Mechanical traction
behaviour of artificial turf

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MECHANICAL TRACTION BEHAVIOUR OF ARTIFICIAL TURF

By

Carolyn Helen Webb

A Doctoral Thesis Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University

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ABSTRACT

Artificial surfaces are increasingly more common in a number of sports including football, rugby and hockey. Each specific sport has mechanical properties designed to suit the requirements of the sport which can be achieved through appropriate selection of surface specification, as well as the appropriate selection of footwear.

In player-surface interactions, traction is a key system property that needs to be measured for comfort, performance and any potential injury risk. Many of the current industry tests used to measure traction are simplistic and have limitations when used in tests.

The aim of the thesis was to make a contribution to knowledge with regard to the mobilisation of traction and apply this to the understanding of shoe-surface interactions. This was achieved by completing a number of objectives. These included reviewing current knowledge of player-surface interaction behaviour in relation to traction and obtaining relevant human boundary conditions for biofidelic mechanical test development. The mechanisms of traction were then investigated and the variables in the mobilisation of traction identified. The traction forces developed were quantified with appropriate measurement systems. Mechanical test equipment was then developed along with protocols to replicate the translational and rotational lower limb behaviour during sport specific behaviour. This included the standard FIFA rotational device being modified to include two sensors which record continuous data throughout a trial to allow for more than a peak torque value to be analysed. In addition, a piece of equipment to measure translational traction was developed and constructed to support the rotational traction device and help to understand the mobilisation of traction. The device pulled a tray containing a surface sample, with a shoe/plate placed on the sample. The horizontal force was measured, as well as the amount of stud penetration into the surface.

It was also necessary to characterise the state of the surface and the effects that any changes may have on the traction that is mobilised. Testing completed involved repeated testing on both the rotational and translational to allow for comparison. Changes in the surface properties were made such as the number of fibres in a set area and the rubber infill density as well as shoe properties such as stud spacing, stud type and number of studs. In the results, the initial stiffness response of the surface was often focussed on as it was
stated that this may be a better indicator of the mechanisms involved in the traction mobilised by subjects, compared to peak torque. This is due to actual foot rotation measured in subject testing being observed to be much smaller than the rotation/distance required to produce the peak force. The larger angles/displacements were also considered to help inform the mechanisms of traction.

The final objective was to refine the mechanisms based on the experimental design. This all adds to the contribution of knowledge regarding the mobilisation of traction.

A key outcome from the thesis is the effect the surface and shoe properties have on traction, therefore it is essential to state the specification when reporting results otherwise comparisons are not able to be made. The mechanism of traction has not previously been fully understood, with this thesis beginning to understand the details of how the change in surface or shoe properties affect how the surface reacts during shoe-surface interactions.

Keywords: Traction, artificial surfaces, shoe-surface interaction, Football, Rugby, mechanical testing.
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CHAPTER ONE – INTRODUCTION

1.1 Background

Artificial turf surfaces were developed to replicate the playing characteristics of natural pitches, in an attempt to increase sport participation and reduce costs (Dragoo et al., 2010). Around 50 years of research has culminated in the development of third generation (3G) turf, the most technologically advanced artificial turf and the focus of this study. Initially, the artificial surfaces did not replicate the characteristics of natural pitches, with many governing bodies stating that they contributed to an increase in injuries due to too much traction (Williams et al., 2013). Development has improved these artificial surfaces with the number of surfaces increasing amongst a range of sports. These surfaces are often used instead of natural turf and, particularly for American Football and field hockey, is the surface of choice.

Traction is a key property occurring at the shoe-surface interface during sport specific movements (Fleming et al., 2011). Footwear traction is categorised by both translational and rotational components (Wannop et al., 2015). Generating traction between a player’s footwear and the surface is a crucial factor influencing the player’s performance. Too much traction and the player’s shoe may become fixed into the surface, potentially causing an ACL injury. Too little traction and slipping may occur. Traction performance of a 3G artificial surface is also relevant in terms of comfort.

The traction mobilised allows the player to accelerate, decelerate and change direction. A wide number of factors affect the traction produced, which contributes to the difficulty in understanding how traction is mobilised. Understanding these mechanisms will help to optimise surface performance and reduce injury.

Traction testing is typically completed using both mechanical and subject testing. It is widely reported that testing using human subjects is important to support mechanical testing and to understand the player-surface interface (Muller et al., 2010). Mechanical test devices aim to replicate the interaction between the shoe and surface for game-relevant movement and loading. A number of governing bodies use a rotational traction device to measure the peak torque of a surface (FIFA, World Rugby, RFL). However, the use of such a device to measure peak force or a point at a later displacement/angle may not be suitable for studies
investigating shoe-surface interactions, as they may not sufficiently replicate sport-specific movement (Livesay et al., 2006; Twomey et al., 2011). There are also a large number of bespoke mechanical test devices which have been developed by individual institutions to understand the shoe-surface interface.

It has been reported by Severn et al. (2010b) and Clarke et al. (2012) that there is a need for improved scientific understanding of the mechanism of interaction between the shoe and the surface and the high number of variables involved.

The mechanisms can be hypothesised with the help of mechanical test devices which have been designed with the awareness of human boundary conditions. By simplifying the testing completed at the shoe-surface interface, an understanding of the forces can be developed, with the properties varied to further understand the mechanism hypotheses.

1.2 Aim and Objectives

1.2.1 Aim
The aim of the research documented in this thesis is to make a contribution to knowledge with regard to the mobilisation of traction and apply this to the understanding of shoe-surface interactions. In order to achieve this aim, a number of objectives were formulated, as documented in Section 1.2.2.

1.2.2 Objectives
1. Review current knowledge in player-surface interaction behaviour in relation to traction.
2. Obtain relevant human boundary conditions for biofidelic mechanical test development.
3. Investigate and identify the mechanisms and variables involved in the mobilisation of traction.
4. Develop appropriate measurement systems to quantify the traction forces.
5. Develop mechanical test equipment and protocols to replicate key translational and rotational lower limb behaviour during sport specific behaviour.
6. Investigate the effects of changes in surface system design and shoe properties on the measurement of traction.
7. Refine the mechanisms based on the experimental design.
Details of how the aim and objectives were met are presented in Chapter three (Section 3.2).

### 1.3 Definitions of terms

A list of definitions of terms used throughout the thesis is shown in Table 1.1. These are terms that occur frequently.

Table 1.1: Definitions of terms throughout thesis.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Traction</td>
</tr>
<tr>
<td>2</td>
<td>Translational traction</td>
</tr>
<tr>
<td>3</td>
<td>Rotational traction</td>
</tr>
<tr>
<td>4</td>
<td>Mechanism of traction</td>
</tr>
<tr>
<td>5</td>
<td>Mobilisation of traction</td>
</tr>
<tr>
<td>6</td>
<td>Compaction</td>
</tr>
<tr>
<td>7</td>
<td>Compression</td>
</tr>
<tr>
<td>8</td>
<td>Shearing force</td>
</tr>
<tr>
<td>9</td>
<td>Ploughing</td>
</tr>
<tr>
<td>10</td>
<td>Stud penetration</td>
</tr>
<tr>
<td>11</td>
<td>Stiffness</td>
</tr>
<tr>
<td>12</td>
<td>Undisturbed/disturbed</td>
</tr>
<tr>
<td>13</td>
<td>Surface system</td>
</tr>
</tbody>
</table>
1.4 Thesis structure

The structure of the thesis is described below with a summary of each chapter. Figure 1.1 illustrates how each chapter links together to form the overall thesis.

Chapter One: Introduction
Chapter one provides an introduction to the thesis including a brief background of the research area, the aim and objectives and the structure of the thesis.

Chapter Two: Literature Review
Chapter two presents a review of previously published literature, outlining relevant literature and the subject of traction on third generation artificial surfaces whilst identifying any gaps in knowledge.

Chapter Three: Research Philosophy
Chapter three highlights how the objectives aim to be achieved. The mechanisms of rotational and translational traction are hypothesised and the plans for the mechanical tests set out to fulfil the hypotheses. The relevant testing variables are also presented to aid in the understanding of the mobilisation of traction.

Chapter Four: Player Movement Study
Chapter four presents a player movement study with the data presented and discussed in regard to both rotational and translational traction devices. Relevant variables were determined from Chapter two and used to aid the design of the methods and the mechanical tests, to increase the validity of the measurements.

Chapter Five: Development of mechanical test devices/Methodology
Chapter five details the development of the rotational and translational mechanical test devices. The methodologies for the areas of testing are presented along with the methods of analysis.

Chapter Six: Results
Chapter six presents the results from the testing completed using the rotational and translational traction devices along with observations from the results stated.

Chapter Seven: Discussion
Chapter seven includes a discussion of the results illustrated in Chapter six. Hypotheses of the mechanisms have been refined based on the results and deductions have been made.
Chapter Eight: Conclusions

Chapter eight brings together the overall findings of the research project presenting the conclusions of the research. The limitations of the project are presented along with the recommendations for future work.

Figure 1.1: Flow diagram showing thesis structure.
CHAPTER TWO – LITERATURE REVIEW

2.1 Introduction

The following chapter presents a thorough literature review of previously published, relevant literature on traction of third generation artificial surfaces with the aim of identifying any gaps in knowledge.

The literature review begins with an introduction to artificial surfaces with its history and advantages and limitations in Section 2.2. It then introduces the concept of traction and relevant terminology in Section 2.3. Section 2.3.4 presents the player testing, including the movement descriptions and player requirements. Section 2.3.5 presents the mechanical testing, with testing standards used for traction, as well as any bespoke mechanical test devices. Section 2.4 and 2.5 gives an overview of the surface and shoe properties involved in traction and shoe-surface interactions. It includes the physical characteristics and mechanical properties that influence the player characteristics. Section 2.6 looks at the analysis of traction and includes the interpretations when analysing traction. Section 2.7 looks at the mechanisms involved in traction. Finally, Section 2.8 presents a discussion on the key points found with the gaps in knowledge and any need for further research.

2.2 Development of artificial turf

Artificial surfaces were developed to mimic the playing characteristics of natural pitches (Dragoo et al., 2010). They have been developed over the last 50 years starting with first generation and spanning to more recent third generation turf. These surfaces are often used instead of natural turf, and particularly for American Football and field hockey, is the surface of choice. The number of artificial turf pitches has increased dramatically over the years (FA, 2014) with funding being increased in the following years (Department for culture, media and sport, 2015). Third generation turf was developed in the late 1990s with further padding added, longer pile length and improved infill characteristics compared to earlier generations, to provide increased cushion and minimise friction (Dragoo et al., 2010).
2.2.1 Construction of 3G turf

Third generation turf, the surface focussed on in this thesis, is made up of a number of layers, detailed in this section. Figure 2.1 shows a typical construction of third generation turf (FIFA, 2009).

![Figure 2.1: Typical construction of third generation artificial turf with illustrated layers as reproduced from Forrester and Tsui (2014).](image)

The lower levels are designed to provide support and an even surface for the pitch. Drainage is also important to take away excess water, which is incorporated into the lower base levels.

The shockpad, situated beneath the carpet has the purpose of providing cushioning and reducing the impact forces on the players. They are often prefabricated products including tiles or roll but are increasingly laid on site (Fleming et al., 2011). It is often made from rubber or open cell foams and a depth of between 12 and 30 mm for third generation surfaces.

On top of the shockpad is the carpet, made up of a polypropylene or polyethylene 40-65 mm carpet fibre. The plastic fibres are tufted, weaved or knitted to a backing textile material (Severn et al., 2010b). They are either monofilament or fibrillated with a low tuft density compared to previous generations.

Two infill layers are used in third generation turf, each with their own role. Compared to first and second generation surfaces, the volume of infill is much higher. A sand layer is used to provide stability and weight to the surface. The silica sand granules are between 0.25 and
0.39 mm in size. The sand has a high density due to its non-compressible nature and the small amount of void space between the sand particles.

The top layer consists of rubber crumb, providing comfort and a surface for players to interact with. The rubber crumb is often produced from recycled tyres, made of styrene butadiene rubber (SBR) ranging in size between one and two millimetres in diameter. The rubber infill particles differ in shape due to the shredding process which creates variable shaped pieces. The infill is often filled to a depth of two-thirds the pile height, and can be 120 tonnes of recycled rubber for a full sized football pitch (Fleming et al., 2011). Any free-standing fibre showing above the infill is important for surface friction, such as the amount of ball roll. Due to the compressibility of the rubber crumb and the number of air voids, it can be compacted with ease compared to sand.

2.2.2 Advantages and disadvantages of 3G turf

There are many advantages to 3G artificial surfaces which have been well documented since its development and increased use. These advantages are often compared to natural pitches and used as the argument and justification for replacing natural pitches with artificial pitches.

With the introduction of third generation surfaces, many of the problems associated with earlier generations have been eradicated. These include high stiffness, increased friction, higher amount of skin abrasion and a distorted bounce/roll of the ball (Burrillo et al., 2012). Shorten et al. (2003) stated that the later infilled third generation pitches tend to have lower translational traction values compared to the traditional Astroturf. However, fewer differences were apparent when rotational traction was measured.

One advantage of 3G turf is the availability for use with the number of hours of use per day being far greater than a natural pitch (Zanetti et al., 2012). This is in part due to the artificial pitches ability to be less dependent on the weather condition (Kirby et al., 2006). Natural pitches are often expensive to maintain, particularly in areas of high temperature and low annual rainfall (Orchard, 2002). Artificial pitches are found to give more consistent playing conditions (Bjorneboe et al., 2010; Kirby et al., 2006) with little variation between positions. Conversely, natural pitches tend to change throughout a season (Williams, 2011) due to wear, with ball rebound resilience and rotational resistance being found to decrease (Kirby et al., 2006). Artificial turf is often said to be low maintenance, and although it requires less
than natural pitches (Bjorneboe et al., 2010; Zanetti et al., 2012), they still need the aftercare that various performance standards specify (Fleming et al., 2011).

2.3 Player-surface interaction

Traction is one of the key factors that has a major effect on athlete performance and is the focus of shoe and surface designers. Being able to generate traction between the shoe and surface is crucial in influencing the player’s movement and performance (Fleming et al., 2011). Movements such as running, quick changes in direction, stopping and starting, result in high horizontal forces between the shoe and the surface. During a cutting movement (a sudden change in direction) for example, the sideways forces may reach or exceed the athlete’s bodyweight. To prevent slipping, a high traction coefficient between the shoe and surface is required (Shorten et al., 2003). The amount of traction at the shoe-surface interface can contribute to or cause an injury with too little resistance force resulting in slipping, and too much causing the shoe to stick (Fleming et al., 2011) causing a high force on the joints.

Footwear traction is categorised by both a translational and rotational component (Wannop et al., 2015). A majority of previous studies have focussed on rotational traction with less of a focus on translational traction. However, it has been observed that translational traction plays a big part in movements used in various sports.

The mechanism of traction is the process of a shoe-surface movement and the forces that make up the overall movement. In past studies, it has often not been documented and the movement not been broken down to fully understand the process in detail. It is important to take into account both forms of traction to be able to fully understand the mechanism.

2.3.1 Friction and Traction

Friction and traction are both used to describe shoe-surface interactions. Shorten et al., (2003) state that both describe the dissipative force that resists relative motion between two surfaces in sliding contact. Friction is often identified by static friction, which is described as the resistance at the point of impending motion and is helpful in determining when a slip begins (Pedroza et al., 2010), and dynamic friction, described as the resistance during relative sliding motion at constant velocity (Shorten et al., 2003) and more closely mimics active motion (Pedroza et al., 2010). Coefficients of friction are material-dependent
constants, independent of time, velocity and contact pressure (Shorten et al., 2003). The static coefficient will always be larger than the dynamic coefficient.

This friction principle described above is fairly simplistic and does not necessarily describe the complex interactions between compliant, non-uniform surfaces found in 3G surface and shoe interface problems (Shorten et al., 2003), therefore traction is normally used when the classic laws of friction do not apply.

