 44 (US size, 8½-9½).

The Regional Ethical Committee assessed that the study was outside its authority and hence granted permission for the study to be carried out without its specific approval. All subjects signed an informed consent form before the experiment and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Equipment and Data Collection

Running tracks were constructed around a BP6001200 AMTI 3D force plate (Advanced Medical Technology, Inc, Watertown, Massachusetts), with 3 FieldTurf (FieldTurf Tarkett, Calhoun, Georgia) 3G turf systems (Table 1) alternately fastened to the force plate with 3M Dual Lock reclosable fasteners (3M Norway AS, Skjetten, Norway). The turf systems were Duraspine ULTRA 42 (DU42, professional level with underlying shock pad), Duraspine ULTRA 50 (DU50, recreational level), and Duraspine ULTRA 60 (DU60, professional level without underlying shock pad) (Unisport Scandinavia AS, Drammen, Norway), all installed with ~75% of the amount of ambient ground styrene-butadiene rubber (SBR) infill detailed in the producer's specifications, in accordance with the producer's instructions to ensure ~1.5 cm of free fiber above the infill. This method is customary to avoid excess infill at installation, rather opting for additional infill at a later point. Running tracks were all covered with DU50.

Three pairs of photo cells (TC-PhotoGate A&B; Brower Timing Systems, Draper, Utah) were placed along the in-run ~1 m above the turf, transmitting running time data to a handheld receiver (TC-Timer; Brower Timing Systems). Force data were recorded using Qualisys Track Manager version 2.5.595 (Qualisys, Gothenburg, Sweden) at a sample rate of 1000 Hz, obtained through a DSA-6 digital strain gage amplifier (Advanced Medical Technology, Inc) and processed further in MATLAB 7.9.0.529 (MathWorks, Natick, Massachusetts). Measured by a La Crosse Technology WS-868025 weather station (La Crosse Technology, La Crosse, Wisconsin), ambient laboratory temperature was consistently ~20°C. The dimensions of the laboratory setup can be seen in detail in Figure 1. Three soccer shoes (Figure 2), each representing a different cleat configuration (Table 2), were included in the study: the Adidas Mundial Team TF (turf cleats), Adidas Copa Mundial FG (traditional round cleats), and Adidas adiPURE 3 TRX FG (bladed cleats) (Adidas, Beaverton, Oregon).

Protocol

For each turf system, the subjects completed a separate day of testing consisting of 10 minutes of self-regulated warm-up running on a treadmill (Woodway, Waukesha, Wisconsin), weight measurement, and 30 short maximum-effort

TABLE 1
Detailed Specifications of the Turf Systems[a]

	DU42	DU50	DU60
Fiber			
Type	Monofilament	Monofilament	Monofilament
Material	Polyethylene	Polyethylene	Polyethylene
Height, mm	42	50	60
Weight, decitex	11,500	11,500	11,500
Thickness range, micron	80-240	80-240	80-240
Tufts per m^2	9450	8820	8190
Strands per tuft	6	6	6
Tuft pattern	Straight	Straight	Straight
Height above infill, mm	15	15	15
Total weight per m^2, kg	0.956	1.101	1.217
Stabilization infill			
Material	Quartz sand	Quartz sand	Quartz sand
Infill thickness, mm	5	8	13
Weight per m^2, kg	8	12	18
Particle size range, mm	0.4-0.8	0.4-0.8	0.4-0.8
Particle shape	Round	Round	Round
Shock-absorbing infill			
Material	SBR	SBR	SBR
Manufacturing process	Ambient ground	Ambient ground	Ambient ground
Infill thickness, mm	20	27	32
Weight per m^2, kg[b]	7.5	10.5	12
Particle size range, mm	1-3.15	1-3.15	1-3.15
Particle shape	Angular	Angular	Angular
Shock pad			
Type	Recticel Rebound	—	—
Material	Composite foam	—	—
Thickness, mm	12	—	—
Weight per m^2, kg	3.1	—	—

[a]Turf system produced by FieldTurf Tarkett (Calhoun, Georgia). DU, Duraspine ULTRA (Unisport Scandinavia AS, Drammen, Norway); SBR, styrene-butadiene rubber. —, not applicable.
[b]Approximately 75% of amount detailed in producers' specifications, as described in the text.

TABLE 2
Detailed Specifications of the Cleat Configurations

Shoe Model	Cleat Type	Surface	Number of Cleats, Back/Front	Cleat Height, Min/Max, mm
Adidas Mundial Team TF	Turf	Turf/gravel	20/45	6/9
Adidas Copa Mundial FG	Traditional circular	Firm grass	4/8	9/11
Adidas adiPURE 3 TRX FG	Bladed	Firm grass	4/9	11/13

sprints. Two different running tasks were included in the study: a straight sprint with rapid deceleration (stop sprint) and a sprint with a 90° cut to the left (cut sprint). The subjects were instructed to come to a complete stop within 2 steps after making contact with the force plate for stop sprints and to perform a 90° cut to the left for cut sprints, striking the designated contact area (60 × 60 cm) with their right foot for both tasks. After the subjects were allowed to familiarize themselves with both tasks, 10 sprints (5 of each task) were performed with each shoe. To avoid fatigue, the subjects rested 30 to 45 seconds between sprints and >2 minutes between groups of 10 sprints. The sequences of all factors (turf system, cleat configuration, running task) were counterbalanced to avoid systematic order effects.

Data Analysis

Dynamic signals were low-pass filtered at 100 Hz using an eighth-order Butterworth filter, after which an offset was removed if necessary. Body mass was determined from the mean of the 3 weight measurements. Impact was identified using the standard deviation (SD) of force during baseline measurements. The impact period was defined as the time when vertical force exceeded 2 SD above the mean of the force baseline. Peak impact (f_{imp}) relative to

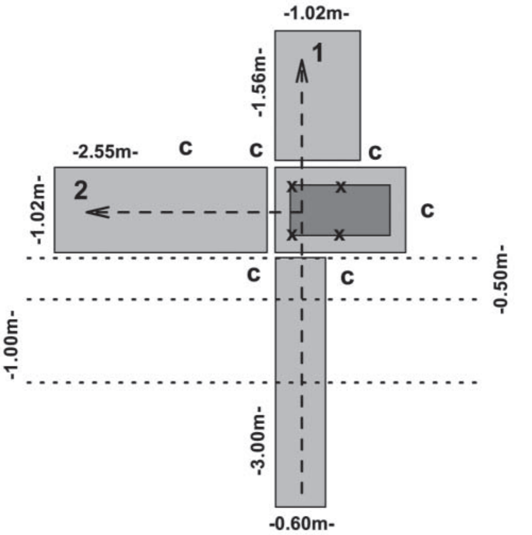

Figure 1. Dimensions of the experimental setup. The 0.6 × 1.2-m force plate (dark gray square) is surrounded by running tracks (light gray squares), with 6 cameras (c) angled toward the designated contact area (x). Horizontal dotted lines represent photo cell trigger beams. Dashed line arrow represents movement direction of both running tasks: (1) stop sprint and (2) cut sprint.