The traction developed is affected by a number of factors; these include the surface (ground hardness, ground coefficient of friction), the shoe (length of studs/cleats), the mass of the player, the velocity of the player, the contact area, the cutting angle, the pressure and the position of the foot (McGhie et al., 2013; Shorten et al., 2003; Bostingl et al., 1975; Alentorn-Geli et al., 2009). The high number of variables will be discussed in detail later.

2.3.2 Definitions of Traction

One of the problems with the high volume of studies completed is the number of different definitions used to describe traction. A range of these are shown below.

Table 2.1: Range of definitions for traction.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Traction description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell et al. (1985)</td>
<td>The term traction should be used only when footwear containing studs, spikes, or cleats are in contact with a turf.</td>
</tr>
<tr>
<td>Baker and Canaway (1993)</td>
<td>Traction is expressed in terms of coefficients expressing the ratio of horizontal force to vertical force.</td>
</tr>
<tr>
<td>Shorten and Himmelsbach, (2002)</td>
<td>The traction coefficient τ, describes the ratio of traction force and normal force. τ is not a simple material constant and is free to vary with time, normal load and pressure, contact area and sliding velocity. Both translational and rotational traction can be static or dynamic in nature.</td>
</tr>
<tr>
<td>Young (2006)</td>
<td>Used when the force is generated by interlocking of the contacting objects, such as studded shoes penetrating a grass surface and is known as form locking.</td>
</tr>
<tr>
<td>Kirk (2008)</td>
<td>Traction is defined as the horizontal resistive force during the interaction of the shoe with the surface. Traction comprises all the physical mechanisms which give rise to the horizontal force.</td>
</tr>
<tr>
<td>Severn (2010)</td>
<td>The force needed to grip or hold to a surface while moving without slipping.</td>
</tr>
</tbody>
</table>
Clarke (2011) | Described as the horizontal resistive force resisting movement.
---|---
Wannop et al. (2015) | Linear translational traction is dependent on both the force normal and horizontal to the surface and is usually described as a coefficient defined by the ratio of horizontal to vertical force. Rotational traction is generally described using the moment of rotation with respect to the centre of pressure, which refers to rotation of the foot around a point of contact on the shoe sole.

There are a range of definitions, from the relatively simple (Bell et al., 1985) to the more detailed (Wannop et al., 2015). In general, the definitions agree with each other with no contradictions, and only minor variations. Although the risk is that traction is often simplified and this leads to the mechanism not being fully understood. The definition for traction used in this study (Table 1.1) is ‘The resistive force during a shoe-surface interaction, often made up of both rotational and translational components’.

2.3.3 Traction testing

The following section includes details of both mechanical and subject testing and the importance of these. It describes testing standards, mechanical test devices, injury studies and the various factors contributing to shoe-surface interaction.

2.3.3.1 Importance of traction testing

Testing using human subjects is very important to support mechanical testing and help to understand player-surface interface. It has been widely recognised that it is not sufficient to solely perform mechanical testing (Muller et al., 2010; Kuhlman et al., 2010). Potthast et al. (2010) comments that mechanical tests do not often reflect the response of the human body, particularly physiological processes, hence why player testing is required.

An advantage of performing tests using subjects is that they can provide realistic boundary conditions (Kirk et al., 2007). Traction is one of the main surface characteristics that may be related to injury on both natural and artificial surfaces (Stiles et al., 2009) and a combination of biomechanical and mechanical testing can help to develop the knowledge and understanding of ways to prevent injury by looking at boundary conditions and representative quantitative data.
Player testing can be intrusive and suffer from poor repeatability between players due to the difficulty in controlling the loading conditions and completing an identical movement (Clarke and Carre, 2010). It can also give uncertainties when subtle changes in variables are introduced (Kirk et al., 2007). Often, player testing does not appeal to athletes because it can be intrusive to training (Clarke and Carre, 2010). During player testing, the laboratory environment may influence the movement pattern because of the lighting or the time taken between trials (Kirk et al., 2007). Subjects may change their stride length or adjust their movement so they fit the force plate which may also affect the results collected (Kaila, 2007).

Conversely, mechanical testing has the advantage of being a repeatable measure and can create objective loading conditions (Clarke and Carre, 2010). It is clear that mechanical testing needs to be as biofidelic as possible, which is important when designing a mechanical testing device. Otherwise, the results risk being interpreted incorrectly (Fleming et al., 2011).

2.3.4 Player testing

There are a large number of studies that have been completed which include the participation of subjects both in the lab and on the field. It is not feasible to capture an injury in a laboratory environment due to ethical reasons. Therefore, other methods have been used to understand injuries and the mechanisms involved such as mathematical models and cadaver studies (Krosshaug and Bahn, 2005). However, specific movements can be performed in the laboratory to collect and analyse data. In the lab, it is possible to integrate artificial or natural turf and collect kinematic and kinetic data from a player completing a movement. Kinetic data such as ground reaction forces and plantar pressure measurements can be collected as well as three dimensional kinematic data from the foot and lower limbs (Kirk et al., 2007). The following section sets out to look at the specific movements performed during testing, the types of injuries sustained and the variables that affect a players movements and results collected from previous studies which can be used to inform mechanical devices.
2.3.4.1 Movement descriptions

In previous research, many authors have used their own definitions for the specific movements involved in sport. There are occasional cross-overs but the movements have various names, which may depend on the country of the paper or the authors own interpretation. The movements have been split into three tables showing straight line running, cutting movements and shooting movements, and show a selection of the movements used in literature with any necessary descriptions.

Table 2.2: Straight line running movements with descriptions from various authors.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Movement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirk et al., (2007)</td>
<td>Push-off sprint</td>
<td>An anterior-posterior translation of the shoe forefoot where the player seeks sufficiently high traction to avoid slipping when accelerating from rest or jogging.</td>
</tr>
<tr>
<td>Kaila, Rajiv (2007)</td>
<td>Straight ahead run</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sprint</td>
<td>At maximum speed</td>
</tr>
</tbody>
</table>

Table 2.3: Cutting movements with descriptions from various authors.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Movement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45º side cut</td>
<td>Pushing off to the medial direction of the planting foot.</td>
</tr>
<tr>
<td>Nigg et al., (2009)</td>
<td>Side-shuffle</td>
<td>Described as the participant approaching from the left side, landing on the right foot and then moving directly back to the left side</td>
</tr>
<tr>
<td></td>
<td>V-cut</td>
<td>Participant approached at a 45º angle, from the left-back to the right-front, landed on their right foot, and then moved directly off to the left side.</td>
</tr>
<tr>
<td>Kaila, Rajiv (2007)</td>
<td>A sidestep cutting manoeuvre at 30º</td>
<td>Manoeuvres can be seen in diagram below. A sidestep cutting manoeuver is described as a rapid change in direction, a</td>
</tr>
</tbody>
</table>
sudden forceful twisting of the lower limb when the foot is on the surface and the knee is flexed.

Cutting manoeuver
At approximately 70% of maximum speed using a slalom course

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Movement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirk et al., (2007)</td>
<td>Heel plant during kicking</td>
<td>Subjects stepped in the gaps of a training ladder before reaching a region where they undertook the specific movement at a velocity of $2.25 \pm 0.63 \text{ m s}^{-1}$.</td>
</tr>
</tbody>
</table>

**Table 2.4: Shooting movements with descriptions from various authors.**

### 2.3.4.2 Player requirements

Different player movements have different traction requirements and will use different amounts of translational and rotational traction. For example, Wannop et al. (2015) described two movements, the v-cut (a pivot movement where the athlete planted their foot and pivoted to maintain a high movement speed), and the s-cut (a start and stop movement to facilitate the rapid change in direction – still incorporating a pivoting movement). Rotational traction is more important for pivoting on the surface, which explains why rotational traction affected the transverse plane loading for both movements, while translational traction did not. The translational traction was more important for the rapid change in direction of the s-cut, because of its ‘plant and cut’ movement, which explains the fact that translational traction had an influence on frontal plane loading during the movement (Wannop et al., 2015).
It has long been believed that a potential cause of non-contact lower extremity injury is due to the interaction of the shoe and the surface, with traction being the primary cause (Wannop et al., 2015). It has been previously reported that 70% of all ACL (anterior cruciate ligament) injuries occur in non-contact situations, during changes in direction, landing on a hyperextended, internal tibial rotated knee (Cross et al., 1989) and typically when decelerating (Kaila et al., 2007), in reference to Australian rugby league football and football.

Many studies have been completed investigating the link between traction and non-contact injury. Lambson et al. (1996) and Wannop et al. (2012) found that footwear that had significantly greater rotational traction were linked to higher ACL injury and non-contact lower extremity injury rates in football. A relationship was also found between translational traction and injury, which has been investigated less frequently. Based on this, translational traction should not be ignored and is as important as rotational traction when related to injury risk (Wannop et al., 2015) and performance.

Cross et al (1989) analysed the side-step cutting manoeuvre to determine the stress placed on the ACL. The study found that under normal circumstances, when performing a side-step cutting manoeuvre, maximum internal tibial rotation would not occur. Therefore, the ACL is not being placed under excessive strain, and is not susceptible to rupture. If the ACL does tear when performing the manoeuvre, then a likely cause is the loss of ability to control internal tibial rotation of the knee (Cross et al., 1989).

The argument between injury on artificial and natural pitches is common, with authors coming to different conclusions and outcomes. Skovron et al., (1990) found that there was a 30 to 50 % increase in lower-limb injury risk on artificial turf, however Nigg and Segesser (1988) found that there was an increase in less serious injuries on artificial turf, a possible increase in severe injury and ankle injuries on artificial turf, but no difference in severe injuries of all types for artificial turf when comparing to natural grass.

There are many potential mechanisms for differing injury patterns on artificial turf suggested by Williams et al. (2011). These include the increased peak torque properties and rotational stiffness properties of shoe-surface interfaces, the differing foot loading patterns and detrimental physiological responses compared to natural turf surfaces.

Although it has been mentioned that injury patterns may differ, there does not appear to be a significant different between the overall injury rate on third-generation artificial and
natural surfaces. It is worth noting that a number of other factors affect the injury rates such as the sport and the environmental conditions (Dragoo et al., 2010).

2.3.4.3 Vertical load
By altering the technique, speed or movement being performed, these influence the way the surface is loaded and the amount of traction mobilised between the boot and surface. The ground reaction force when performing a movement is dependent on a number of factors. Firstly, the particular movement being performed, as a movement with a higher velocity is likely to produce a higher force; the surface where differing properties will affect the force reduction; and the athlete’s body weight (BW) and acceleration.

Studies often normalise the results and present the ground reaction force (GRF) as a multiple of the athlete’s body weight. It has been widely reported that as the amount of player weight which is supported by the shoe increases, the torque between the shoe and the surface increases (Bostingl et al., 1975). Different GRFs have been found, depending on the movement. Several studies have been completed for running with a range of results found. Ozkaya and Nordin (1999) estimated that the peak vertical ground reaction force in running is equal to 2.8 times the body weight. Cavanagh (1990) found that the force exceeds 2.5 times the body weight. Muller et al. (2010) and Schrier et al (2014) found GRFs in the magnitude of 2.3 BWs. Hamill et al. (1996) found an increase in GRF when only the running speed variable was increased.

In more dynamic and complicated movements, the GRF is likely to be higher. However, Blackburn (2005) found that during a 45° turn, the maximum vertical forces measured were between 0.6 – 1.8 times the body weight which is lower than the studies shown above. A more extreme cutting movement gave a maximum vertical force of 2.00 BW (Adrian and Xu, 1990) and ~2.50 BW (Stiles et al., 2009).

Nigg et al. (2009) investigated the forces produced in different directions. It was found that the ground reaction forces in the vertical direction were higher than in the medio-lateral and antero-posterior directions for both a side-shuffle and v-cut. The peak vertical forces were about 1.5–2.5 times body weight (BW), with the peak medial forces being about 1.0 BW. The posterior forces were about 0.25 BW for the side-shuffle and about 0.5 BW for the
v-cut. Comparatively, Adrian and Xu (1990) found a maximum horizontal force of 0.67 BW for a cutting movement.

Kuhlman et al. (2010) used a range of vertical loads on a mechanical test device measuring both rotational and translational traction, from a load of 20 kg, up to approximately 180 kg (equivalent to about two body weights). The study found that the traction coefficient only decreased a small amount between the 888 N and 1776 N conditions (Figure 2.2). This shows that it may not be necessary to measure traction under a higher load. Perhaps, this is a justification for using a vertical load of one body weight when developing a test device, to make operating the device more user friendly. However this is only one study, therefore additional testing may be required. Above a load of 1776 N, the artificial turf surface was permanently damaged which highlights the problem of testing at loads reached during sport-specific movements.

Figure 2.2: The average traction coefficient versus vertical load condition across a range of loading conditions for the static, peak and dynamic traction variables as the shoe cleats engage with the surface, representing a hard stop by an athlete (Kuhlman et al., 2010).
2.3.4.4 Foot rotation

One of the important links between player testing and mechanical testing is the amount of foot rotation or translation on impact of the surface. Many mechanical tests measure and report the peak torque, which is reached at high rotations (often around 40°).

El Kati (2012) used human subjects to perform sport specific movements including a stop and turn manoeuvre on a 3G surface. For more details on this case study, see section 2.3.5. It was found that rotation of the foot was in fact, quite small. On average, the foot rotated a total of 11.6° in the turning direction with the majority of movement occurring during the weight acceptance and final push-off stance phases (Figure 2.3, bottom). The figure shows how the foot rotation is not always linear and does not always rotate continuously in the direction of turn. Similarly, Kirk et al. (2007) used high speed cameras to analyse the foot angles and velocities during football related movements. It was concluded that after impact, the boot moved by a negligible amount horizontal to the surface. Figure 2.3 (top) shows the mean vertical resultant ground reaction force produced during a cutting movement with the various stance phases illustrated (Kaila, 2007) and below, the foot rotation of two subjects during a stop and turn movement as mentioned above (El Kati, 2012).

![Figure 2.3](image)

**Figure 2.3** – (Top) Mean vertical resultant ground-reaction force during a cutting movement showing three phases, reproduced from Kaila, 2007. (Bottom) - Two examples of foot rotation during ground contact of a stop and turn manoeuvre (El Kati, 2013).
Driscoll et al. (2012b) looked at the influence of the outsole configurations on the centre of rotation during a movement used by football players to change direction. This involved a participant performing a 30° side-cut with the motion of the shoe being captured. Five outsoles were tested with a range of stud heights, shapes and configurations. It was found that only 48% of the shoes rotated during the movement. For those that did rotate, the rotation occurred just before push-off when only the forefoot studs were in contact with the surface. The mean rotation angle was 15 ± 8°. This is less than the angle of rotation tested during traction assessments, although there was a high standard deviation and was suggested that the outsole influenced the amount of rotation.

These studies show that it may be more appropriate for mechanical tests to measure the initial movement involved in rotational and translational movements, rather than the higher angles reached at peak torque during the rotational traction standards (Section 2.3.5.1.1). It is worth identifying whether a small rotation can be compared to a translational movement to allow for comparison.

2.3.4.5 Velocity on impact

The velocity of the foot on impact is an important factor to consider when looking at developing a mechanical test device. Zanetti et al. (2012) completed a mechanical friction test under three low velocities (0.33 mms⁻¹, 0.67 mm s⁻¹ and 1 mm s⁻¹) but made the observation that when a subject impacts the surface, the speed reduces from its initial value to zero, while the force varies from zero to its peak value. Therefore, considering using low velocities in mechanical tests may not be an unrealistic scenario. It is hypothesised that the velocity that a player hits the surface at will have an influence on the traction. If a player impacts the surface at an increased velocity, it can be assumed that the studs will penetrate the surface more and therefore create a higher traction.

2.3.5 Case study

El Kati (2012) completed a study with the aim to analyse the human interactions during two movements on 3rd generation artificial turf. This helped to contribute new data in relation to a greater range of movements, relevant in-game scenarios and the use of carefully controlled surfaces. This was acknowledged as the most comprehensive study of boot
surface interaction. The data from this study will be analysed further in Chapter Four. The method used during subject testing is detailed below.