Figure 2. Soccer shoe models included in the experiment. From the top: Adidas Mundial Team TF (turf cleats), Adidas Copa Mundial FG (traditional round cleats), and Adidas adiPURE 3 TRX FG (bladed cleats) (Adidas, Beaverton, Oregon).

body weight (W) was used to indicate impact absorption of turf systems and cleat configurations, calculated as

$$f_{imp} = \frac{F_{peak}}{W},$$

where F_{peak} is the peak of total force (ie, vector sum of vertical and horizontal force) during impact. Time of contact (t_{con}) was defined as the length of the impact period. Approach velocity (v_{app}) was calculated based on the last 1.5 m before the force plate in an effort to diminish accidentally distorted recordings from triggering the photo cells with, for example, an outstretched hand. As a result of equipment error, 137 of 990 (13.8%) stop sprint recordings and 31 of 990 (3.1%) cut sprint recordings were discarded across all subjects and cleat configurations with regard to v_{app} analysis. The discarded recordings were distributed evenly among cleat configurations.

Statistical Analysis

Data are presented as mean ± SD. Statistical analyses were performed using PASW Statistics 18 (SPSS, Inc, an IBM Company, Chicago, Illinois), release 18.0.0. The effects of surface and shoe on f_{imp} and t_{con} were analyzed using a 2-way analysis of variance (ANOVA) for repeated measures, corrected for between-subject effects. Degrees of freedom were adjusted using the Huynh-Feldt correction in cases where sphericity could not be assumed. Post hoc least significant difference correction was applied where a significant F value was present. Because of random missing values as a result of equipment error, a linear mixed model with turf system and cleat configuration as fixed effects was applied to v_{app} to analyze their respective overall effects. Statistical significance was set at $P < .05$.

RESULTS

Tables 3 and 4 show mean ± SD f_{imp} and t_{con} across turf systems and cleat configurations for both running tasks. Mean v_{app} of 3.50 m·sec^{-1} and 2.93 m·sec^{-1} were achieved for stop and cut sprints, respectively (Table 5), with bladed cleats producing slower running velocities than turf cleats and traditional round cleats in cut sprints. For all combinations of turf system and cleat configuration, f_{imp} ranged from 2.94 to 3.18 W in stop sprints and from 2.77 to 3.01 W in cut sprints (Figure 3), and t_{con} ranged from 170 to 194 milliseconds in stop sprints and from 326 to 341 milliseconds in cut sprints (Figure 4). Among turf systems, DU50 consistently displayed inferior impact absorption compared with DU42 and DU60, with an increased f_{imp} in stop sprints and a decreased t_{con} in both running tasks. The only statistical difference found between DU42 and DU60 was a longer t_{con} on DU42 in stop sprints. The

TABLE 3
Impact (Relative to Body Weight) Across All Turf Systems and Cleat Configurations[a]

	Turf System					
	DU42	DU50	DU60	*df*	*F*	*P* Value
Stop sprint	3.01 ± 0.74	3.12 ± 0.81[b]	3.02 ± 0.75[c]	2, 176	5.64	.004
Cut sprint	2.89 ± 0.60	2.93 ± 0.64	2.88 ± 0.60	2, 176	1.59	.208
	Cleat Configuration					
	Turf Cleats	Round Cleats	Bladed Cleats	*df*	*F*	*P* Value
Stop sprint	3.01 ± 0.76	3.06 ± 0.77	3.08 ± 0.77	2, 176	1.96	.144
Cut sprint	2.84 ± 0.54	2.99 ± 0.68[b]	2.87 ± 0.61[c]	2, 176	20.79	<.001
	Interactions (Turf System × Cleat Configuration)			*df*	*F*	*P* Value
Stop sprint				4, 352	1.89	.112
Cut sprint				4, 352	2.24	.064

[a]Values are expressed as mean ± standard deviation. DU, Duraspine ULTRA (Unisport Scandinavia AS, Drammen, Norway).
[b]Significantly different from DU42/turf cleats.
[c]Significantly different from DU50/round cleats.

TABLE 4
Time of Contact (in Milliseconds) Across All Turf Systems and Cleat Configurations[a]

	Turf System					
	DU42	DU50	DU60	*df*	*F*	*P* Value
Stop sprint	191 ± 45[b]	175 ± 36[c]	185 ± 46[b,c]	2, 176	59.02	<.001
Cut sprint	337 ± 74	328 ± 76[c]	335 ± 73[b]	2, 176	7.50	.001
	Cleat Configuration					
	Turf Cleats	Round Cleats	Bladed Cleats	*df*	*F*	*P* Value
Stop sprint	189 ± 47[b]	183 ± 44[c]	179 ± 36[b,c]	2, 176	30.27	<.001
Cut sprint	333 ± 76	333 ± 73	333 ± 75	2, 176	0.01	.990
	Interactions (Turf System × Cleat Configuration)			*df*	*F*	*P* Value
Stop sprint				4, 352	4.11	.003
Cut sprint				4, 352	2.71	.030

[a]Values are expressed as mean ± standard deviation. DU, Duraspine ULTRA (Unisport Scandinavia AS, Drammen, Norway).
[b]Significantly different from DU50/round cleats.
[c]Significantly different from DU42/turf cleats.

responses to changes in cleat configurations were more varied, although turf cleats consistently indicated greater impact absorption where differences were found. Traditional round cleats produced an increased f_{imp} in cut sprints compared with turf cleats and bladed cleats, whereas t_{con} progressively increased from bladed cleats to traditional round cleats to turf cleats in stop sprints.

For t_{con}, significant turf system–cleat configuration interactions were also discovered (Table 4): in stop sprints, there was a larger effect of cleat configuration on DU60 and a larger effect of turf system with turf cleats; in cut sprints, there was a larger effect of cleat configuration on DU42 and a larger effect of turf system with traditional round cleats.

DISCUSSION

To the best of the authors' knowledge, this study is the first to analyze the surface-athlete impacts of different 3G turf systems in combination with various cleat configurations in vivo using force plate technology. The main findings reject the hypothesis that an underlying shock pad would result in the most impact absorption and confirm the hypothesis that turf cleats produce lower impact forces (f_{imp}), albeit with some reservations. Although significant differences between the use of an increased infill amount (DU60) and a shock pad (DU42) were not discovered, the turf system with an increased infill amount had the aid of a greater total height of components subject to deformation. Turf cleats

TABLE 5
Approach Speed (m·sec^{-1}) for All Combinations of Running Task and Cleat Configuration[a]

	Turf Cleats	Round Cleats	Bladed Cleats	*df*	*F*	*P* Value
Stop sprint	3.51 ± 0.55	3.47 ± 0.52	3.50 ± 0.52	2, 828.76	0.60	.550
Cut sprint	2.97 ± 0.34	2.93 ± 0.35	2.89 ± 0.37[b,c]	2, 935.13	6.40	.002

[a]Values are expressed as mean ± standard deviation.
[b]Significantly different from turf cleats.
[c]Significantly different from round cleats.

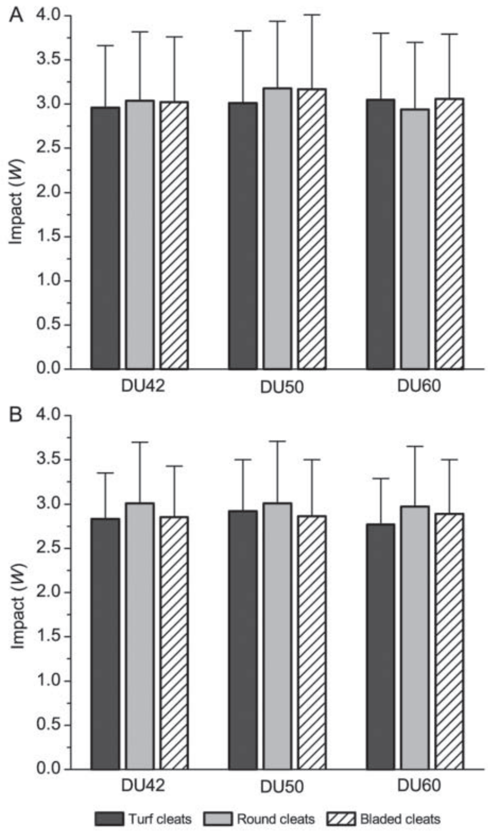

Figure 3. Mean ± standard deviation peak impacts (*W*) for all combinations of turf system and cleat configuration for stop sprints (A) and cut sprints (B). See Table 3 for statistical comparisons. DU, Duraspine ULTRA (Unisport Scandinavia AS, Drammen, Norway).

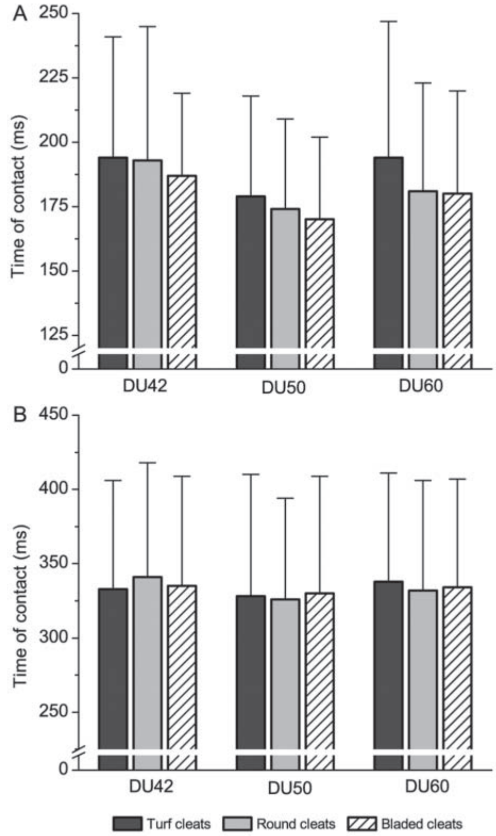

Figure 4. Mean ± standard deviation time of contact (msec) for all combinations of turf system and cleat configuration for stop sprints (A) and cut sprints (B). See Table 4 for statistical comparisons. DU, Duraspine ULTRA (Unisport Scandinavia AS, Drammen, Norway).

produced impacts that, although being lower, were not significantly different from those produced with bladed cleats. The turf system intended for recreational use (DU50) provided the least impact absorption among the turf systems in stop sprints. This may be an important finding because of the vast number of players potentially affected.

Artificial Turf and Experimental Challenges

Performing experiments on existing 3G turf fields effectively circumvents the difficulties of constructing proper fields in a laboratory and is important to the ever-growing knowledge base on 3G turf. However, the approach used here was chosen to acquire the desired data while maintaining genuine, although standardized, athletic movements. A common criticism of the setup chosen for the current experiment is the claim that placing a 3G turf system over a force plate will alter the data registered.[26] Synchronous Artificial Athlete[10] and force plate measurements revealed that the force plate recorded a mean peak impact across all turf systems that was 98.7% ± 1.2% (range, 98.0%-99.8%) of the mean peak impact recorded by the Artificial Athlete. Complying with FIFA standards,[10] data from both devices for this purpose were low-pass filtered at 120 Hz using a second-order Butterworth filter. Force profiles also failed to show signs of being influenced by any added surface, maintaining normal shapes throughout data collection. It is worth noting that the experiment was carried out solely under dry conditions. Force may be affected under wet conditions, as players possibly modify their movement.

The turf systems chosen here represent only part of today's wide selection, but they still largely cover what is in extensive use at both the recreational (DU50) and professional (DU42, DU60) level. Unfortunately, attributing results to specific turf system components is challenging, as proper surface specifications are often absent in research on 3G turf.[3,12,27,32] The potential effect of a constant running track surface on intersurface reliability should be negated not only by the outward similarity of the 3 turf systems, illustrated by the fact that none of the subjects displayed the ability to discern between them, but also by previous findings showing humans running at velocities similar to those recorded in the current experiment to adjust leg stiffness for the first step on a new surface without affecting ground reaction force.[11]

In the present study, relative impact forces derived from the vector sum of vertical and horizontal forces are used, despite vertical impacts alone being the traditional method of choice, in an attempt to more accurately assess the total force working on the athlete. A significant effect of cleat configuration was found in stop sprints when considering only the vertical impact, with turf cleats displaying a decreased impact force compared with traditional round cleats and bladed cleats, an effect that was not present for total force. By including horizontal force, the relative impacts increased on average across turf systems and cleat configurations by 3.7% in stop sprints (range, 3.4%-4.9%) and by 15.5% in cut sprints (range, 14.1%-17.4%).

Impact

For the most part, research regarding impacts on 3G turf not based on mechanical devices has been performed with pressure insoles,[3,12,27,32] the focus usually being on pressure distribution. Impact forces typically reach 2 to 3 W in running[13,22] and have been recorded in a similar range during sports-specific athletic movements.[31] On both 3G turf[19,20,27] and grass,[29] impact forces have generally been found to be between 2.3 and 2.6 W. These results are either based on straight running,[19,20,29] with one instance of cutting,[20] or derived from pressure insoles.[27] When compared with force plate data, pressure insoles register lower forces[2] and consequently do not provide an accurate assessment of the impact experienced by the athlete. However, this in itself does not make pressure insoles a useless tool for comparing impacts on 3G turf. For example, using pressure insole measurements, passive impact peaks have been found to decrease consistently across different shoes.[2] The results from the present study show impacts ranging from roughly 2.8 to 3.2 W, with stop sprints generally producing impacts of higher magnitudes than cut sprints. Note that the increased impact in stop sprints holds true despite the inclusion of horizontal forces, which constitute a greater proportion in cutting. It is reasonable to believe that the straight sprint with a stopping motion employed here, a common movement in sports typically played on 3G turf such as soccer or American football, is more forceful than a straight run more reminiscent of a jogging motion. The impacts resulting from athletic movements with, for example, sudden changes in acceleration or direction are not necessarily consistent with those experienced during continuous running.[31] The increased v_{app} in stop sprints compared with cut sprints may also be a factor leading to comparably lower impacts in cutting.