Two movements were chosen by the author (El Kati, 2012) after a player focus group and questionnaires were completed. These were a stop and turn movement and a stop-jump movement as they were seen to be the most frequently performed during a match by the players.

16 male football players were chosen, from the 1st, 2nd and 3rd Loughborough University football teams to ensure they had a good level of experience. This was to make sure the movements were completed in a consistent manner. They had an average age of 20 ± 1 year with an average body mass of 74.7 ± 6.6 kg and average height of 178 ± 4.8 cm.

The laboratory setup involved a runway with the ability to change the surface conditions. The runway was 12 m long, 1.5 m wide and consisted of four areas, as shown in Figure 2.4 below. The movements were made on top of the force platform.

![Figure 2.4: Scaled overview of set-up for biomechanical tests of runway, large force platform, timing gates and high speed video, taken from El Kati, (2012). The run-way was divided into four sections: (a) 7.5 m run-up area, (b) 2.1 m pre-movement area, (c) 0.9 m force platform and (d) 1 m extra area. (e) Timing gates were used over a two metre long area to measure the approach speed of the players.]

A Vicon 3D motion analysis system was used to track the movements of the player. This consisted of 12 cameras positioned to cover the force platform and surrounding area. A force platform was used to collect the ground reaction force data. This was 0.9 x 0.6 metres to ensure that the players did not have to aim to land on the force platform and to ensure a
natural movement. Timing gates were used to monitor the approach speed of players. A high speed video camera was used to film the foot contact with the surface. The whole body was tracked using the Vicon 3D motion analysis system through 39 markers placed on the body landmarks. All the subjects wore adidas Copa Mundial football boots for consistency.

There were four different surface conditions which were used with different hardness and rotational traction properties. The four combinations were:

- Hard surface and high traction;
- Hard surface and low traction;
- Soft surface and high traction;
- Soft surface and low traction.

There were 10 trials completed for each condition, with each condition having five with an opponent and five without (to resemble an in-game scenario).

The stop and turn players were instructed to start at the beginning of the runway and accelerate towards the timing gates. Between the timing gates they were required to reach a speed of between 12 and 14.5 km/h for a trial to be valid. Players were then instructed to start decelerating at the second timing gate, after which they had to land with their preferred foot on the force platform and turn 180°. They then had to accelerate back towards the first timing gate. They were given one-minute rest between trials and 5-10 minutes between surface conditions. A trial was discarded if a marker was lost during the movement.

El Kati (2012) found that both surface hardness and rotational traction can affect the human movement dynamics. The largest effects were found with the stop and turn movement, in comparison to the jumping and heading movement. With the stop and turn movement, the soft and high traction surface condition caused an increased average ground reaction force during mid-stance and a decreased ground contact time. During peak push off it appeared that the players were able to generate a larger force on the hard surfaces.
2.3.6 Mechanical testing

Many mechanical test devices attempt to replicate the interaction between the shoe and surface for game-relevant movement and loading (Carré et al., 2007). This section, 2.3.5, focusses on mechanical testing which include standards from governing bodies through to bespoke mechanical devices, designed and developed in previous studies.

2.3.6.1 Standard test devices

The governing bodies across a range of sports use test standards to quantify the play performance of a surface. The Federation Internationale de Football Association (FIFA) have a number of tests for football turf pitches that allow for consistent high quality pitches around the world. Once the football turf pitches pass the laboratory and field tests, they are awarded a FIFA Recommended One or Two star level (FIFA, 2015).

The standards relating to rotational traction are described below. Although they are often simplistic and limited in their replication of in-game scenarios, they have lasted a number of years and have a place in ranking pitches and assessing relative behaviour (Fleming and Forrester, 2014).

2.3.6.1.1 FIFA standards

Rotational resistance standard

The standard test equipment for measuring rotational resistance uses a torque wrench to measure the peak torque (Figure 2.5). The studded sole consists of six football studs equally spaced on the bottom of the surface, 46 ± 1 mm from the centre of the disc. Three weights are placed above the studded plate. The total mass of the studded disc, weights and shaft is 46 ± 2 Kg. The method involves lifting the test foot and dropping it onto the surface from a consistent height of 60 mm to control the level of penetration. The torque wrench is then turned manually, moving the test foot smoothly at a target rate of 12 rev/min until a rotation of at least 45° has occurred. The peak torque is reported to the nearest 1 Nm with an uncertainty of ± 2 Nm.

The guidelines state that an ‘ideal’ natural turf pitch has a rotational resistance of between 35 and 45 Nm while a good natural turf pitch has a value of between 25 and 50 Nm. If the torque is too low, the surface is said to be too slippery and too high a torque represents the possibility of ‘foot lock’ which results in ankle injuries (Fleming et al., 2011).
The FIFA guidelines state that for laboratory testing, the rotational resistance should be

determined in five positions, ensuring the test foot is at least 100 mm from the edge of the
test specimen. The test specimen is stated as a minimum of one metre by one metre. The
test should also be completed in dry and wet conditions. In field testing, five individual
measurements must be completed in each test location, at least 100 mm apart.

![Figure 2.5: Rotational Traction FIFA device](image)

There is no justification given for why the speed should be 12 rev/min and why it should be

rotated to at least 45°. When testing a number of operators, Twomey et al. (2011) found a

low level of reliability. This is most likely due to the lack of control and quantification of the

speed at which the device is rotated. As the peak rotational result is desired, the operator

turns the torque wrench until they feel the device ‘give’ and may be open to subjectivity

(Twomey et al., 2011).

The stud configuration used does not reflect the configuration on many of the football boots

used by players. A more realistic testing method would be to have the ability to attach an

interchangeable shoe onto the bottom of the device. Another limitation of the device is how

it only gives an output of the peak torque which may not necessarily represent the torque

that a player reaches, as discussed later in Section 2.6.
Translational standard test

Up until October 2015, a standard existed to test the slip resistance. This used a slip resistance tester (Figure 2.6) to assess how much horizontal movement the player will feel in the surface upon acceleration/deceleration. A studded test foot strikes the surface and comes to rest on a numbered scale. A low value indicates a slippery surface and a high value a surface that doesn’t allow sufficient movement and is dangerous to the player. Values of between 120-220 for horizontal movement have been found to give sufficient grip. A second measurement is taken which is the deceleration of the foot as it stops. High decelerations will cause soft tissue damage to the joints. Values between 3.0 and 6.0 g have been measured on good natural turf. Lower values indicate a surface with low grip and higher values with high grip. However, this standard has been removed from the FIFA Quality program for football turf (2015), perhaps due to its limited replication to player-surface interaction.

Figure 2.6: Slip resistance tester
2.3.6.1.2 World Rugby

World Rugby uses the same apparatus as FIFA for both rotational and translational testing (Section 2.3.5.1.1). The laboratory test requires that the values of traction for World Rugby standard rugby pitches are between 32 and 43 Nm with outdoor field testing being between 30 and 45 Nm. The linear friction test required the same values as Section 2.3.5.1.1 for lab testing, with no test standard for outdoor field testing. Similar to the FIFA tests, these are reasonably simple tests and may not represent human movements and interactions between themselves and the surface, as well as the stud configuration not reflecting the stud configuration on the bottom of football or rugby boots.

2.3.6.1.3 Rugby Football League (RFL)

The Rugby Football League (RFL) use standards based on the European standard BS EN 15330-1: Surfaces for Synthetic Turf and Needle-punched surface: Part One – Specification for synthetic turf surfaces. These have been modified for the requirements of Rugby League. As many Rugby League surfaces are used by Football and Rugby Union, the standard and test method is the same as with the FIFA and World Rugby standards (Section 2.3.5.1.1 and 2.3.5.1.2).

The expected output using the rotational traction device was between 35-50 Nm for stadium use surfaces and between 25-55 Nm for community use surfaces. The standard also tests a dimpled rubber sole and has an expected output of between 25-50 Nm for community use surfaces. No linear friction test was stated in the RFL standards.
2.3.6.1.4 Summary of Governing Body standards

Table 2.5 shows a summary of the torque ranges with Table 2.6 showing a summary of the linear friction ranges, given in the various governing body standards discussed above.

The 13 mm football studs used are a standard specification, stated in the FIFA handbook of test methods (2015).

Table 2.5: Torque ranges from governing body standards.

<table>
<thead>
<tr>
<th>Governing body</th>
<th>Test plate</th>
<th>Torque range (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIFA (Federation Internationale de Football Association)</td>
<td>Six studs (13 mm football studs)</td>
<td>‘Ideal’ turf = between 35 and 45 Nm. ‘Good’ turf = between 25 and 50 Nm.</td>
</tr>
<tr>
<td>World Rugby</td>
<td>Six studs (13 mm football studs)</td>
<td>Between 32 and 43 Nm (lab testing). Between 30 and 45 Nm (outdoor testing).</td>
</tr>
<tr>
<td>RFL (Rugby Football League)</td>
<td>Six studs (13 mm football studs)</td>
<td>Stadium use = between 35 and 50 Nm. Community use = between 25 and 55 Nm.</td>
</tr>
<tr>
<td></td>
<td>Dimpled rubber sole</td>
<td>Community use = between 25 and 50 Nm.</td>
</tr>
</tbody>
</table>

Table 2.6: Linear friction ranges from governing body standards.

<table>
<thead>
<tr>
<th>Governing body</th>
<th>Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIFA (Federation Internationale de Football Association)</td>
<td>Linear Friction - Stud Deceleration Value</td>
<td>120 – 220</td>
</tr>
<tr>
<td></td>
<td>Linear Friction - Stud Slide Value</td>
<td>3.0 – 6.0 g</td>
</tr>
<tr>
<td>World Rugby</td>
<td>Linear Friction - Stud Deceleration Value</td>
<td>120 – 220</td>
</tr>
<tr>
<td></td>
<td>Linear Friction - Stud Slide Value</td>
<td>3.0 – 6.0 g</td>
</tr>
<tr>
<td>RFL (Rugby Football League)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The torque values between governing bodies are very similar, with the higher specification pitches having a smaller range of permitted torque. The linear friction test is only used by the International Rugby Board, with the test being omitted from the FIFA standards.
2.3.6.2 Research bespoke mechanical test devices

There are a number of mechanical test devices which have been developed and implemented in various studies throughout different research institutes. Although there is not always a comparison between the test methods and the player-surface interaction, it is often stated that there is a need for these devices. However, a compromise is needed between the complex human interactions and the test devices repeatability and ease of use (Fleming et al., 2011).

All the test devices have different input parameters and test methods. These include the area of contact, the magnitude of normal load, the foot attachment used, the rate of loading and the interpretation of data. When searching through the literature, authors often do not state how the surface was prepared or the specification used which makes comparison very difficult (Fleming et al., 2011). One limitation of the current mechanical test devices is their application of a constant static normal load during testing, which conflicts with the foot contact of an athlete. In real life, it is the combination of vertical load and the traction response that develops the surface’s resistance to traction movement (Fleming et al., 2011).

The following table shows the range of bespoke mechanical test devices that have been developed. It includes a description of the device and comparable measures. They have been ordered by number of degrees of freedom increasing as the table progresses.
Table 2.7: Table of bespoke test devices to measure traction/friction.

<table>
<thead>
<tr>
<th>No. of DOF</th>
<th>Author</th>
<th>Photo</th>
<th>Description</th>
<th>Measure- ment</th>
<th>Field/lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 1          | Livesay et al., 2006 | ![Diagram](2006_Simple_Crossbar.jpg) | - Simple structure comprising of a vertical shaft was rigidly connected to the forefoot of the shoe and was used to generate a relative rotation between the shoe and the playing surface.  
- Torque-thrust sensor and rotary potentiometer.  
- Compressive load applied by hanging weights on the crossbar at the top of the vertical shaft. | Rotational torque  
Rotation                        | Both          | 34 kg          |
| 2          | Kirk, 2008        | ![Image](2008_Hydraulic_Ram.jpg)       | - Developed to represent a football player performing a forefoot push-off.  
- Uses a hydraulic ram which provides a vertical load applied to a stud plate.  
- The rig allows for the attachment of different stud types and configurations.  
- A high-pressure pneumatic ram provides a controlled driving force in the horizontal direction. | Horizontal force  
Displacement          | Lab          | 35 kg          |
<table>
<thead>
<tr>
<th>No. of DOF</th>
<th>Author</th>
<th>Photo</th>
<th>Description</th>
<th>Measure- ment</th>
<th>Field /lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 3         | Villwock et al., 2009a. | ![Diagram](image1.png) | - The frame supported the surrogate lower limb, a suspended 425-N weight attached to a 0.25-m radius gear that was used to produce a torque on the shoe.  
- Rate of rotation chosen to represent a high-speed injury situation.  
- Apparatus designed to simulate the anthropomorphic data of a 95th percentile male. Surrogate lower limb was fabricated with a tibia length of 44 cm to be realistic of the length of a male’s leg.  
- Centre of rotation (COR) on the test device was adjustable. | Rotational torque | Both | 102 kg |
| 4         | Wannop et al., 2012. | ![Diagram](image2.png) | - A tester with a stiff base which a single guide rail was mounted on. A platform slides freely on the guide rail and the platform holds a vertical shaft which can rotate freely.  
- A force transducer was attached.  
- Tester moves at a speed of 90°/s (close to 72°/s, FIFA recommended speed) for rotational traction.  
- Ability to change shoes | Translational traction coefficient  
Rotational torque | Both | 60 kg |
<table>
<thead>
<tr>
<th>No. of DOF</th>
<th>Author</th>
<th>Description</th>
<th>Measurement</th>
<th>Field/lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 5         | Blackburn et al., 2005 | - Based on a drop-mass/spring/mass system.  
- Use of two weighted pendulum systems to apply loads in a vertical, horizontal and rotational direction.  
- Electromagnets were triggered to release the pendulums at the same time.  
- Loads were applied to a test foot with a pimpled rubber or studded tread design to allow testing on different types of surfaces. | Translational traction coefficient  
Rotational torque  
Applied impact loads  
Accelerations | Both      | NA            |
| 6         | Kirk, 2008            | - adidas in-house bespoke piece of equipment.  
- The speed and distance of movement can be controlled and sports specific footwear can be attached to make it more realistic.  
- The test equipment is controlled pneumatically. | Translational traction coefficient  
Rotational torque  
Horizontal force  
Torque/time and displacement | Lab       | 71 kg         |
<table>
<thead>
<tr>
<th>No. of DOF</th>
<th>Author</th>
<th>Photo</th>
<th>Description</th>
<th>Measurement</th>
<th>Field/lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 7         | Kent et al., 2012       | ![Image](image1.png) | - Consists of a foot connected to a shaft which moves horizontally and vertically along a frame and is able to rotate.  
- The foot is powered by a high-speed pneumatic actuator connected to the shaft by a steel cable.  
- Uses a plantar outsole | Torque and force in vertical, horizontal and rotational direction  
Rotation Displacement | Both | 285 kg |
| 8         | McNitt, 1997            | ![Image](image2.png) | - Comprises of an inner and outer frame with a leg-shoe assembly and an aluminium foot attached to the end which allows for a shoe to be attached and changed.  
- Weights can be added to the top portion of the leg to apply various vertical forces. | Translational traction coefficient  
Rotational torque | Both | 116 kg |
<table>
<thead>
<tr>
<th>No. of DOF</th>
<th>Author</th>
<th>Description</th>
<th>Measure - ment</th>
<th>Field / lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 9         | Heidt et al., 1994      | - Looked at the differences in friction and torsional resistance in shoe-turf surface interfaces in American Football.  
- A pneumatic testing system was used with linear and rotary pneumatic actuators used to apply translational force and rotational torque.  
- A rigid prosthetic foot with no anatomic approximation of an ankle joint has a shoe fitted to the end with a load cell used to record the forces produced. | Translational traction coefficient  
Rotational torque | Both         | 11.35 kg      |
| 10        | Kuhlmann et al, 2010.   | - It is fully automated and tests translational and rotational motion, with the ability to change loading conditions.  
The angle of the shoe can be altered between trials to imitate movements.  
- Aimed to remove operator error from testing procedures.  
- It was found to be repeatable, giving consistent results between trials. | Translational traction coefficient  
Rotational torque  
Velocity  
Displacement | Both         | 23-181 kg     |
<table>
<thead>
<tr>
<th>No. of</th>
<th>Author</th>
<th>Description</th>
<th>Measurement</th>
<th>Field/lab</th>
<th>Vertical load</th>
</tr>
</thead>
</table>
| 11    | Grund et al., 2007. | - Four main components: a stable frame, an artificial lower leg, the load application unit and the pneumatic control unit.  
- Two pivoting frames against each other – one supports the artificial lower leg and the complete load application unit and can tilt in the sagittal plane while the other is parallel to the ground and enables tilting in the frontal plane.  
- Using a silicone cast allows for reproducible yielding characteristics of the foot so deformation of the foot can be taken into account. | Forces, Plantar pressure, Angular displacements in ankle | Both | Varied |
| 12    | Wannop et al., 2010. | - A six degrees of freedom testing machine allows for flexibility in the amount of movement it can perform.  
- A triaxial load cell measured forces and moments in the anteroposterior, mediolateral and inferosuperior directions during the testing procedure.  
- Platform rotating at a speed of 75 deg/s for rotational traction. | Translational traction coefficient, Rotational torque | Lab | 76 kg |
The advantage of a number of the devices is the ability to be able to test both translational and rotational traction without the need to two separate devices (4, 5, 6, 7, 8, 9, 10 and 12). However, this leads to the devices being very large in size with difficulties in portability and therefore, restraining the devices to the laboratory.