In stop sprints, f_{imp} was significantly higher on DU50 than DU42 and DU60. To some degree, this contradicts the theory that a greater potential for deformation of a surface leads to improved absorption of impact forces,[28,30] as only DU60 has a markedly higher total height of components that are subject to deformation (shock pad, sand, and SBR) than DU50 (45 mm vs 35 mm, respectively), whereas DU42 (37 mm) is similar to DU50 in this regard despite demonstrating significantly improved impact absorption. Based on this, it appears as though the underlying shock pad may have a greater effect on impact absorption than the infill. In line with higher f_{imp}, t_{con} was shorter on DU50 than DU42 and DU60 in stop sprints. This was also true for cut sprints, where no difference was found in f_{imp}. The fact that the turf system generally intended for use at the recreational level, DU50, provides less impact absorption (ie, greater impact force, shorter contact time) than the 2 turf systems marketed for the professional level, DU42 and DU60, may be an important finding, as recreational playing fields normally affect a greater amount of people at a much higher rate of use than professional playing fields. However, it is worth mentioning that the accumulated time spent on 3G turf for each individual is far greater at the professional level. In a sense, these differences illustrate the problem of routinely comparing 3G turf to grass as if either surface is devoid of variation within its respective group. Contact time has been shown to not differ between 3G turf and grass in cutting,[12] whereas the present results suggest that t_{con} varies between different 3G turf systems. Although comparisons with grass may be beneficial, it appears obvious that 3G turf systems merit being evaluated on an individual basis as opposed to as a uniform group.

The use of bladed cleats was found to result in significantly slower v_{app} than turf cleats and traditional round cleats in the cutting task. In general, faster running should result in increased impact force[15,17,19,29] and shorter contact time. However, this does not hold true as there was no significant difference in t_{con} between the different cleat configurations for cut sprints. This is in agreement with previous findings of similar contact time between turf cleats, traditional round cleats, and bladed cleats in cutting.[27] The greatest difference in v_{app} was between bladed cleats and turf cleats at 0.08 m/sec, though, and presumably not of a magnitude great enough to influence force measurements in a meaningful way. Shoe comfort was shown in a recent survey[16] to be the feature holding highest priority among players when selecting soccer shoes. Interestingly, injury protection was considered a low priority, perhaps pointing to players not viewing the shoes as a possible source of injury. Yet, the present results show that turf cleats and bladed cleats provided significantly lower f_{imp} in cut sprints than traditional round cleats. Whether this was a function of the cleat configuration or additional impact-absorbing qualities of the shoe construction is impossible to decipher from these results. Given the effect of an underlying shock pad on the turf system, it seems plausible that for turf cleats, the shoe construction was the deciding factor rather than the cleat configuration. This notion is further strengthened by the fact that t_{con} was longer with turf cleats than traditional round cleats and bladed cleats, although only for stop sprints. However, the somewhat surprising results of bladed cleats rather point toward a lack of impact-absorbing qualities in traditional round cleats, whether related to cleat configuration or general shoe construction.

Even though differences between both turf systems and cleat configurations were found, it is worth noting that the magnitudes of f_{imp} discovered in the present study are not indicative of the 3G turf systems being playing surfaces of increased danger, despite what may be widely believed. Peak impact and time of contact were chosen here to represent impact absorption. Naturally, other factors may also prove important in shedding light on the impacts transferred from surface to athlete. To gain a more complete understanding of how surfaces and shoes affect the athlete, it has been postulated that impact properties should be viewed in the context of traction properties, as a surface that allows the athlete to slide also acts to absorb forces during impact.[30]

CONCLUSION

Theoretically increasing the impact-absorbing properties of a 3G turf system resulted in improved impact absorption in the form of lower impact forces during standardized athletic movements. This was achieved through the inclusion of either an underlying shock pad or an increased amount of infill. Increased shoe material and a larger distribution of cleats also appeared to aid in impact absorption. However, the impacts were not of an order of magnitude indicative of hazardous shoe-surface combinations with regard to impact absorption. Future research should investigate the differences in horizontal force components between 3G turf systems, because of the potential injury implications, and focus on ways to improve surface conditions for the vast number of recreational players.

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Paper II

Is not included due to copyright

Paper III

Footwear Science

On the "Trench Effect" Theory: A Biomechanical Analysis of the Relationship between Traction and Shoe Angle on Third-Generation Artificial Turf

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Abstract

Background: Based on mechanical device testing on third-generation artificial turf (3G turf) it has been theorised that transverse plane rotation of cleated shoes increases the number of separate cleats forced to carve unique paths through the infill, thus increasing translational traction. The aim of the study was to investigate whether shoe angle affected traction across cleat configurations and 3G turf systems during a standardized *in vivo* change of direction movement.

Methods: Twenty-two male soccer players (mean ± SD: age, 23.1 ± 2.8 y; height, 1.81 ± 0.06 m; body mass, 77.5 ± 6.0 kg) performed five short sprints with a 90° cut over a turf covered force plate for each combination of three turf systems and three cleat configurations. The relationship between traction coefficient and transverse plane shoe angle across cleat configurations and turf systems was determined with an ANCOVA and shoe displacement was assessed with a linear mixed model.

Results: There was a significant positive slope of the traction coefficient – shoe angle relationship, with a predicted increase in traction coefficient of .0017 for every degree of medial shoe rotation. The relationship did not differ between cleat configurations or turf systems. Across all shoe-surface combinations, mean ± SD shoe displacement was 1.33 ± 0.60 cm.

Conclusion: During a standardized *in vivo* change of direction movement, an increase in shoe angle was accompanied by an increase in traction coefficient. The order of occurrence of these variables in such a movement makes it reasonable to assume that the increase in shoe angle causes the increase in traction coefficient. However, the magnitude of shoe displacement makes it difficult to support the abovementioned theory for controlled human movement.

Keywords: artificial turf; biomechanics; cleats; shoe angle; shoe-surface interaction; traction

Introduction

Due to the development of new cleat configurations and the ever increasing use of third-generation artificial turf (3G turf), the traditional round cleat can no longer be considered the default for soccer shoes. Irregular cleat shapes, among them bladed cleats, are rapidly gaining ground, despite having previously been deemed a contributing factor to severe soccer injuries (Lambson et al. 1996). In line with this, bladed cleats provide greater traction coefficients than traditional round cleats on 3G turf (Kuhlman et al. 2009), with the results, as previously (Lambson et al. 1996), attributed to cleat shape. However, recent research on 3G turf fails to distinguish bladed cleats from traditional round cleats (Sabick et al. 2009, Wannop et al. 2012, McGhie and Ettema 2013b) and turf cleats (McGhie and Ettema 2013b) with regard to traction coefficient.

When subjected to excessive forces, 3G turf fields are for all practical purposes limited to an elastic response, resisting deformation. Natural grass fields, on the other hand, possess the ability to undergo deformation that is, at the very least, semi-permanent in nature (i.e., kicking up dirt). Nevertheless, bladed cleats have also been accused, in professional circles, of being dangerous in combination with firm grass fields (Taylor 2010). However, cleat shape alone does not dictate the resulting traction. While the geometry of traditional round cleats makes the optimum cleat orientation for maximum penetration into the surface perpendicular to the shoe sole due to their symmetrical, conical shape, bladed cleats may achieve maximum surface penetration at other orientations (Kirk et al. 2007). Likewise, the effects of shoe orientation in the transverse plane could also differ between cleat configurations.

In an attempt to mimic a cutting movement, the relationship between traction and angle of transverse plane shoe orientation on 3G turf has previously been investigated by means of a mechanical testing device, showing shoe angle to affect traction to a greater degree than cleat configuration (Sabick et al. 2009). Traction coefficient approximately doubled with an increasing angle of medial rotation from 0° to 60° while remaining similar across a range of cleat configurations, with a further increase to 90° resulting in a slight decrease in traction coefficient. Since a change in transverse shoe angle cannot be accompanied by a change in the number of cleats or, for some cleat configurations, of cleat surface area in contact with the surface, it was deduced that the most obvious explanation was the alignment of cleats relative to movement direction. The cleats generally align when a shoe is placed at 0° relative to the direction of movement on the turf system, which results in few unique pathways in the turf system infill and hence reduced resistance for the trailing cleats. Rotation of the shoe forces a greater number of cleats to carve their own path through the infill (Figure 1), potentially increasing the resistance to linear translation. This was termed the "trench effect" (Sabick et al. 2009). However, the "trench effect" theory only holds true to a certain degree of rotation. Rotating the shoe as much as 90° may realign several cleats, explaining the decrease from 60°. It is important to distinguish shoe angle when cutting from cutting angle (i.e., the change in whole body movement direction), as they are not necessarily related but rather dependent on individual technique. E.g., it is possible to perform a 90° cut with the shoe at 0° relative to pre-cut movement direction, i.e., a completely lateral movement.

Another factor that needs to be taken into consideration is cleat shape. With the shoe at a 0° angle relative to the direction of movement on the turf system, bladed cleats have a small surface area working against the resistance of the turf system. As the angle of the shoe relative to movement direction increases, the shape of bladed cleats causes this surface area to progressively increase. Conversely, the geometry of traditional round cleats ensures that the size of the surface area working against the resistance of the turf system remains identical irrespective of shoe angle.

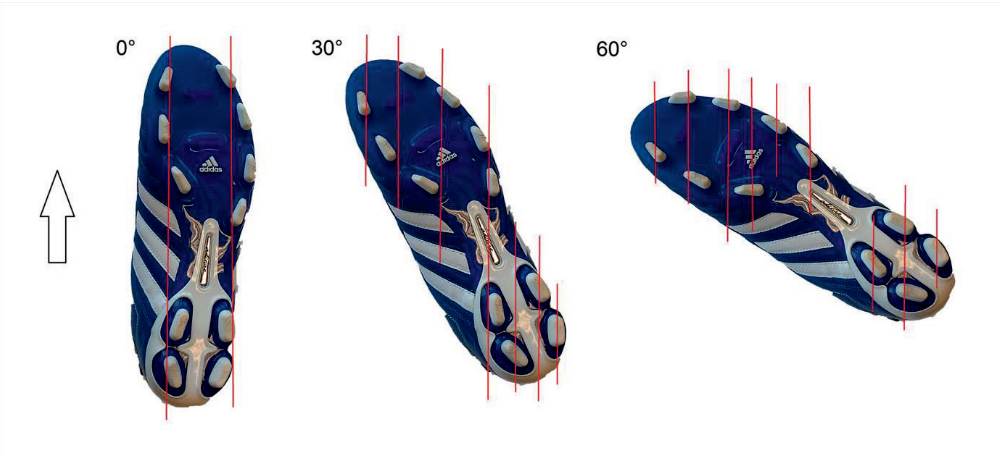

Figure 1. Graphic presentation of the principle behind the "trench effect" theory (Sabick et al. 2009): as medial rotation of the shoe progresses, the number of cleats forced to carve their own path through the turf system infill increases. Arrow indicates direction of shoe displacement.

A concept similar to the "trench effect" has been alluded to from mechanical device testing of various 3G turf systems (Severn et al. 2011), with traction coefficient increasing with infill density, which in turn can increase with a greater infill amount and frequent use (Severn et al. 2011). Contrary to this, traction coefficient has also been found to decrease in areas of a field which are subject to excessive use (Wannop et al. 2012). The result is an unclear picture of infill with regard to the supposed "trench effect", although it seems reasonable to assume that infill characteristics play a role in determining the resistance encountered by the cleats.

The aim of the present study was to investigate whether shoe angle affected traction for various cleat configurations and 3G turf systems when performing a standardized *in vivo* change of direction. In line with the aforementioned "trench effect", it was hypothesized that an increase in shoe angle is accompanied by an increase in traction. Keeping with the "trench effect" theory, bladed cleats were hypothesized to increase traction with increasing shoe angle at a higher rate than traditional round cleats and turf cleats as a function of their irregular geometry leading to an increased cleat surface area with increased horizontal rotation. No specific hypothesis regarding turf systems was formulated, since it remains unclear whether fibre density or infill density provides the most resistance.

Methods

Subjects

Twenty-two healthy, right leg dominant, male recreational to professional soccer players (mean ± standard deviation (SD) age 23.1 ± 2.8 years, height 1.81 ± 0.06 m, and body mass 77.5 ± 6.0 kg) participated in the study. Permission to conduct the study was given by the Regional Ethical Committee. Prior to the experiment, all subjects signed an informed consent form and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Equipment and Data collection

Details of the experimental setup have previously been published elsewhere (McGhie and Ettema 2013a). In short, three FieldTurf (FieldTurf Tarkett, Calhoun, GA, USA) 3G turf systems (Table 1) were alternately fastened to a BP6001200 AMTI 3D force plate (Advanced Medical Technology, Inc., Watertown, MA, USA), around which running tracks consistently covered with one turf system were placed. Photo cells (TC-PhotoGate A&B, Brower Timing Systems, Draper, UT, USA) were placed along the in-run for monitoring of approach velocity during the last 1.5 m of the in-run (mean ± SD approach velocity 2.93 ± 0.19 $m \cdot s^{-1}$). Six motion capture cameras (ProReflex, Qualisys, Gothenburg, Sweden) were strategically placed around the force plate. Dimensions of the laboratory setup can be seen in Figure 2. Force data were sampled at 1000 Hz. Synchronously, position data were sampled at 500 Hz, obtaining a spatial resolution of 0.3 mm. Three shoe models with typical cleat configurations (turf cleats, traditional round cleats, and bladed cleats) were tested, each fitted with six reflective markers on the right shoe (Figure 3). For turf cleats, traditional round cleats, and bladed cleats, respectively, the number of cleats at the back/front of the shoe was 20/45, 4/8, and 4/9 and cleat height range was 6-9 mm, 9-11 mm, and 11-13 mm. All shoes used in the experiment were between size 42 and 44 (US size, 8½-9½) and manufactured by adidas (adidas, Beaverton, OR, USA).

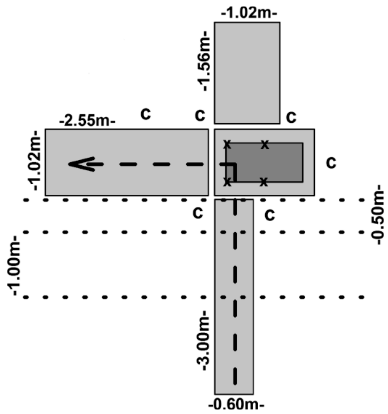

Figure 2. Dimensions of laboratory setup. The 0.6*1.2 m force plate (dark grey square) is surrounded by running tracks (light grey squares). Six cameras (c) are angled towards the designated contact area (x). Dashed line arrow represents movement path. Horizontal dotted lines represent photo cell trigger beams.