The devices have been listed in terms of degrees of freedom. Higher degrees of freedom are deemed more biofidelic due to the similarities to a human foot in its flexibility of movement. The majority of devices shown are controlled either by pneumatics or a hydraulic ram which are argued to allow for more consistent, comparable trials. They also take away the element of operator error such as device one, or the FIFA rotational traction device. This is a key advantage due to the differences in operator methods.

The vertical loads used over the test devices vary from between 11.35 kg up to 285 kg. However the most popular loads used were between 60 and 75 kg. The wide range of vertical loads makes comparison between devices difficult, however similarly loaded devices are able to be likened. The authors often don't give justification for the values of vertical load used, which may suggest that they have a poor understanding of the loading conditions that are appropriate in sport-specific movements. However, often a high load is not possible due to constraints.

A number of the devices used real shoes for use during testing. This allows for biofidelic testing to be completed, with comparisons between shoes possible. A number of them were also able to simulate forefoot impact on the surface, which is an advantage as many shoe-surface interactions in sport utilise the forefoot for traction and performance.

The table shows the wide range of bespoke mechanical devices available, with many others available. Each device has individual advantages and disadvantages, with a number of these mentioned above. When designing a mechanical device, the needs of the testing and the desired specification need to be considered. It is obvious that compromises are often made depending on the setup available or the resources available. However, each device holds its own purpose.


2.4 Surface properties

The layers of an artificial surface were described in Section 2.2.1 along with a general description of each layer. This section will go into further detail along with the physical characteristics and mechanical properties that may influence the player.

Severn (2010) came up with a list of the physical characteristics and mechanical properties of the carpet layer and the infill that influence the player characteristics (Table 2.8). By understanding these physical characteristics and mechanical properties of the component surface system material that influence the player-surface interactions, this will allow for better decisions to be made when designing a surface system, ultimately benefitting the players using the surfaces.

Table 2.8: Surface variables thought to influence behavioural properties at the shoe-surface interface (Severn, 2010).

<table>
<thead>
<tr>
<th>Surface Layer</th>
<th>Physical Characteristics</th>
<th>Mechanical Properties of Individual Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carpet</td>
<td>Pile Height</td>
<td>Compressive Behaviour</td>
</tr>
<tr>
<td></td>
<td>No. of Tufts per Unit Area</td>
<td>Surface Roughness</td>
</tr>
<tr>
<td></td>
<td>Fibre Material</td>
<td>Tensile Strength</td>
</tr>
<tr>
<td></td>
<td>Fibre Width</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fibres per tuft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tufts per sqm</td>
<td></td>
</tr>
<tr>
<td>Infill (Sand and Rubber)</td>
<td>Material</td>
<td>Compaction</td>
</tr>
<tr>
<td></td>
<td>Size</td>
<td>Compression</td>
</tr>
<tr>
<td></td>
<td>Shape</td>
<td>Shear Strength</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>Net bulk Density</td>
</tr>
</tbody>
</table>
2.4.1 Surface components

2.4.1.1 Sand

The layer of sand in 3rd generation artificial turf has the function of weighing down the turf and has been found to have a significant influence on the performance of the surface (Alcantara et al., 2009). In the samples with no sand, the values for force reduction and standard deformation parameters were outside the specifications determined by FIFA. The values found were higher than the FIFA values, so it is suggested that the composition of materials would require alternative stiffer constructions or materials to meet the FIFA requirements. The results from this study can be seen in Figure 2.7 below. For force reduction, the FIFA recommended one star pitch states between 55% and 70% and for a two star pitch, between 60% and 70%. For vertical deformation, the FIFA recommended one star pitch states between four and nine millimetres, and for a two star pitch, between four and eight mm. It is worth noting that it was not reported that a shockpad was used, which may alter the result if one were added.

![Figure 2.7: (Left) Force reduction (FR) and (Right) vertical deformation (StV) with sand and without sand. (No = without sand; Yes = with sand) as reproduced from Alcantara et al. (2009).](image)

It is possible that the studs reach the sand layer underneath the rubber crumb, either with longer studs or a high vertical force. There may not be a distinct interface between the sand and rubber crumb in the 3G artificial surfaces due to them being mixed by maintenance and use of the surface. This needs to be considered due to the properties of the two materials. In older systems the rubber and sand was more mixed with less of an effort on the two layers. Sand is less able to compress because it does not hold elastic properties but the small particles allow it to easily fit in the larger air voids amongst the rubber crumb infill.
James and McLeod (2008) investigated the effect of sand infill depth on the rotational traction. The quantity of sand was increased on the 2G surface with a 23 mm fibre length. With a volume of between 0 and 20 kg/m$^2$, the rotational traction was found to be similar at between 30 and 33 Nm. When the sand volume was increased, between 20 and 35 kg/m$^2$, there was a reduction in rotational traction from 30 to 17 Nm. This showed that less resistance to movement is generated as the depth of sand infill height increased. By increasing the depth, this reduced the amount of stud penetration into the sand due to the high density of the sand, causing the studs to become less entangled in the fibres. This allowed the studs to move freely through the sand, producing the lower values of torque. It is for these reasons, amongst others, that being able to measure the stud penetration on a mechanical test is useful to determine the point that the studs reach in the surface.

2.4.1.2 Performance infill

The layer of infill on top of the sand is typically made out of rubber, either recycled rubber (SBR), Ethylene Propylene Diene Monomer (EPDM) or Thermoplastic Elastomers (TPE). There are other materials on the market, such as acrylic coated sand (Durafill), however these are uncommon compared to rubber.

A significant role is credited to the performance of the infill at a mechanical and biomechanical level. It is related to the pitch’s response against vertical loads to impacting force reduction, vertical deformation and ball bounce, many of which relate to injuries or fatigue throughout a game (Alcantara et al., 2009). As shown in Table 2.8, there are a number of physical characteristics such as the material, size, shape and thickness which can affect the traction. There are also the mechanical properties such as the compressibility, ability to compact, shear strength and net bulk density which affect the traction developed. Severn et al., (2011) came up with a way for estimating the rubber infill density in isolation, which was referred to as the ‘net’ bulk density. This calculation found the volume of the carpet fibre (from dimensions) and the sand infill (from mass and density) and deducted this from the total volume occupied by the carpet fibre, sand infill and rubber infill as shown below.
P = m/ (V_{sys} - V_{f}) \quad \text{(Severn, 2010)}

Where: P = Net bulk density of the rubber infill layer (g/cm$^3$)

- m = Mass of the rubber infill (g)
- $V_{sys}$ = Volume of the rubber infill layer (cm$^3$)
- $V_{f}$ = Volume of the fibres within the rubber infill layer (cm$^3$)

By compressing and compacting the surface (with a roller or by foot), the rubber infill net bulk density increases due to the infill height reducing. Shear strength of the rubber infill material was also shown to be influenced by net bulk density, increasing with a higher net bulk density. By knowing the net bulk density of the rubber infill layer, this may help to predict the traction produced at the shoe-surface interface.

An equation for the air void percentage in the layers of infill was also formulated. This is calculated by knowing the volume of the solid and the volume of the infill sample. This is a useful calculation as comparisons between systems can be made as well as knowing how the air void percentage changes with rubber infill net bulk density. As expected, Severn (2010) showed the low percentage of air voids in sand, with much higher values for rubber infill. The equations for air void percentage can be seen below:

e = [(V_r - V_s)/V_r] \quad \text{(Severn, 2010)}

Where: e = Air void percentage (%)

- $V_r$ = Volume of infill sample (cm$^3$) which is the volume of the fibres within the infill layer subtracted from the volume of the rubber infill layer.
- $V_s$ = Volume of the solid (cm$^3$) which was an estimation for the volume of a solid rubber block and is calculated by dividing the mass of the rubber infill layer by the particle density of rubber.

Severn (2010) investigated the increase in rubber infill net bulk density and the effect it had on both rotational and translational traction. When using the FIFA rotational traction device, no effect was seen in the peak rotational traction with an increase in rubber infill net bulk density on the four carpets tested. When testing with test device two (a bespoke piece of equipment developed by adidas), a small increase in the rotational traction was measured with an increase in the initial rubber infill net bulk density prior to loading of the test apparatus.
Translational traction was tested using a second bespoke test device. When four different carpets were tested with an increasing initial rubber infill net bulk density, an increase in translational traction was seen (Figure 2.8). It is discussed that this is due to the compaction of the infill causing a higher resistance when the studs are ploughing through the infill.

![Figure 2.8: The effect of initial rubber infill bulk density on the peak coefficient of translational traction measured for four carpets at a vertical load of 44.3 kg using test device two (Severn, 2010).](image)

Villwock et al., (2009b) investigated the effect of various infill, fibre structure and shoe designs on generating rotational traction on an artificial surface using a portable testing apparatus (Table 2.7, number three). Three different infill materials were tested and peak torque was found to be significantly affected by the different types. This was found to possibly be due to the fineness of the infill. For example, a finer infill (Infill A) may cause a higher compacted structure of infill which consequently creates a higher resistance against the studs and therefore, a greater rotational traction.

The results for the three infills and their peak torques can be seen below, with infill A having the highest peak torque, as described above.
Figure 2.9: Median peak torque with upper and lower quartiles for three types of infill, with infill information in figure 2.10 (Villwock et al., 2009b).

The infill sizes of the three types of infill types can be seen in the figure below:

<table>
<thead>
<tr>
<th>Infill</th>
<th>Mean Diameter (mm)</th>
<th>Number of Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.73</td>
<td>114</td>
</tr>
<tr>
<td>B</td>
<td>2.39</td>
<td>73</td>
</tr>
<tr>
<td>C</td>
<td>2.40</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 2.10: Infill sizes and number of particles for the three samples tested in figure 2.9 (Villwock et al., 2009b).

This section has shown that the properties of the performance infill have an effect on the traction that is mobilised. This includes the size and shape of the infill and how this can change the mechanism of traction by affecting how much stud penetration or compaction of the infill occurs. The net bulk density is an appropriate measurement for estimating the rubber infill density (and sand if necessary). The following section highlights the mechanical properties of the performance infill.
2.4.1.3 Mechanical properties

The rubber infill has changeable mechanical properties which need to be understood to determine the mechanisms of traction and to understand the behaviour at the shoe-surface interface.

2.4.1.3.1 Compaction

The compaction of the infill is defined as the permanent change in the net bulk density. It has been previously reported in literature that the rubber infill material compacts with repeated loading (Severn, 2010; Anderson, 2007). Compaction of the infill can lead to a change in the performance characteristics of the surface, such as the resilience (the ability of a material to absorb energy when it is deformed elastically, and release that energy when unloaded). It may also affect the stiffness of the surface, the frictional properties of the infill and the stud penetration into the infill (Severn, 2010). Tipp and Watson (1982) and Kieft (2009) suggested that the surface will become harder over time with repetitive mechanical loading from the players as well as from maintenance equipment as the infill material compacts. Fleming et al., (2014) stated that a harder surface will produce a decrease in the resilience as more energy is dissipated.

Severn (2010) investigated the rubber infill bulk density of two test methods under compaction (the Proctor test and vibrating compactor) using SBR 0.5 – 1.5 mm infill, to determine the repeatability of the methods. The two test methods produced similar bulk densities of between 0.60 g/cm³ and 0.61 g/cm³.

Figure 2.11 shows the results using the vibrating compactor (a vibrating hammer). There was an initial strain of 0.2 as the rubber infill compressed with the introduction of weight. This was before any compaction took place. Subsequently, there was a further small increase in strain after compaction took place between 0.23 and 0.25, increasing as the compactive effort increased. Once the weight of the hammer was removed, the rubber particles recovered and the recoverable strain was approximately 0.12. For the next 30 minutes, there was a further recovery of the rubber infill material, although very small, with the final non-recoverable strain for all four tests being very similar at 0.1.
Figure 2.1: The strain measured before and during compaction and during recovery of SBR rubber infill material over four timescales using the vibrating compactor (Severn, 2010).

The non-recoverable strain of 0.1 represents the compaction that has taken place through permanent change in particle packing and is described in terms of air void percentage. Before testing took place, the percentage of air voids in the sample equalled 60%. This subsequently reduced to 56% after compaction. A maximum level of compaction was achieved after just 0.5 minutes with between 0.60 g/cm$^3$ and 0.61 g/cm$^3$.

The second method was the Proctor test method (a mechanical hammer) with results illustrated in Figure 2.12.

Figure 2.12: The strain measured during compaction and recovery of SBR rubber infill material at three compactive efforts using the Proctor test (Severn, 2010).
After completing the compaction, before recovery took place, there was a strain of 0.2 for 27 blows increasing to 0.24 with 81 blows. After 0.5 minutes of recovery, each of the three compactive efforts recovered by 0.2 resulting in a strain of 0.18 for 27 blows and 0.22 with 81 blows. Over the next 30 minutes, there was a small recovery of the rubber infill material (similar to the vibrating compactor method). The final non-recoverable strains for the three compactive efforts were similar, at 0.18. There was an 11% reduction in terms of air voids from an initial percentage of 58% decreasing to 47% after compaction. In terms of bulk density, all three tests measured a bulk density of 0.59 g/cm³ after 30 minutes of recovery. The proctor test achieved a greater level of compaction compared to the vibrating compactor with a denser rubber infill of 0.59 g/cm³ achieved compared to 0.51 g/cm³.

2.4.1.3.2 Compression
The compression of the infill is defined as how recoverable the infill is under loading. Anderson (2007) tested the compressibility of the infill using a vertical compression test. The results showed that under an applied load, the rubber particles displaced up to 55 mm for one cycle. As the number of cycles increased, the maximum displacement reduced to 20 mm. This showed that the initial cycle displaced the majority of the rubber particles into the available air voids causing compaction of the sample. The subsequent cycles measured the compressional behaviour of the rubber infill particles with only a small influence from the air voids.

Severn (2010) also investigated the compressive behaviour of the rubber infill material, using a vertical static loading test. Two initial conditions of SBR 0.5 – 1.5 mm infill material were created in a compression mould to simulate a ‘loose’ and ‘dense’ condition. 0.47 g/cm³ was chosen for the ‘loose’ condition and 0.61 g/cm³ for the ‘dense’ condition. The force against displacement behaviour was measured to four maximum forces; 0.65 kN, 0.85 kN, 1.45 kN and 2.0 kN for each initial condition.