Figure 3. Cleat configurations included in the experiment. From the top: Turf cleats (adidas Mundial Team TF); Traditional round cleats (adidas Copa Mundial FG); Bladed cleats (adidas adiPURE 3 TRX FG); Placement of reflective markers on shoe (pictured: adidas adiPURE 3 TRX FG). All markers were placed at 5 cm height: one at the heel, one at the toe, and four bilaterally 6 cm in from both heel and toe. Note: sixth marker (back left side) not visible in photograph.

Table 1. Detailed specifications of the turf systems.

		DU42	DU50*	DU60
Fibre				
	type	monofilament	monofilament	monofilament
	material	polyethylene	polyethylene	polyethylene
	height (mm)	42	50	60
	weight (dtex)	11500	11500	11500
	thickness (micron)	80 – 240	80 – 240	80 – 240
	tufts/m^2	9450	8820	8190
	strands/tuft	6	6	6
	tuft pattern	straight	straight	straight
	height above infill (mm)	15	15	15
	total weight/m^2 (kg)	0.956	1.101	1.217
Stabilization infill				
	material	Quartz sand	Quartz sand	Quartz sand
	infill thickness (mm)	5	8	13
	weight/m^2 (kg)	8	12	18
	particle size (mm)	0.4 – 0.8	0.4 – 0.8	0.4 – 0.8
	particle shape	round	round	round
Shock absorbing infill				
	material	SBR	SBR	SBR
	manufacturing process	ambient ground	ambient ground	ambient ground
	infill thickness (mm)	20	27	32
	weight/m^2* (kg)	7.5	10.5	12
	particle size (mm)	1 – 3.15	1 – 3.15	1 – 3.15
	particle shape	angular	angular	angular
Shock pad				
	type	Recticel Rebound	--	--
	material	composite foam	--	--
	thickness (mm)	12	--	--
	weight/m^2 (kg)	3.1	--	--

Turf systems produced by FieldTurf Tarkett (Calhoun, GA, USA). DU, Duraspine Ultra (Unisport Scandinavia AS, Drammen, Norway); SBR, styrene-butadiene rubber; --, not applicable.

* Turf system used for running tracks surrounding the force plate.

** Approximately 75% of amount detailed in producers specifications, as per producer's instructions (McGhie and Ettema 2013b).

Protocol

As part of a larger experiment (McGhie and Ettema 2013a), the test protocol included a warm-up of ten minutes self-regulated treadmill running (Woodway, Waukesha, WI, USA), weight measurement, and 15 sprints at close to maximum speed (five with each cleat configuration) for each turf system. In an effort to avoid systematic order effects, the sequence of turf systems and cleat configurations were counterbalanced. The subjects were instructed to strike the designated contact area (60 x 60 cm) on the force plate with their right foot and execute a 90° cut to the left. They were afforded 30-45 s rest between each sprint and >2 min rest after every change of cleat configuration to avoid fatigue.

Data Analysis

Force and position data were low-pass filtered at 100 Hz using an 8th order Butterworth filter. After adjusting for minor force offsets if necessary, impact was determined to occur where vertical force exceeded mean baseline force by 2 SD and the period of full sole-surface contact was identified from the vertical position of the toe and heel (as detailed in McGhie and Ettema 2013b). The angle of sliding direction (relative to initial running direction) was estimated from positional data as the angle of displacement from the beginning to the end of sole contact. Traction coefficient (μ) during sole contact was calculated as

$$\mu = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{F_h}{F_v}\right)_i \tag{1}$$

where F_h is horizontal force in sliding direction, F_v is vertical force, and N is the number of data points during sole contact, and deemed invalid if sliding of ≥3 mm (ten times the resolution) did not occur as determined through linear regression (for specifications, see McGhie and Ettema 2013b). Transverse plane shoe angle (α) was determined as the mean angle of shoe orientation during sole contact relative to the angle of sliding. The magnitude of the shoe angle indicates the degree of medial rotation relative to sliding direction. Shoe displacement during sole contact was determined from positional data as the displacement in cm in sliding direction. A total of 304/990 files (30.7 %), distributed evenly among turf systems and cleat configurations, either did not meet the demands for valid traction coefficients or were unable to provide a proper basis for determining shoe angle or shoe displacement due to missing data.

Statistical Analysis

Statistical analyses were performed using PASW Statistics 18 (SPSS, Inc., an IBM Company, Chicago, IL, USA), release 18.0.0. The relationship between μ and α across cleat configurations and turf systems were assessed with an ANCOVA, with μ as the dependent variable, α as the covariate, and cleat configuration and turf system as factors. Linearity of the data was assessed through ordinary least squares regression. Due to the large sample size, normality was assumed if both skewness and kurtosis fell between -1 and 1. Homogeneity of variance was supported ($F_{8,677} = 1.08$, $p = .372$), assessed with Levene's test for equality of error variances. If any non-significant factor-covariate interaction was present, the interaction term was removed and the model re-run. Repetition was not included as a fixed factor in the model since neither learning effects nor exhaustion was expected from the first to the last repetition within a specific combination of cleat configuration and turf system. Missing data were deleted list-wise. Due to random missing values, shoe displacement was assessed with a linear mixed model with cleat configuration and turf system as fixed effects, accounting for intra-individual variance as a random effect. To better assess the main effects, the interaction effect was removed from the model if non-significant. Statistical significance was set at $p < .05$.

Results

The results from the ANCOVA revealed a significant positive relationship between μ and α ($F_{1,680} = 57.46$, $p < .001$), with the predicted increase (i.e., the slope of the μ – α relationship) being .0017 per degree of medial rotation (Figure 4). This relationship was neither affected by cleat configuration ($F_{2,680} = 1.29$, $p = .277$) nor turf system ($F_{2,680} = 0.05$, $p = .950$). Mean ± SD shoe displacement across all shoe-surface combinations was 1.33 ± 0.60 cm. The displacement was significantly greater with traditional round cleats than with turf cleats and bladed cleats, but remained unaffected by turf system (Table 2).

Table 2. Comparison of shoe displacement (cm) between cleat configurations and turf systems

				df	*F*	*P* value
	Turf cleats	Round cleats	Bladed cleats			
Mean ± SD	1.29 ± 0.56 *	1.46 ± 0.65	1.24 ± 0.58 *	2, 662.22	13.01	<0.001
Median	1.15	1.33	1.07			
Range	0.48 – 3.86	0.45 – 3.69	0.44 – 4.27			
	DU42	DU50	DU60			
Mean ± SD	1.34 ± 0.59	1.34 ± 0.64	1.33 ± 0.59	2, 662.50	0.20	0.822
Median	1.17	1.18	1.14			
Range	0.48 – 4.27	0.45 – 3.86	0.44 – 3.34			

* Significantly different from round cleats/DU50; † Significantly different from bladed cleats/DU60

Discussion

The main findings confirm the hypothesis that an increase in shoe angle is accompanied by increased traction. Notably, this relationship was not affected by cleat configuration, rejecting the hypothesis that bladed cleats would increase traction with increasing shoe angle at a higher rate than traditional round cleats and turf cleats, nor was it affected by turf system. In general, shoe displacement appears insufficient for the “trench effect” to be a factor.

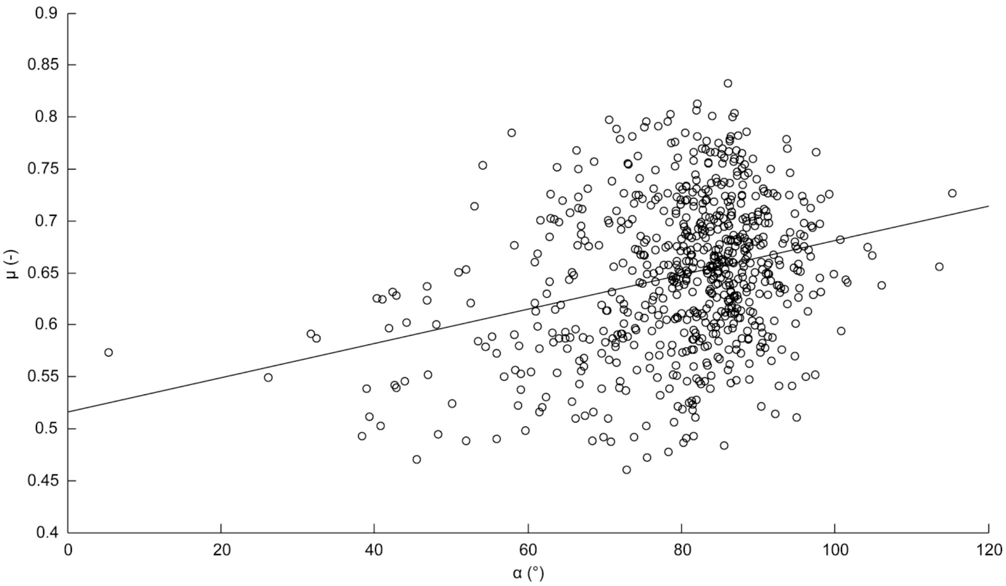

Figure 4. Correlation between traction coefficient (μ) and shoe angle (α). No significant differences were identified between cleat configurations or turf systems. Solid line represents least squares regression for all cleat configurations and turf systems (slope = .0017).

Comparing mean values of traction coefficient and shoe angle

At first glance, it may seem unorthodox to utilize the mean values of traction coefficient and shoe angle to highlight the relationship between the two. To date, there is no consensus in the literature on how to report traction coefficients to achieve the most accurate result (as discussed in McGhie and Ettema 2013b). Hence, one can point to both positive and negative aspects of any method chosen. Neither shoe angle at peak traction coefficient nor traction coefficient at peak shoe angle fully represents the interaction that is present. On the contrary, the entire movement throughout sole contact time is important. However, comparisons at every instant captured in the measurement process are unsuitable due to the inherent variation that exists within both force and movement, and possibly other influencing variables, leaving the interaction between traction coefficient and shoe angle without pattern (Figure 5). That does not mean that no pattern exists. Rather, it's a function of a natural limit to the level of accuracy that is possible to achieve. Using mean values allows for evaluating the relationship taking the entire movement into account while still including the effect of the peak. Illustrating the relative accuracy of utilizing the mean value of shoe angle (which may not be as common), the mean ± SD range of shoe angle during sole contact was 3.83 ± 1.75°, with similar ranges across both cleat configurations and turf systems; 4.25 ± 1.74° for turf cleats, 3.73 ± 1.71° for traditional round cleats, and 3.56 ± 1.74° for bladed cleats; 3.86 ± 1.86° on DU42, 3.70 ± 1.75° on DU50, and 3.92 ± 1.62° on DU60. Note that the range of shoe angles during sole contact is substantially smaller than the range of shoe angles presented in the main results (Figure 4).

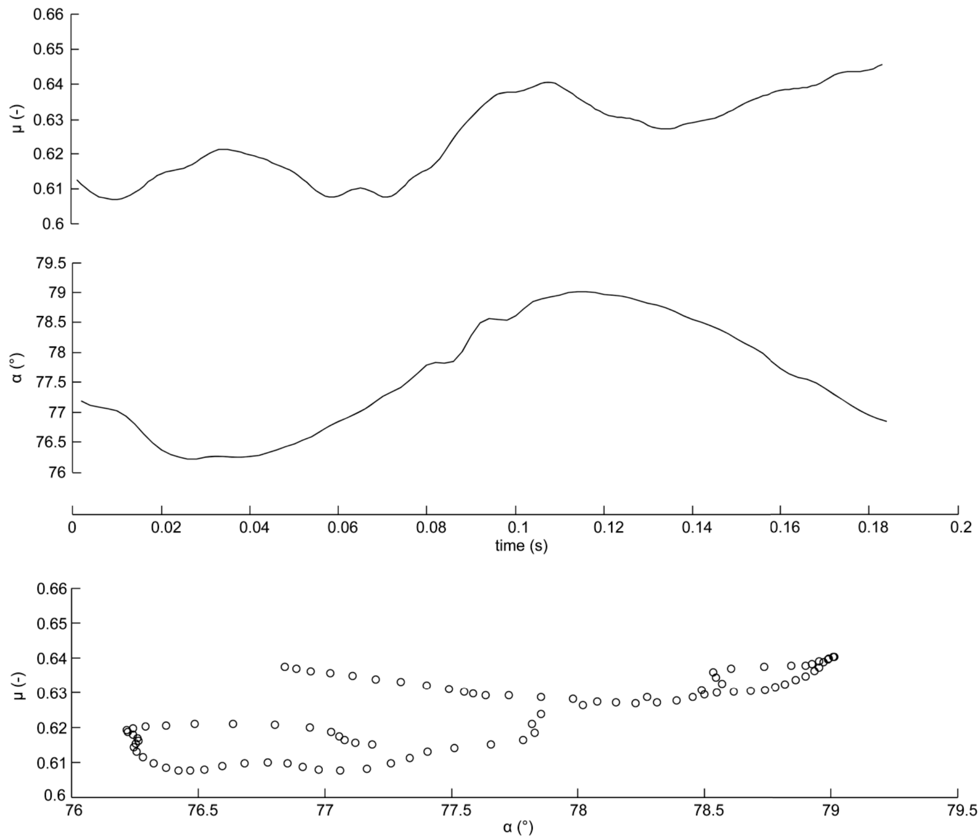

Figure 5. Illustration of the interaction between traction coefficient and shoe angle during sole contact. Top: time course examples of variation in traction coefficient and shoe angle. Bottom: relationship between traction coefficient and shoe angle. The natural variation occurring in each of the variables makes comparisons at each instant unsuitable.

Shoe Angle and Traction

A significant positive relationship between μ and α was observed. As is the nature of correlation analysis, more insight in a potential cause and effect relationship is not provided. Hence, variation in α may cause variation in μ or variation in μ may cause variation in α. However, in this particular instance, it is reasonable to assume that variation in α causes variation in μ rather than vice versa, as α is largely determined prior to surface contact (with limited variation during surface contact) whereas μ necessarily is determined during surface contact.