The same patterns of loading were followed, with similar levels of stiffness as the displacement increased with an increase in the normal stress applied. The rubber infill material began to recover as the material was unloaded. The rubber infill samples did not follow the same path upon unloading as when the sample was loaded, a hysteresis effect occurred due to the energy lost in the system by work done and heat, for all conditions.
The ‘dense’ condition compacted to 0.61 g/cm$^3$ before compression took place, was much stiffer initially, as the volume of air voids reduced. The dense condition compressed less than the loose condition which had a higher air void content of 58% compared to 47% for the dense condition. It was also reported that the loose condition produced permanent deformation from compaction of the rubber infill.

Figure 2.13 illustrates the non-recoverable displacements between 7.57 and 9.51 mm for the initial loose condition, which increases with normal stress. The initial dense condition (0.61 g/cm$^3$) is seen to completely recover.

Additionally, a selection of four different particle size and material types were tested. Similar to the testing above, a loose and dense condition was created prior to loading. When the size of the SBR infill particles were increased, the displacement decreased. This indicated that by increasing the particle size of the same infill material, this produced a stiffer sample.

2.4.1.3.3 Shear strength

The shearing force is defined as the force between two parallel planes that occurs when one plane slides over the other. The shear strength is the maximum shear load the infill can withstand before failure occurs. The greater the shear strength, the larger the traction force produced (Severn, 2010). The shear stress was tested with an increase in the normal stress.
over two conditions, loose and dense. Results illustrate that when increasing the normal stress, the shear stress increased (Figure 2.14).

It is worth noting that the maximum normal stress applied caused compression of the rubber infill material prior to shearing. The vertical displacement was measured and found that the initial ‘loose’ condition compressed a higher amount compared to the initial ‘dense’ condition. These are shown in Table 2.9.

Table 2.9: Bulk densities derived from the shear box testing after loading from two initial conditions (Severn, 2010).

<table>
<thead>
<tr>
<th>Maximum Normal Stress Applied (kPa)</th>
<th>Initial Loose Condition (0.47 g/cm³)</th>
<th>Initial Dense Condition (0.55 g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>111.4</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>176.8</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>242.2</td>
<td>0.89</td>
<td>0.87</td>
</tr>
</tbody>
</table>

The angles of friction (angle measured between the normal force and resultant force, determined when failure occurs in response to a shearing stress) were calculated from the
results produced. The dense condition produced a lower angle of friction of 11.58° compared to 14.22° for the loose condition. These are considered to be low compared to the majority of soils and sands which are normally larger than 25°. It is hypothesised that this is due to the elastic nature of the rubber infill material as the rubber compresses under load. There was no peak observed in the shear stress which suggested that the distance of travel using the shear tester (at 19 mm) was not great enough to identify a peak shear resistance.

2.4.1.4 Fibres
In third generation turf, the polymers fibres are often made of either polyethylene or polypropylene compared to earlier generations which were generally made of nylon. These earlier generation fibres tended to have a high level of abrasion, causing burns to players. However, the later materials provide better abrasion resistance, reducing the risk of burns (Severn, 2010). There are no standard specifications in terms of the fibre length, width, thickness or composition. However, SAPCA (2009) give the general guidelines that the pile height can be up to 65 mm for 3G surfaces.

The synthetic turf surface will degrade over time and with increased use when exposed to environmental influences and user traffic which may influence the mechanical properties of the surface (Severn et al., 2007). It has been suggested in previous literature that with increased wear of the surface, the fibres begin to split and lay flat to the carpet. This may cause entanglement of the studs with the fibres, increasing the traction. Severn (2010) found this with the older surfaces tested and highlighted the importance of maintaining a surface.

Villwock et al. (2009b) tested three different fibre structures and the rotational traction produced. They were monofilament polyethylene fibres, one parallel slit polyethylene fibres and the other monofilament polyethylene fibres in conjunction with a nylon root zone (Figure 2.15) with the results for peak torque for the three fibre types in Figure 2.16.
Figure 2.1: (From left to right) Monofilament polyethylene fibres (I), parallel slit polyethylene fibres (II), monofilament polyethylene fibres with a nylon root zone (III) (Villwock et al., 2009b).

Figure 2.16: Median peak torque with upper and lower quartiles for three different types of fibre, illustrated in figure 2.15 (Villwock et al., 2009b).

There was found to be no statistical differences in peak torque between the first two fibres. The presence or absence of the nylon root zone was found to possibly be the variable which affects the generation of torque the most. A lower peak torque was found with a nylon root zone which may be due to the system needing less infill, which would affect the initial bulk density of the infill and how compact the infill was.

Severn (2010) investigated four different carpet types, which were a range of heights and densities. The volume of carpet fibres were found to have had a minimal influence on the thickness, bulk density or air void percentage of the rubber infill material measured when deducted from the total volume occupied to isolate the rubber infill layer. Conversely to Villwock et al. (2009b), the effect of the carpet fibres were found to be minimal throughout the project. The only variables found to have an influence were the length of the carpet fibres and to a small extent, the volume of fibres per unit area. This is due to them having an influence on the quantity of infill that could be used and the initial net bulk density of the rubber infill layer. This was only apparent with the carpet fibre with the highest volume.
2.4.1.5 Shockpad

The purpose of the shockpad is to provide cushioning and reduce the impact forces on the players through its shock absorbency. The thickness of the shockpads can vary with thicker specifications being used in more recent 3G surfaces. Young (2005) investigated the Force reduction of shockpads and found that it increased by 20% when increasing the thickness between 6 and 20 mm. A reduction in peak deceleration was also found when increasing the thickness. Therefore, having a thicker shockpad reduces the impact force. When tested with a ‘new’ synthetic turf on the shockpad, Anderson (2007) found an increase of 10% in force reduction and a reduction of 45g when using a Clegg Hammer when the depth was increased from 8 to 20 mm.

In field testing carried out by Severn (2010), it was found that the inclusion and/or thickness of the shockpad layer had a greater influence on the hardness measured compared to the thickness of the infill material alone. Severn (2010) found that as the rubber infill layer became thicker, the effect of the shockpad layer was reduced. The peak rotational traction was measured against rubber infill thickness with no significant differences found between the shockpad thicknesses (15 and 30 mm). This suggests that the rotational traction behaviour is determined by the synthetic turf carpet and infill layers, particularly with the low level vertical loading of the FIFA rotational traction device. Compression of the shockpad may happen at higher loads but this is something that needs to be investigated further. Low infill heights would cause penetration into the shockpad and affect the traction.

Other factors that affect shockpads include resiliency and its ability to retain its properties over a period of time and climatic conditions (Tipp and Watson, 1982).

2.5 Shoe properties

It is the aim of shoe manufacturers to find a balance between an outsole that improves performance but also minimises the risk of injury (Driscoll et al., 2012). Footwear is considered a potential risk factor for ACL injuries, since it controls foot fixation during the game. The number of studs, length and placement of the studs/cleats have been found to be associated with the chance of ACL injuries (Alentorn-Geli et al., 2009). There is often a lack of education by players on their choice of the appropriate footwear which has a
significant influence on their performance, comfort and chances of sustaining an injury (Kirk, 2008). This section looks at the different types of boot, the effect of altering the studs and stud type and the mechanisms involved.

2.5.1 Boot types in football

There are a number of different boot types and styles which can be classified into different categories depending on their use and surface. These are listed below.

Hard ground: These boots can be used on artificial surface and have a high number of small moulded studs to distribute the pressure over a higher area. This means the studs do not penetrate the surface as much.

Soft ground: These are used on natural pitches and contain long changeable screw-in studs or blades. They are good for muddy conditions due to the studs designed for higher penetration.

Firm ground: There generally have rubber mould studs or blades and are shorter than soft ground cleats. They can be used on artificial surfaces as well as hard grass.

Artificial ground (often on Astroturf): These have shorter, sharper studs. The studs often differ in size and shape to offer the highest possible traction.

Figure 2.17: From top left clockwise – Soft ground, firm ground, hard ground and Astroturf football boots.
2.5.2 Altering the studs

It has been widely investigated and hypothesised from the early first generation surfaces in the 1970s that an increase in the length of studs increased the traction produced (Orchard, 2002). Lambson et al., (1996) investigated the relationship between ACL injuries and length of cleats and found that wearing shoes with longer and more peripheral cleats caused an increase in shoe-surface traction and ACL injuries.

Villwock et al. (2009b) investigated the role of infill material and fibre structure on the rotational traction associated with American football shoes on infill-based artificial surfaces. 10 different shoes were used with a range of stud patterns including 12 studded moulded cleats, moulded blades, moulded cleats and replaceable cleats. A difference in peak torque was found between shoe designs which highlights the impact the shoe design has on rotational traction. The shoes with a higher number of studs and/or large cleats around the edge of the sole produced a higher peak torque than shoes with fewer or smaller cleats. The turf shoe (88 short moulded nubs) produced significantly lower torques compared to all other designs, hypothesised to be due to the cleats not penetrating the infill layer as much as longer studs (Villwock et al., 2009a).

Stiles et al. (2009), stated that a definitive conclusion on stud length and configuration to minimise injury had not been reached because of the ethical considerations that have to be taken as it is not possible to give a player a high traction boot and test their response as it is considered reckless. Severn (2010) found that stud configuration did have an influence on rotational traction when performing mechanical testing. The spacing of the studs from the central pivot point required for rotational movement was found to significantly influence the rotational traction measured, increasing as the stud spacing increased. There was also a slight increase in rotational traction as the number of studs increased. Figure 2.18 shows the different stud configurations used in the study and the increase in the number of studs.
Figure 2.18: Four different stud configurations used in study by Severn (2010b) with increasing number of studs.

Figure 2.19 shows the peak rotational traction measurements of three surface systems using four types of stud configurations (as above in Figure 2.18) at a conditioned state of 50 rolls. It shows the increase in rotational traction with an increase in the number of studs. The configuration with two studs gave a peak rotational traction of approximately 26 Nm, then an increase of 15% to the stud configurations with three and four studs to approximately 30 Nm, then another increase of 10% to 33 Nm for the stud configuration with six studs.

Figure 2.19: The peak rotational traction measurements of three surface systems using the four stud configurations in Figure 2.18 (Severn, 2010b).
Clarke (2011) looked at the effect of changing stud length on traction, and the vertical displacement of the outsole plate into the surface. It was found that as stud length increased, the penetration of the outsole plate decreased. No correlation was found with traction force, however a significant relationship between traction and stud length for one surface with a higher pile length and higher density of rubber crumb was found. It is suggested that because of the higher density of rubber crumb, the ploughing traction (where the studs clear a path through the surface) is far greater. As the length of the stud increases, the ploughing traction will become a more dominant contributor to the overall traction (Clarke, 2011).

Clarke (2011) looked at the effect of stud width on traction force and vertical displacement of the outsole plate into the surface. It was found that as the stud width increased, the amount of stud penetration decreased. No significant relationship was found between stud width and traction. The surface with a low density of rubber crumb allowed for a greater penetration of the thin stud, which causes the outsole plate to move vertically, compressing the fibres and infill around the studs. The ploughing traction caused by the studs, and the friction between the outsole plate and the surface results in a high overall traction force (Clarke, 2011). The results for this surface can be seen in Figure 2.20 below.

![Figure 2.20: Mean vertical displacement for studs and outsole plate, and mean horizontal traction force for surface using different stud widths (Clarke, 2011).](image-url)
As the stud width increases, it was found that the resistance to penetration increases and the more the surface is compressed rather than penetrated. When the studs compress the infill and fibres, it causes a high density of infill underneath the stud, but a low density of infill resisting horizontal movement which causes a relatively constant overall traction (Clarke, 2011). A larger stud diameter reduces the penetrability into the surface shown in Figure 2.21 and the outsole starts to lose contact with the surface which reduces the friction (Clarke, 2011).

![Figure 2.21: Mean vertical displacement (± 1 standard error) of studs and stud plate at time of initial movement on 3rd generation artificial surface (Clarke, 2011). Shaded in area shows stud plate penetration.](image)

### 2.5.3 Stud plate

It is hypothesised that the stud plate plays a large part in the traction produced, alongside the studs (Clarke, 2011). Clarke and Carre (2010) used a mechanical device with a custom-build stud plate with interchangeable studs to measure the translational traction. Results showed that longer studs that did not fully penetrate the surface produced a lower traction, possibly due to the stud plate not contacting the surface. This reduced the friction force between the stud plate and the surface and did not cause compaction and compression of the infill. Severn et al., (2010b) also identified that while testing with the FIFA rotational
traction device, the surface of the stud plate causes friction with the fibres and infill along with compression occurring underneath the plate, affecting the zone of infill. Driscoll (2012) highlighted the advantage of repeatable results using a studded plate; however it may be an issue due to the other contributing factors between the plate and the surface. If these contributing factors are taken into account, they can be added to the overall traction force produced.

2.6 Analysis of traction

When measuring both rotational and translational traction, the collection of data, its analysis and how it is interpreted is a topic of interest in recent studies depending on how the author interprets the data. As previously discussed, a majority of the test devices record a value for peak torque. As with many other authors, the suitability of using peak force or a point at a later displacement/angle has been questioned due to comparisons with a sport-specific movement. Zanetti et al., (2012) found an initial steep increase in force, followed by a smoother increase of force with additional displacement (Figure 2.22). A peak force was then reached, before relative slippage between the plate and the surface.

![Figure 2.22: Force against displacement for a friction test (Zanetti et al., 2012)](image)

Zanetti et al., (2012) suggests that depending on the wanted outcome of the study, either the peak force or the earlier slope of force/displacement should be taken. If injury is the main factor, the peak force may be adequate as it measures the maximum force which can
be produced by the surface. However, if wear or fatigue is being investigated, the most recurring activities should be taken into account, therefore the slope may be more relevant. Williams et al. (2011) defined rotational stiffness as the rate at which torque increases with applied rotation at the shoe-surface interface. A number of authors have suggested that this is a more sensitive measure of the mechanical interaction between shoe and surface. A lower rotational stiffness indicates a lower rate of loading on a joint and may allow more time for a protective form of neuromuscular control to stabilise the ankle and knee joints during certain manoeuvres, potentially reducing the injury (Williams et al., 2011).

It has also been found that ACL injuries occur very soon after the foot strikes the surface, in the range of 50 – 250 milliseconds after ground contact (Grund et al., 2010). This adds to the argument for measuring initial rotational stiffness.

When observing the push-off manoeuvre for a football player, it was found that the shoe only moved approximately 10 mm in the horizontal direction until the shoe lifts off the surface. Similarly, as discussed in Section 2.3.4.4, the rotation of the foot during stop and turn or cutting movements was often found to be in the region of 10-15°, which shows that the initial movements may be a more appropriate measure for mechanical tests, rather than the higher angles reached at peak torque.

Livesay et al. (2006) investigated the peak torque and rotational stiffness when testing a number of surfaces and shoe types, using a rotational mechanical test device which included a biaxial load cell and goniometer to measure the torque and rotation angle during the measurements. A typical graph of two different scenarios is shown in Figure 2.23.

![Figure 2.23: Representative torque against rotational for a turf shoe - 1st generation artificial surface and the grass shoe - grass surface combination (Livesay et al., 2006).]
Two stiffness regions were found, the first region was characterised by an initial steep increase in torque with applied rotation of the shoe (between 0 and 2°), with the second region being where there was a linear increase in torque with additional rotation (between 2 and 10°) before peak torque was reached. Livesay et al., (2006) also found in their testing that peak torque and rotational stiffness scaled linearly with compressive load by performing five trials at five different compressive loads, up to 511 N.

Figure 2.24: (Top) Mean peak torque versus compressive load for a grass shoe and turf shoe on the outdoor Astroplay surface (just rubber infill). A linear relationship observed between the peak torque and amount of compressive load for both shoes ($r^2 > .99$). (Bottom) Mean rotational stiffness (initial region, 0°-2°; linear region, 2°-10°) versus compressive load for both shoe types on same surface. Linear relationships were observed between rotational stiffness and compressive load for both stiffness regions for both shoe types (Livesay et al., 2006).
It was found that the rotational stiffness produced on artificial turf did not vary significantly from that found on grass, and both turf shoes and grass shoes produced a similar initial rotational stiffness on third generation artificial turf and natural turf. However, it is worth noting that these compressive loads are fairly low compared to the body weight of a human.

2.7 Mechanisms

It has been reported by Fleming et al. (2011), Severn et al. (2010) and Clarke et al. (2012) that there is a need for improved scientific understanding of the mechanism of interaction between the shoe and the surface and the high number of variables involved. Many studies have omitted details on the surface properties, mostly investigating the traction properties of sports footwear. They often conclude that the traction generated at the shoe-surface interface is generally individual for each shoe-surface combination.

This lack of a traction model/understanding of the mechanisms is a gap in the knowledge which needs further investigation. Understanding how traction is developed with aid the improvement of surfaces and footwear construction (Severn et al., 2010). These can then be effectively changed to maximise performance and minimise injury risk (Clarke et al., 2012).

2.7.1 3G artificial surface mechanisms

Figure 2.25 shows an illustration, according to Severn (2010) of the forces involved at the shoe-surface interface in the production of traction. However, this is a very simplistic diagram, missing some important components, such as the forces that make up rotational and translational traction.
Severn (2010) suggested that there are many traction mechanisms at work while an athlete carries out a sports specific movement such as a side step or turning movement. Ground reaction forces are produced in three directions as the foot is planted into the surface. These forces are dependent on the mass of the athlete, the running speed, loading rate, direction of movement, the surface, contact time and the contact area of the foot with the surface (Severn, 2010). The studs create several small areas of high stress due to the small surface area of a stud (Severn, 2010).

Severn (2010) stated that the ability of the studded footwear to penetrate the surface system and move through the surface is dependent on the specific playing surface and the player’s boot. It was suggested that under an applied normal stress, frictional resistance will occur between individual surface components such as two rubber infill particles or between the stud and the rubber infill material and between the fibres. The resistance of the surface
system to shear horizontally as the studs move through the surface system will generate a traction force (Severn, 2010).

Figure 2.26 shows the component forces at the stud-surface interface according to Kirk, (2008). This diagram would apply to both natural and artificial surfaces and is dependent on the characteristics of the footwear and the surface conditions. Kirk (2008) highlights that the horizontal traction developed from stud-surface contact, termed ‘traction mechanism’ is dependent on the three basic force components shown in Figure 2.26. The friction force ($\mu_p$) due to the interaction between the outsole plate and the surface, the ploughing traction force ($F_p$) due to the stud and plate clearing a path through the surface and the skin friction force ($\mu_s$) due to the interaction of the stud material and the surface. These are all definitions described by Kirk (2008) and begin to understand the forces developed during a movement.

![Diagram showing component forces at the stud-surface interface](image)

**Figure 2.26:** The component forces at the stud-surface interface with a single stud once penetrated the surface, as reproduced from Kirk, 2008.

Driscoll (2012) investigated the patterns of stress during a running movement using photoelastic images, shown in Figure 2.27. There were limitations involved in the study including the players being unable to perform realistic movements and the fact it was performed on photoelastic material which is likely to give different shear patterns around the studs to artificial surfaces. However Figure 2.27 begins to acknowledge the patterns of stress during a running movement. It also shows how with studs adjacent to each other, the areas of disturbed infill around the studs begin to overlap with each other.
Figure 2.27 - Time series of stress patterns. Heel-strike and forefoot push-off photo elastic images during running in studded outsoles (t = 0.04 s). (Driscoll, 2012).

Stud penetration

Kirk et al. (2007) looked at measuring stud penetration using a drop hammer. An illustrated photo of the drop hammer is shown in figure 2.28.

Figure 2.28: SERG (Sports Engineering Research Group) drop hammer with attached stud and accelerometer (Kirk et al., 2007).

This drop hammer incorporates an accelerometer encased in a hammer, which is dropped normally onto the surface. The device allows for changes in studs which is useful for a variety of results. No data of the amount of penetration is presented in the study but it was suggested that a more appropriate test could be one that impacts the surface at an oblique
angle, as may be the scenario when someone is coming in from an angle to contact the surface. It is stated that studs with low cross-sectional areas have better penetration properties at orientations other than perpendicular to the shoe sole.

2.8 Discussion

This chapter has presented an overview of the previous literature related to traction on artificial surfaces. The following section gives an outline of the current knowledge and discusses any gaps in knowledge of the research.

The construction of third generation artificial turf was described with the purpose of each layer identified. The variety of materials and quantities for a range of specifications were highlighted. However, the described governing body standards require all manufacturers to provide similar surfaces which output properties within a range. The literature shows the advantages and disadvantages of artificial surfaces when compared to natural turf, as well as the advantages compared to earlier generations of artificial surfaces. The advantages of 3G surfaces are obvious when looking at the availability of use, being less dependent on weather and being less susceptible to wear.

Traction was identified as one of the key factors that has a major effect on athlete performance and being able to generate the ‘correct’ amount of traction without sustaining injury is vital. Both the translational and rotational components were identified as equally significant when performing movements. It was often found that rotational traction is the focus of the majority of studies; however it is important to take into account both forms of traction to fully understand the mechanism. The number of definitions used to describe traction were identified, which may not necessarily be clear when reading through the literature; this highlights the need for a clear and set definition for traction (amongst other words).

The difference between friction and traction was recognised, however the principle of friction was described as fairly simplistic and does not necessarily describe the complex interactions between compliant, non-uniform surfaces found in 3G surface and shoe interface problems, therefore traction is a better description when the classic laws of friction do not apply.
The importance of testing, both mechanically and when using subjects has been highlighted along with the advantages and disadvantages of each method. It was concluded that when designing a mechanical test, it needs to be as biofidelic as possible, otherwise there is a risk of the results being interpreted incorrectly.

The standard for measuring rotational resistance for both football and rugby involves a mechanical device which measures the peak torque. There are a number of limitations with this device which include the recommended speed for the rotation of the torque wrench. There has been a low level of reliability found when testing a number of operators due to the lack of control, quantification of the speed and the subjective manner of the device. Another limitation of the device is how it only gives an output of the peak torque which may not necessarily represent the torque that a player reaches.

Alongside the governing body standards used for traction, the bespoke mechanical test devices developed and implemented by a number of studies were identified. These devices show the wide range available; however a disadvantage of this can be the number of inputs and outputs. As mentioned above, the ideal situation is having a mechanical test as biofidelic as possible which many of these bespoke tests do not achieve. One of the limitations of these studies includes the omission of information of how the surface was prepared or the exact specification of the surface. This makes comparison of data between studies difficult.

Proceeding the mechanical testing, the studies involving player testing were discussed. It is not possible to capture an injury in a laboratory environment due to ethical reasons; however specific movements can be performed to collect and analyse data and speculation on the causes of injury can be made. It is known that first and second generation surfaces are associated with higher injury rates which is often why players are dubious about playing on third generation. However, they are much safer than the previous generations due to reductions in abrasions and lower translational traction. The literature generally states that there does not appear to be a significant difference between the overall injury rates when comparing to natural surfaces. It has been found that the injury patterns may differ, but it is worth noting that a number of factors may contribute to injury rates such as the environmental conditions.

The vertical loads found during player testing should guide the vertical loads used in mechanical testing. They were often found to be between two and three times BW.
depending on the movement. Mechanical tests often only use a maximum of one times the body weight, with many using less. However, one study investigated a range of vertical loads and found that the traction coefficient only increased slightly at increased loads of 888 N (about 90 kg). This could be seen as justification for using a vertical load of one body weight when developing mechanical tests. It is also worth noting that an advantage of the mechanical tests is remaining portable which may not be possible when using over one body weight.

The amount of rotation of the foot or translation on impact of the surface is also an important link between player testing and mechanical testing. As discussed in Section 2.3.4.4, a number of studies found that on average the foot only rotated between 10 and 20°. This suggests it may be more appropriate for mechanical tests to measure the traction in the initial movements, rather than the higher angles reached at peak torque (such as the FIFA standard for rotational resistance). Another important factor to consider when developing a mechanical test is the velocity of the foot on impact. Although the velocity of the body and foot may be high when coming into contact with the surface, the speed once the foot hits the surface reduces. This may be a reason for considering lower velocities when using a mechanical test. Many tests use lower velocities due to limitations of the equipment.

The physical and mechanical surface properties that influence the mechanical behaviour of the surface were identified. The physical characteristics included the carpet pile height, the number of tufts per unit area, the fibre material, fibre width, fibres per sqm, infill material, infill size, infill shape and the shockpad thickness and material. The mechanical properties include the compressive behaviour, surface roughness and tensile strength of the fibres and the compaction, compress, shear strength and net bulk density of the infill. The literature has identified how the rubber infill has changeable mechanical properties which need to be understood to determine the mechanisms of traction. The compaction, compression and shear strength have been detailed which will aid in the interpretation of results. By understanding the influence these properties have, well informed decisions can be made when selecting specific surface specifications for the desired sport/use. The large number of components involved in a 3G surface results in a complicated composite system.

The shoe used by a player obviously plays a large part in the outcome of a movement and contributes to the performance and any potential for an injury. The shoe needs to find a
balance between improving performance and minimising the risk of injury; however it is often the aesthetics that manufacturers focus on due to commercial pressures. The research is frequently unable to state exactly how changing shoe properties affects the traction, with most making generalisations without further detail. The large number of shoe types and stud and cleat shapes makes comparisons between studies more difficult. However, this should not stop fundamental understanding of the traction produced when altering stud length or type.

When measuring both rotational and translational traction, the analysis of data changes between authors with various justifications provided. A majority of the test devices record a value for peak torque. As with many other authors, the suitability of using peak force or a point at a later displacement/angle has been questioned due to comparisons with a sport-specific movement. As mentioned above, rotation of the foot may only occur between 10-15° or 10 mm in the horizontal direction which may justify using the initial movements for mechanical tests, rather than the higher angles reached at peak torque.

The analysis of traction links into the mechanisms of traction and how the surface is behaving at the various stages of a movement, whether in the initial movements or at higher displacements and angles. There is a key gap in knowledge and a need to further the understanding of the mechanisms of interactions between the shoe and the surface and the high number of variables involved. An attempt has been made in the literature to introduce the mechanisms involved in stud penetration and movement of the studs through the surface; however it has often been simplistic or measured inconsistently. There is a need for a traction model to fill this gap in knowledge and help to further understand traction to aid with the improvement of surfaces and footwear. This could then help to minimise the injury risk and maximise performance.
CHAPTER THREE – RESEARCH PHILOSOPHY

3.1 Introduction

The literature review completed in Chapter two highlighted the gaps in knowledge related to traction in shoe-surface interactions. A key area where improvement is required is knowledge of the mechanisms of traction. As mentioned in Section 2.7, this details what is occurring between the shoe and the surface, and the processes involved. Another area where improvement is required is the communication of the surface system by authors. It is clear from literature that the specification of the surface influences how the surface reacts, however if this is often not communicated during studies it makes the comparison of results difficult.

The aim of this thesis is to make a contribution to knowledge regarding the mobilisation of traction and apply this to the understanding of shoe-surface interactions. This will be achieved by successfully reaching the objectives set out in Chapter one. This includes designing and conducting tests to provide data that can improve understanding of the interaction between the studs and the surface and subsequently help to identify the mechanisms involved in traction.

Rotational traction has been the main focus of many previous studies, as outlined in Chapter two. Translational traction is often under investigated, however, as established in the literature review (Section 2.3) it is worth acknowledging as it may also result in injury and both rotational and translational traction studies can help to inform each other.

This chapter documents the overall plan of the thesis and how the specific objectives will be achieved. It details the hypothesised mechanisms involved in translational and rotational traction. It highlights the development of mechanical tests and the variables tested, along with how the tests were setup. This chapter introduces the main content of the thesis and aims to provide evidence supporting the planning of the tests performed.
3.2 Achieving the objectives

The following objectives were previously defined in Chapter one, to support addressing the aim of this project.

1. Review current knowledge in player-surface interaction behaviour in relation to traction.

Objective one was achieved by conducting a review of the current literature (Chapter two). This included identifying the key gaps in knowledge related to traction.

2. Obtain relevant human boundary conditions for biofidelic mechanical test development.

This involves reviewing previous player testing data to gather appropriate information about human player movements to inform the development of biofidelic mechanical tests (Chapter four). It was not in the scope of this project to complete a study involving human participants but it is sufficient for this study to use data collected in previous studies at Loughborough University. This also involves player testing data acquired from the literature.

3. Investigate and identify the mechanisms and variables involved in the mobilisation of traction.

The mechanisms of rotational and translational traction have been hypothesised and the variables involved have been identified based on the literature review. The effect of the variables on the traction mobilised has also been hypothesised (Chapter three). The mechanisms are a main theme of this project and will be referenced throughout the thesis.

4. Develop appropriate measurement systems to quantify the traction forces.

A discussion of how traction can potentially be measured is presented based on the literature review (Chapter three). The final methods used to measure rotational and translational traction with the mechanical devices have also been detailed (Chapter five).
5. Develop mechanical test equipment and protocols to replicate key translational and rotational lower limb behaviour during sport specific behaviour.

Rotational and translational mechanical test devices have been developed which attempt to emulate sport specific movements (Chapters four and five).

6. Investigate the effects of changes in surface system design and shoe properties on the measurement of traction.

Using the equipment developed in Objective five, studies have been conducted to investigate changing variables, such as change in stud configuration and change in infill density, and their effect on traction performance analysed (Chapter six).

7. Refine the mechanisms based on the experimental design.

Based on the variables investigated in Objective six using the mechanical test devices, the mechanisms set out in objective three to understand the mobilisation of traction have been refined.

3.3 Mechanisms of rotational and translational traction

The mechanism of traction is the process involved in the shoe-surface interaction and the forces that make up the overall movement. Traction is important in sport-specific movements to allow the movement to be successfully completed and to prevent injury. Too little resistive force can result in slipping, with too much causing the shoe to stick. Hence why it is important to understand the mechanisms while traction is being mobilised. The mechanism is often ignored with the overall movement being the primary focus.

The following section involves a commentary of the mechanisms during a movement involving both rotational and translational components. A general non-specific movement is being used to describe the mechanisms and simplify the processes, especially as both translational and rotational traction are involved in the majority of sport specific movements (Wannop et al., 2015). The purpose of the mechanisms commentary is to break down the movement involved in the interaction between the shoe/plate and the surface.
when using a mechanical test. The movement is split into a number of sections, including the state of the surface and the shoe properties with added illustrations to aid understanding.

### 3.3.1 Initial state of the surface

The literature review highlighted key findings related to the surface components and properties. This section focuses on the state of the surface initially, defined in this thesis as how the surface has been conditioned before a test is performed e.g. the number of rolls the surface has had or the height of the infill.

There are a number of measurements and observations that can be taken from the surface which will all have an effect on traction. These are listed below with reference to the appropriate section in the literature review.

- The height of the sand/rubber infill, measured using an infill depth gauge (Section 2.4.1.1).
- The size, shape and material of the rubber infill (Section 2.4.1.2).
- The total height of the carpet fibres, as well as the free pile height, which affects the distance of ball roll (Section 2.4.1.4).
- The number of fibres per tuft/number of tufts per sqm/number of fibres per sqm and the fibre thickness (Section 2.4.1.4).
- The material of the fibres (polyethylene/polypropylene) and the type (monofilament – single strand fibres; or fibrillated – manufactured from thin sheets of plastic that are slit and twisted to form thicker filaments that form the pile) (Section 2.4.1.4).
- The density of the rubber infill measured from the volume of rubber infill, the volume of fibres and the mass of the rubber infill (Section 2.4.1.2).
- The air void percentage measured from the volume of fibres, the volume of infill, mass of infill and particle density (Section 2.4.1.2).
- Any contaminants which have been added to the surface or whether water has infiltrated the infill.
- The height and material of the shockpad (Section 2.4.1.4).
A number of these properties have been investigated in previous studies but are often not looked at collectively to form a picture of the overall mechanisms, which the following section aims to do. How the surface is initially set up is imperative to how it works. The initial state is often not characterised in previously conducted research studies. By knowing the initial state, this can help to understand how the surface changes before and after testing. It would also allow for comparison between research studies. Consistency is important to ensure the surface responds and performs the same for every impact and avoids causing an injury. The variables in the above list are quantified either in the surface specification or are stated in the methods and testing sections.