In the present study, a predicted increase in μ of .0017 was found for every degree of medial rotation. For a player with a body mass of 70 kg, this means that a difference in medial rotation of 60° (roughly the range of the majority of measured shoe angles; Figure 4) potentially corresponds to an additional ~70 N, or ~0.1 times body weight, of traction force ($F_h = \mu F_v = 0.1 * 70$ kg * 9.81 m·s^{-2}). Taking the magnitude of μ into account, a change in traction coefficient of 0.1 does not appear impactful compared to previous recommendations for suitable traction coefficients (Frederick 1993, Lloyd and Stevenson 1990). Further, considering a previous analysis has shown traction forces to be ~1.6 times body weight (McGhie and Ettema 2013b), an increase of ~0.1 body weight, corresponding to a ~6 % change, seems unlikely to affect the traction force working on the body in a meaningful way. It is worth noting that it remains unclear if subjects intentionally chose a particular shoe angle in an effort to obtain a desired μ (and within it, a desired friction force), which would render the previous statements somewhat redundant.

In the present study the majority of α was between 40° and 100°, exceeding the angle of 60° at which the threshold for increase in traction coefficient has been identified previously using a mechanical device (Sabick et al. 2009). Following the "trench effect" theory, a further increase in traction coefficient above shoe angles of 60° relative to sliding direction should not occur due to the directional specifics of cleat configurations, realigning a number of cleats. This does not hold true for *in vivo* measurements, where μ continued to increase with α above 60°. On a side note, it is interesting that in the present study no subjects chose a medial rotation relative to initial running direction greater than ~60°, regardless of whether this was done on the basis of anatomical constraints or for traction related reasons, and that, despite a shift of roughly 40°, the range of α chosen was similar to the range of shoe angles supposedly eliciting an increase in traction coefficient using a mechanical device.

A likely explanation for the discrepancy between mechanical device testing and *in vivo* testing can be found in the shoe displacement. The "trench effect" originated from an experiment where a displacement of 20 cm was employed (Sabick et al. 2009), allowing the distance between a number of different cleats at different angles to be covered. In contrast, with human subjects a mean displacement of 1.33 cm was uncovered. Simply put, for controlled human movement the shoe displacement appears insufficient for the "trench effect" to ever be a factor. Hence, there is no obvious reason why shoe angles exceeding 60° should produce results following a different pattern. That is not to say that the principle behind the "trench effect" theory is not valid, but rather that it may be more so for mechanical device tests than for controlled human movement where the required shoe displacements do not appear to occur. Still, this leaves the question of why μ increases with α, even when disregarding the "trench effect", without an apparent answer. It is possible that further analyses including joint-specific variables at the different shoe angles is needed to uncover the underlying reasons behind the relationship.

Cleat Configuration

Bladed cleats have, as mentioned previously (Lambson et al. 1996, Taylor 2010), been blamed for being harmful due to injuries resulting from increased traction caused by the cleat configuration, and could be expected to produce greater resistance with increasing shoe angle as a function of cleat shape resulting in a progressively increasing surface area in the direction of movement. Traditional round cleats, on the other hand, maintain an identical cleat surface area irrespective of transverse plane orientation, and hence traction should increase with increasing shoe angle only as a result of an increased number of cleats carving their unique path through the turf system. However, even considering it was significantly greater with traditional round cleats, shoe displacement does not appear sufficient for this to be a factor. Regardless, and in this case more importantly, there were no significant differences in the magnitude of the slope of the μ – α relationship between the three cleat configurations, leaving no evidence of cleat surface area in movement direction as a likely cause behind the increase in μ. Acting as something of a mediating factor, a previous analysis found μ to be similar across all three cleat configurations (McGhie and Ettema 2013b). Perhaps most surprising was the fact that turf cleats didn't differ from the two more pronounced cleat configurations with regard to the μ – α relationship, since turf cleats can be assumed to penetrate the turf system to a much smaller degree. This goes against the notion that a reduction in penetration depth is accompanied by a reduction in traction force (Kirk et al. 2007).

It might be that the limited displacement that occurs is the reason why, defying conventional wisdom, none of the quite dissimilar cleat configurations affect the μ – α relationship. The properties of the infill in the turf system, with its combination of loose state and capacity for continuous adjustment, could play an important role in ensuring that, due to the relatively speaking diminutive magnitude of displacement, it maintains a fairly consistent resistance across various cleat surface areas.

In line with previous results derived from a mechanical device (Sabick et al. 2009), the present findings indicate that shoe angle is of greater effect than cleat configuration with regard to traction coefficient also when measured with a standardized movement. Coupled with the recent finding that cleat configuration doesn't appear to dictate traction coefficient (McGhie and Ettema 2013b) it can be argued that injuries that are conventionally attributed to cleat shape should perhaps rather be attributed to the spatial specifics of the interaction between playing surface and shoe. However, it is important to reiterate that the change in traction across the range of shoe angles does not appear to reach a magnitude warranting concern.

Turf System

Disregarding purely material differences between turf systems, of which there are none between those included here, the two main components capable of influencing resistance are fibre density and infill density. As can be seen in Table 1, DU42 has the highest number of tufts per area (i.e., fibre density), followed by DU50 and DU60. With fibre height (minus 1.5 cm free fibre) factored in, the amount of infill per area (i.e., infill density) estimated from the surface specifications is slightly greater on DU50 than DU42 and DU60, which are equal. In the present study, a statistically similar slope of the $\mu - \alpha$ relationship was observed on all three turf systems, singling out neither fibre density nor infill density as a possible reason for the increase in μ with α. Further, the lack of support for one of the basic premises of the "trench effect", namely sufficient displacement, seems likely to diminish any potential effect of fibre density or infill density on resistance, especially when considered in conjunction with the previously discussed adaptive properties of infill.

Using other turf system characteristics to assess the absence of differences in the slope of the $\mu - \alpha$ relationship highlights further similarities. The three turf systems exhibit similar impact absorption (a variable related to, among other things, infill properties) during player-surface impacts (McGhie and Ettema 2013a), which could be assumed to have an effect on μ. In any case, in theory, the impact absorption of a turf system does not change depending on transverse plane shoe angle, and hence should not affect the $\mu - \alpha$ relationship, at least not in a direct manner. Adding to this, μ is also similar across the three turf systems during player-surface interactions (McGhie and Ettema 2013b). One possible reason behind the similarity between the three turf systems, briefly mentioned previously, is the fact that their material composition, a factor which may influence resistance (Villwock et al. 2009), is identical. Nevertheless, the lack of any observed mechanisms, besides potentially the limited cleat displacement, that could cancel out the existing differences in fibre density and infill density between the turf systems leaves their effect on the μ – α relationship still uncertain.

Conclusion

During a standardized cutting movement, an increase in shoe angle was accompanied by an increase in traction coefficient. Due to the order of occurrence of these variables in a cutting movement it is reasonable to assume that the increase in traction coefficient is caused by the increase in shoe angle. However, shoe displacement was not sufficient to support the "trench effect" theory. The reason why the traction coefficient – shoe angle relationship persists despite limited displacement remains unclear, as neither cleat configuration nor turf system appeared to affect the slope of the relationship. Future research on this relationship should attempt to uncover further details on what may be the underlying causes during human movement. In any case, it is worth noting that the increase in traction coefficient over a large range of shoe angles is seemingly not substantial enough to cause any practical implications.

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