3.3.1.1 Shoe/Stud plate used for movement

The interface that interacts with the surface, whether an outsole or a varying shape of stud plate, will also play a part in how the traction is developed. There are a number of variations of shoe, all of which serve a different purpose. It is also worth noting that a number of mechanical test devices, such as the rotational traction device use stud plates instead of a shoe.

The following measurements/observations can be made in relation to the shoe:

- Cross-sectional area of stud/length of studs.
- Material of stud.
- Number of studs.
- Stud spacing and alignment.
- Outsole material.
- Shape of outsole.

The above will all have an effect on the mechanisms of traction and need to be taken into account when analysing the movement and hypothesising the mechanisms, as discussed below. For example, it is hypothesised that a longer stud would produce a higher horizontal force when ploughing through infill due to the higher vertical stud penetration and higher surface area in contact with the infill causing resistance.
3.3.2 Impact of foot/plate onto surface

Although the movement hypothesis has been simplified, it is appropriate to assume that this movement occurs in all player-surface interactions. This process involves the studded shoe impacting the surface. It is worth noting that in a realistic sport-specific situation, the player may be impacting the surface at an angle. However, to simplify the movement, the assumption that the shoe is impacting perpendicular to the surface is made, as shown in figure 3.1.

![Diagram of shoe impact](image)

**Figure 3.1**: The impact of a shoe perpendicular to the surface with direction of impact and components annotated.

There are a number of predetermined factors that can affect the outcome of traction which have been described earlier (the initial state of the surface/shoe design). Aside from this, the mass of the player will also have an effect (or mass used on a mechanical device) as this will affect the amount of force impacting on the surface. The hypothesised forces involved in this process are annotated in figure 3.2.

As the studs are initially impacting the surface it is unclear whether the studs are penetrating the surface (i.e. displacing the infill to the side of the studs) or compressing it (where the infill is recoverable upon unloading). It is hypothesised that it is a combination of both and that there is a zone of stiffer infill produced around the studs after they impact the surface, caused by this initial stud penetration and compression. This zone of stiffer infill is of a higher density where it has been compressed and packed closer together and is
hypothesised to be on all sides of the studs, as well as underneath due to the displacement of the infill. The mass of the player is likely to affect the penetration distance of the studs with an increase expected with a higher mass due to more normal force being exerted. The acceleration of the player will also affect the force produced with a greater acceleration causing a higher force. With a higher penetration into the surface, it is hypothesised that the traction will increase due to the increased density of the infill caused by the compression of the infill from the outsole and stud. If full stud penetration is achieved, the stud plate/shoe outsole will come into contact with the infill, contributing to the confinement and compression of the infill under the stud plate. If the length of the studs is enough to reach the layer of sand underneath the rubber infill, it is feasible that this will affect the traction produced due to the dissimilar properties of the materials. It is also possible that the sand mixes in with the rubber infill as it may not be a discrete interface. It is unknown the effect this has on the traction produced. By measuring the displacement of the studs into the surface, an understanding of the behaviour of the infill around the stud can be hypothesised, as well as determining whether the sand layer is reached.

The forces hypothesised are annotated in figure 3.2 below. The diagram has been simplified to focus on the forces of one stud, with infill and fibres omitted. It shows the normal force (1) as the stud/plate impacts the surface. It also shows the infill resistance with the bottom of the stud (2), the infill resistance with the sides of the stud (3) and the infill resistance on the bottom of the stud plate/outsole (4).

![Diagram of stud vertically impacting the surface, with annotated forces. Normal force (1), infill resistance underneath stud (2), infill resistance with the stud sides (3) and infill resistance on the bottom of the stud plate (4).](image-url)
3.3.3 Horizontal movement of shoe/plate

The subsequent stages of movement have been split into two sections; the initial stages of rotational movement and the latter stages. The forces involved during the horizontal movement can be hypothesised and are illustrated in Figure 3.3 below. It is worth noting that there will also be a number of vertical forces influencing the movement, however these were shown in Figure 3.2 and it was considered clearer to split the directions of force. The diagram has been simplified to focus on the forces of one stud, with infill and fibres omitted. The applied force (1) is the direction the stud is travelling in. This overcomes the friction produced around the stud and stud plate. There is friction between the plate and the infill (2), friction between the sides of the studs and the infill (3) and friction at the base of the stud with the infill (4).

![Diagram of stud moving horizontally with the forces annotated](image)

**Figure 3.3**: Diagram of stud moving horizontally with the forces annotated. Applied force (1), friction between plate and infill (2), friction between the sides of the studs and infill (3) and friction at the base of the stud with infill (4).

3.3.3.1 Initial stages of movement

The initial stages of a rotational movement can also be considered a translational movement if the angle is small enough i.e. a quick change in direction.

As mentioned earlier, the traction developed will partly be influenced by the forces produced during the initial impact of the shoe onto the surface (Section 3.3.2) and the displacement of the studs/stud plate into the infill. It is hypothesised that in the early stages of movement, due to the zone of stiffer infill encompassing the studs, there is an early higher stiffness (the infill is resisting deformation).

The resistance builds up due to the studs ploughing through the zone of stiffer infill. The infill is most likely being displaced and compressed as the studs move. The fibres will also
have an influence, with their purpose of providing reinforcement contributing to a higher resistance by resisting infill displacement or shearing.

Figure 3.4 illustrates a stud ploughing horizontally through the rubber infill and fibres, showing the build-up of infill as it is compressed and compacted. The figure only focusses on the front and underneath of the stud.

![Figure 3.4: Stud moving horizontally through rubber infill illustrating the build-up of infill as a stud moves horizontally through the surface system.](image)

Although the diagrams in this section show a singular stud, it can be assumed that the same mechanisms are taking place with multiple studs. A number of added variables may affect the traction produced. The spacing of the studs and the distance between them would affect where the zones of stiffer infill are and whether they overlap. The increase in the number of studs will cause an increase in the total force mobilised due to the increased surface area and the higher number of stiffer infill zones for the studs to plough through. This also applies to the length of the studs as it is expected longer studs will cause a higher resistance due to the higher surface area in contact with the infill and fibres. It is often reported that when using human operated mechanical tests, for example the FIFA rotational traction device, the initial stages are the most challenging due to the higher resistance when rotating the torque wrench.

### 3.3.3.2 Latter stages of rotational movement

As the foot/plate continues to rotate, the torque continues to increase. However, once the studs pass through the initial stiffer zone (as mentioned in Section 3.3.3.1), it is hypothesised that the stiffness decreases due to the studs moving into an undisturbed section of infill, and therefore the infill is resisting deformation less. The forces continue to
increase due to the infill being displaced and compressed as the studs plough through it, causing a shearing force and a resistance from the carpet fibres.

In situations where there are a series of studs e.g. a stud behind another stud, the infill is likely to act differently. If the example of the FIFA rotational traction device is used again, the peak torque is often reached at ~40-45°. It is hypothesised that the peak torque is reached just before the infill/fibre zone in front of the studs fails, due to shear and/or the stud reaching a point close to the path of the preceding stud (Chapter six). This causes the torque to decrease after peak torque. The distance between the studs on the bottom of the shoe/plate is also likely to influence the displacement/angle that the peak torque is reached. This is illustrated in Figure 3.5, however fibres have been ommitted for simplification.

Figure 3.5: Studs moving through rubber crumb. Diagram does not illustrate fibres.

As mentioned in the literature review, it is questioned whether the peak torque and proceeding results are relevant or is the initial movement more relevant and a better indicator of the mechanism involved in the traction mobilised by subjects. This is also discussed in Chapter four, documenting a player movement study.
3.4 Summary of mechanism hypotheses

Section 3.3 detailed the mechanisms involved in a movement involving both rotational and translational components. The following list summarises these hypothesised mechanisms.

- Stud penetration into the undisturbed infill causes compression and displacement of the infill underneath and around the stud/s.
- This causes a zone of stiffer infill around the studs due to the higher density of infill.
- If the outsole/stud plate comes into contact with the surface, it is hypothesised that it confines the infill, compressing it and causing a layer of higher density of infill as the particles pack closer together.
- Higher vertical stud penetration, caused by higher normal force/torque or acceleration by the player/mechanical device will cause a higher horizontal force/torque. This is due to the higher surface area in contact with the infill, therefore a higher resistance is produced.
- The zone of stiffer infill around the studs causes a higher stiffness in the early stages of movement as the studs/stud plate plough through the infill, causing a shearing force.
- A higher net infill bulk density of infill is likely to decrease the stud penetration of the infill due to the compaction of the infill particles. However, it is hypothesised that the horizontal force/torque will be higher with a higher net bulk infill density due to the higher resistance as the studs and stud plate plough through.
- The fibres contribute to the higher resistance by resisting infill displacement and shearing.
- A higher number of studs will produce a higher force/torque due to the increased surface area in contact with the infill.
- In the latter stages of movement, the force/torque continues to increase, however the stiffness decreases as the studs move into an undisturbed infill mix.
- Stud position/orientation will affect the force/torque produced e.g. the displacement/angle that the peak force/torque is reached at.
These hypothesised mechanisms were identified and used to design and plan the mechanical test equipment and protocols to aim to replicate key translational and rotational lower limb behaviour. These can then be utilised to investigate the effects of changes in surface system design and shoe properties on the measurement of traction. The hypothesised mechanisms can then be further refined to reflect the data collected from the mechanical test devices. The following section begins to set out the mechanical tests and how they were developed to collect the desired results and begin to understand the mobilisation of traction.

### 3.5 Planning the mechanical tests

Mechanical tests were chosen for this project instead of subject based testing as they produce a higher level of repeatability and the variables, such as velocity and normal force, can be controlled more easily. As mentioned in Section 2.3, rotational and translational traction are the two key components involved during sport specific movements. These were focussed on in this project, generating the data to allow the proposed mechanism(s) of traction described in Section 3.4 to be supported. The planning of the mechanical tests, as well as the test setups and properties to be altered during testing will be discussed in the following section.

#### 3.5.1 Rotational traction

The FIFA rotational device (as described in Section 2.3.5.1.1) is the standard test device used to classify pitches and provide a comparison between different pitches. As mentioned in Chapter two, the rotational device holds a number of limitations. This included the output only giving a value of peak traction force. It is apparent that the standard device needs development to provide a more advanced output for improved analysis.

Rather than developing a brand new device, a logical alternative was to develop a standard device already available. Suggestions can then be made to alter the standard rotational traction device to potentially provide an improved method of measuring the rotational traction of a surface. The initial query included the sensors that would be a practical addition to the rotational traction device. It was also worth considering how any modifications would be performed and how additions could be achieved without impairing the movement of the device. It would be desirable to have a rotational sensor to measure
the angle of rotation as the torque wrench moves and the rate of rotation. It would also be necessary to have a torque sensor to continuously measure the torque as the angle increases and to determine how the torque changes over rotation and allow for the stiffness values to be calculated. The amount of stud penetration would also be a useful measure to determine the vertical displacement of the studs. The device still holds limitations, such as the inconsistency of the operator and the rate they rotate the torque wrench, however this was controlled during testing by determining a set of boundaries. The development of the device is discussed in detail in Chapter five.

3.5.2 Translational traction

As the rotational traction device is not able to measure translational traction, a new device was developed to measure this specific component. A number of measurements and features were desired for this device and are stated below:

- The test foot/plate should be interchangeable;
- To measure the displacement of stud and stud plate movement into the infill to understand if full stud penetration is occurring and how this contributes to the horizontal force;
- The horizontal force developed over a period of time/distance should be measurable;
- To change the surface sample being tested to be able to place any sample in the device and allow for conditioning between trials;
- The normal load should have the ability to be altered.

The desired translational traction device will allow for a number of hypotheses from Section 3.4 to be tested. It will allow for the stud penetration to be measured and compared between varying normal loads, surface conditions and shoe properties. The measurement of continuous force will also allow for the stiffness values to be calculated and compared. An interchangeable test foot/plate allows for flexibility in the tested shoe properties, with the ability to test the desired shape/studs for the study being carried out.

The newly developed device allows for comparison with data collected from the rotational device, in terms of the general patterns observed. This will aid in the understanding of the mechanisms of traction. The translational traction device is an automated mechanical
device without any human input. This allows repeatability of the device to be determined between trials with direct comparison between values. The development of this translational traction device is discussed in detail in Chapter five.

3.6 Testing variables

As established in the literature review, there are a large number of variables which can be tested to determine the effect they have on traction and the mechanisms involved. A number of these will be focussed on and be tested in this thesis. However, it is not possible to cover all of them due to time constraints. Many of them have been covered previously by other authors, the results of which can aid the results from the following testing. The next section describes the properties to be tested with a justification and explanation for testing. The table below shows the variables determined from the literature review, the author and after consideration of the mechanisms. The variables chosen will aid in the understanding of the hypotheses set out in Section 3.4.
Table 3.1: Table of variables thought to influence the properties at the shoe-surface interface

<table>
<thead>
<tr>
<th>Shoe</th>
<th>Surface</th>
<th>Player interaction</th>
<th>Outside influences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical</td>
<td>Mechanical</td>
<td></td>
</tr>
<tr>
<td>Number of studs</td>
<td>Pile height</td>
<td>Compression of fibres</td>
<td>Mass of athlete</td>
</tr>
<tr>
<td>Cross-sectional area of studs</td>
<td>No. of tufts per unit area</td>
<td>Tensile strength of fibres</td>
<td>Loading rate</td>
</tr>
<tr>
<td>Stud length</td>
<td>Fibres per tuft</td>
<td>Rubber infill compaction</td>
<td>Angle of foot on impact</td>
</tr>
<tr>
<td>Material of studs</td>
<td>Fibre material</td>
<td>Rubber infill compression</td>
<td>Impact velocity of athlete</td>
</tr>
<tr>
<td>Stud spacing/configuration</td>
<td>Fibre width</td>
<td>Shear strength of rubber infill</td>
<td>Height before contact with surface</td>
</tr>
<tr>
<td>Contact surface area (forefoot/full foot)</td>
<td>Rubber infill material</td>
<td>Rubber infill net bulk density</td>
<td></td>
</tr>
<tr>
<td>Stud displacement</td>
<td>Rubber infill height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outsole geometry</td>
<td>Rubber infill size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outsole material</td>
<td>Sand height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shockpad material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shockpad thickness</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The chosen variables for testing are shown in bold in Table 3.1 above. The objective of the testing was to build up a picture of the mechanisms involved in traction. The properties chosen were designed to give a sufficient range of results to provide the support for the traction mechanism discussed in Section 3.3, without choosing to alter all the properties which were not in the scope of the thesis. A more detailed justification for the chosen variables is below.

The various stud types (and consequently cross-sectional area/material and stud length) have been investigated previously by Clarke (2011) and Severn (2010) amongst others. These variables were chosen to build on this work, and due to the studs being a key variable influencing the interaction at the surface.

The stud spacing was chosen to determine how the stud placement affects the force produced when moving horizontally. This is a continuation of the work completed by Clark.
and Severn, but hopes to go into higher amounts of detail in regard to the mechanism of traction.

The vertical stud displacement was identified as an important variable to measure as this may be able to indicate how much the studs and stud plate affect the force produced and the mechanisms involved. This planned to build on the work of Clarke (2011).

The fibres per tuft were chosen to be altered to investigate how they contribute to the overall force produced. This has been looked at by Severn (2010), however on a smaller scale. This will help to understand the mechanism of the rotational and translational movement. As a consequence of using two surface specifications, the size of the rubber infill particles are tested. By performing identical tests on both specifications, this will help to determine whether it has an effect on the force produced.

The mechanical properties are investigated as a result of the changing variables e.g. compaction/compression of the infill. This is a continuation of the work by Severn (2010) and Clarke (2011), however a more detailed overview of the mechanism during a sport movement will be completed.

The variables relating to player interaction were on occasion, unable to be varied due to limitations of the mechanical devices. The rotational traction device was unable to have the mass increased above 45 kg; however the translational traction device was designed to have a variable normal load (described in chapter 5). This was to allow the mass of an average human to be replicated. The vertical load has also been shown to have a large influence on the force produced and the performance, as discussed in section 3.3.2.

Although the outside influences (right column) are important and have been shown to affect the use of the surface, they were not investigated or tested as they were not in the scope of the project.
3.7 Conclusions

This chapter has outlined the plan for how the objectives will be achieved. It has hypothesised the mechanisms involved in rotational and translational traction by breaking down a movement and determining the forces and detail of how the surface is behaving under load and throughout the movement. The development of the mechanical tests has been outlined with the required specification needed to carry out testing to help further the understanding of the mechanisms. The large numbers of variables present at the shoe-surface interface were illustrated, with the chosen variables justified. Chapter 4 will further help in understanding the mechanisms of traction by understanding boundary conditions during sport-specific movements. The boundary conditions can then be used during use of the mechanical devices to design the methods accordingly.
CHAPTER FOUR – PLAYER MOVEMENT STUDY

4.1 Introduction

As highlighted in Chapter two, it is important to have an understanding of how a human interacts with a surface and to be able to transfer this knowledge when developing and critiquing mechanical test devices. As discussed previously, the validity of the FIFA rotational traction device has been questioned as it is not clear whether the movement accurately represents a human interaction with a surface. It is not always possible to directly replicate a human interaction with a mechanical device due to limitations such as unrealistic normal loads and velocities.

A set of testing was completed by a previous Loughborough University PhD student (El Kati, 2012). The aim of the project was to analyse the human interactions during two movements on artificial turf. This helped to contribute new data in relation to a greater range of movements, relevant in-game scenarios and with the use of carefully controlled surfaces.

The aim of this chapter was to take the relevant variables determined from the literature review from subject testing, analyse the subject data and present and discuss the results in regard to both rotational and translational traction devices. This allows for design of the mechanical tests and the methods involved to be better informed, increasing the validity of the measurements. Further analysis was completed beyond the analysis done by El Kati (2012) to fit the purpose of the current study.

For this study, only the stop and turn movement was analysed as it is a movement that includes a twisting motion and relies on traction to perform the movement. The variables chosen were directly linked to the movement in order to get the most relevant information from the subject data that could be related and compared to mechanical tests.

The identified variables include:

- Foot used for touchdown onto the force plate (Right/Left);
- Orientation of touch down (Flat footed or toe first);
- Bodyweight of the subject;
- Mean contact time of the foot on the force plate;
- Mean ground reaction force during the flat foot phase (FFP);
• Mean foot rotation range over the flat foot phase, in the horizontal plane parallel to the floor;
• Rotational velocity over the flat foot phase in the horizontal plane parallel to the floor;
• Rotational acceleration over the flat foot phase in the horizontal plane parallel to the floor;
• Vertical velocity at touch down.
• Pressure from the foot.

4.2 Method

The method of testing completed during testing by El Kati (2012) is outlined in detail in section 2.3.5. Of the 16 subjects tested by El Kati, only 10 of the subject’s data were used by this study with the other six being discarded. Two players were discarded due to a high number of trials that contained implausible readings (i.e. differed widely from the majority). The other four were discarded because their technique was considered unique and they did not represent the majority of the population and could not be used for comparison against the other subjects.

The markers of interest for this study were the two markers on the boot of the turning foot, one on the toe and one on the heel. The toe marker was placed on top of the second metatarsal head with the heel marker placed on the calcaneus (heel bone) at the same height as the toe marker (Figure 4.1). All the subjects wore adidas Copa Mundial football boots for consistency. The foot size of the players was not presented by El Kati (2012), however it was ensured that they all wore the same shoe type to allow for consistency.
Although the surfaces had an effect on traction and hardness, all the trials were combined for the purpose of this study due to the surface property effects not being the focus of this study. There were 10 trials completed for each condition, with each condition having five with an opponent and five without (to resemble an in-game scenario). However, these were also combined as it was found that they did not have a significant effect on the results. Therefore, all 40 trials were combined and presented together for each player.

4.2.1 Data processing

The Vicon and force plate data were saved as CSV files which were imported into MATLAB and Microsoft Excel for analysis.

The foot used for contact and the orientation of touch down were initially identified. The contact time of the foot was taken as the point from when the foot first impacted the force plate, to the point before the foot was lifted off the force plate. This was identifiable by contact of the player on the force plate.

The data was then broken into three phases; the touch down phase, where the foot makes initial contact with the force plate; flat foot phase where the heel or forefoot was brought to the surface and the weight shifted from the medial part of the foot to the lateral part; and the take-off phase where the foot started to leave the force plate, with the medial part of the foot being the last part to leave the surface. These are shown in Figure 4.2 below.
The middle phase was of interest as this is where the foot was in contact with the surface and the studs were fully engaged with the surface, creating traction. There is also a link to mechanical test conditions which often replicate a full foot contact. A method to define this flat foot phase was used, where the toe and heel markers went below a set vertical velocity threshold close to 0 m/s. This was the point at which the foot was considered flat.

For all variables of interest, all 40 trials were plotted against the stance percentage to allow for comparison between the trials. The ground reaction force was determined to be the data collected while the player was in contact with the force plate. The rotational angle of the foot was the angle that was measured in the horizontal plane, parallel to the floor when the foot was in contact with the surface. The rotational velocity was the differentiated positional data from the rotation of the foot. Subsequently, the rotational acceleration was the differentiated velocity data. The vertical impact velocity was the last value before contact with the force plate occurred in the vertical direction. These results are shown in the following section.
4.3 Results and Discussion

The following section includes the results and discussion for the data that was analysed from the subject testing previously completed by El Kati (2012). It includes a summary table of the results from the 10 subjects, followed by a breakdown of the relevant variables accompanied by graphs and a discussion.

4.3.1 Summary table

Table 4.1 shows a summary of the 10 subjects and the results from the chosen variables. The variables were listed in Section 4.1. The result for each subject represents the mean and standard deviation over the 40 trials completed. The mean of each variable is also calculated, which represents the mean over the 10 subjects i.e. the mean of means.
Table 4.1: Summary table of 10 subjects results over a number of variables. Each subject represents an average of 40 trials.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Foot</th>
<th>Orientation of touch down</th>
<th>Bodyweight</th>
<th>Contact time</th>
<th>Ground reaction force during FFP</th>
<th>FFP Foot rotation range</th>
<th>Touch down vertical velocity</th>
<th>FFP rotational velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean (s)</td>
<td>Mean (BW)</td>
<td>Mean (°)</td>
<td>Mean (m/s)</td>
<td>Mean (°/s)</td>
</tr>
<tr>
<td>1</td>
<td>Right</td>
<td>flat</td>
<td>62</td>
<td>0.43</td>
<td>1.29</td>
<td>4.95</td>
<td>-0.85</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>Right</td>
<td>flat</td>
<td>70</td>
<td>0.46</td>
<td>1.28</td>
<td>5.10</td>
<td>-0.76</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>Right</td>
<td>flat</td>
<td>74</td>
<td>0.48</td>
<td>1.14</td>
<td>8.99</td>
<td>-0.66</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>Right</td>
<td>toe</td>
<td>80</td>
<td>0.50</td>
<td>1.21</td>
<td>4.10</td>
<td>-0.79</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>Right</td>
<td>toe</td>
<td>84</td>
<td>0.48</td>
<td>1.54</td>
<td>5.48</td>
<td>-0.95</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>Right</td>
<td>toe</td>
<td>74</td>
<td>0.49</td>
<td>1.38</td>
<td>8.35</td>
<td>-1.06</td>
<td>0.07</td>
</tr>
<tr>
<td>7</td>
<td>Right</td>
<td>toe</td>
<td>75</td>
<td>0.50</td>
<td>1.29</td>
<td>6.46</td>
<td>-1.15</td>
<td>0.07</td>
</tr>
<tr>
<td>8</td>
<td>Right</td>
<td>toe</td>
<td>88</td>
<td>0.40</td>
<td>1.29</td>
<td>5.64</td>
<td>-0.91</td>
<td>0.11</td>
</tr>
<tr>
<td>9</td>
<td>Left</td>
<td>toe</td>
<td>75</td>
<td>0.48</td>
<td>1.09</td>
<td>3.73</td>
<td>-0.77</td>
<td>0.04</td>
</tr>
<tr>
<td>10</td>
<td>Left</td>
<td>toe</td>
<td>65</td>
<td>0.45</td>
<td>1.34</td>
<td>4.28</td>
<td>-0.99</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td></td>
<td>0.47</td>
<td>1.28</td>
<td>5.71</td>
<td>-0.89</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.12</td>
<td>1.76</td>
<td>0.16</td>
<td>6.31</td>
</tr>
<tr>
<td></td>
<td>Rotational traction device</td>
<td>46 ± 2</td>
<td></td>
<td>0.63</td>
<td>0.61</td>
<td>45</td>
<td>-1.08</td>
<td>72</td>
</tr>
</tbody>
</table>

Mean: 74.7 kg, SD: 7.96 kg, Rotational traction device: 46 ± 2
4.3.2 Contact time

The average contact time was 0.47 ± 0.03 seconds. This shows consistency amongst the 10 subjects. The guidelines for the rotational traction device state that it should be rotated at 72 °/s for a minimum of 45°. This would equate to 0.63 seconds (at 45°), however the distance moved is much further with the rotational device compared to the subject data, as described in Section 4.3.4.

4.3.3 Vertical ground reaction forces (GRF)

Mechanical tests should aim to replicate the ground reaction forces produced by humans to ensure they are as biofidelic as possible. The pattern found amongst the subjects was an initial vertical peak at touchdown, which was found to have an average of 1.9 ± 0.5 bodyweights (BW). The ground reaction force then reduced and flattened for the majority of the flat foot phase movement. The forces then reduced as the subject’s foot lifted off the surface. Over the flat foot phase the ground reaction force was an average of 1.28 ± 0.12 BW. It could be considered that the surface system is most pushed to its limit towards the end of the movement as the player turns and pushes off (towards the end of FFP). This could be considered the point where slipping, and consequently injury, is most likely. The vertical ground reaction force is between 1 and 1.5 BW at this point (70-80 % of the stance phase).

Figure 4.3 shows an example of one subject and the 40 trials which were completed. The three phases are marked on the graph. The marked phases are only an approximate as they differed from trial to trial depending on the velocity of the markers.
The rotational traction device uses a mass of 46 kg weights. This is below the average bodyweight of the subjects used in the testing outlined in this chapter, however it does allow for the device to be portable and user friendly. This would not be possible if there was 75 kg on the device. The translational traction device which has been developed and outlined in Chapter five is able to hold a higher normal load to ensure it is as biofidelic as possible.

The pressures that occur underfoot can be calculated from the ground reaction forces. This pressure will have an impact on the traction mobilised. If the area of the stud plate was reduced, this would increase the pressure underfoot and the studs and stud plate may penetrate the surface further.

To calculate the pressure for the subjects, an average size eight outsole was taken (0.0179 m$^2$). The average ground reaction force calculated was 936 N which gave a pressure of 52 kPa. When comparing this to the FIFA rotational traction device, which has an area of 0.0177 m$^2$ and a mass of 46 kg, the pressure calculated was 26 kPa. This is half the pressure compared to the average pressure produced by the subjects. When testing using the translational traction device, and measuring the pressure value with a plate measuring 120 mm x 120 mm at 70 kg, the pressure calculated was 15 kPa which is again lower. The two devices could be altered to make the pressure comparable, by increasing the mass or reducing the area of the stud plate.
4.3.4 Rotational angle

The rotation of the foot was measured in the horizontal plane parallel to the floor. The average rotational range during the flat foot phase was $5.71 \pm 1.76^\circ$. In the majority of trials, most of the rotation happened at the start and end of the movement at touch down and take-off as observed in Figure 4.4. Less rotation is observed during the flat foot phase when the studs are in full contact with the surface. The marked phases are an approximate as they differed from trial to trial depending on the velocity of the markers.

![Figure 4.4: Rotational angle of the foot in the horizontal plane for all 40 trials of one player against stance percentage. Three phases are shown; Touchdown (TD), flat foot phase (FFP) and take-off (TO).](image)

The FIFA device states that it must be rotated by a minimum of $45^\circ$ which is considerably higher than the values shown above. This supports the theory that the initial stiffness may be a better indicator of shoe-surface interactions. When using the rotational device, the peak torque normally occurs around $35-40^\circ$, however if the subject data from above is used, the first 0-6° may be a more appropriate number.
4.3.5 Rotational velocity

The rotational velocity was measured parallel to the ground in the horizontal plane. The average rotational velocity over the 10 subjects during the flat foot phase was 6.41 ± 6.31 °/s. As discussed earlier, the rotational FIFA device states that it should be rotated at 72 °/s. This is much higher than the average value found for the 10 subjects, even with the high standard deviation. However, the rotational velocity at the start (touchdown) and end (take-off) of the movement gave much higher values, where the majority of the foot rotation took place. From testing completed on the rotational traction device (see Section 5.2.3.2), it was found that by lowering the rotational velocity, the torque reduced. Therefore, this may affect the results if the velocity was reduced to coincide with the results below.

![Figure 4.5: Rotational velocity against stance percentage for all 40 trials for one player. Three phases are shown; Touchdown (TD), flat foot phase (FFP) and take-off (TO).](image)

4.3.6 Rotational acceleration

The analysis completed showed that the foot only rotates a few degrees when fully engaged with the surface (Section 4.3.2), supporting the literature in Section 2.3.4.4. It is important that at the start of movement, consistent data is recorded. When using the FIFA rotational traction device, there is no velocity at the start of the moment, before it accelerates to the target velocity of 12 rev/min over the first few degrees of motion. During the FFP, the rotational acceleration for all the players averaged 248 ± 92 °/s². The acceleration peaked
before levelling out once the foot became fully planted. Due to this reason, it may be more appropriate to match an acceleration profile or limits rather than a target velocity to be able to ensure that the initial movements are biofidelic. The mean over the FFP was calculated as the maximum or minimum values were too high to be replicated by the rotational traction device. Between 35% and 80% of the FFP phase, the foot was close to stationary, as the rotational velocity was close to $0^\circ/s^2$.

![Figure 4.6: Rotational acceleration against stance percentage for all 40 trials for one player. Three phases are shown; Touchdown (TD), flat foot phase (FFP) and take-off (TO).](image)

4.3.7 Vertical impact velocity

The vertical impact velocity was taken as the last value before contact with the force plate. This impact velocity will have an effect on the penetration of the studs into the surface. The players impacted the surface at an average vertical velocity of $0.89 \pm 0.16 \text{ m/s}$. When comparing this value to the rotational traction device dropped from a height of 60 mm, which has a vertical velocity of $1.08 \text{ m/s}$ (assuming no friction on the central column when dropped). This is comparable to the value from the players; however, the rotational traction device only takes into account the vertical velocity. There was also a value calculated for the impact velocity in the horizontal direction. This equated to $1.32 \pm 0.47 \text{ m/s}$, greater than the vertical impact velocity.
4.4 Limitations

There are a number of limitations with this subject testing. There was only data available for 10 subjects due to the other six subjects having different techniques or a large number of erroneous trials; however, the majority of subjects had similar techniques. Another limitation is that only one movement has been analysed, which was performed at one speed. It is worth noting that this is a common movement, but it is highly feasible that other movements may produce alternative values for the variables identified. However, it was not in the scope of this PhD to analyse a high quantity of movements. The testing was completed in a laboratory environment with the main limitation being a limited run up. This lab setup may cause the participants to perform unnatural movements, however the lab did have the advantage of allowing for a large quantity of data to be collected including Vicon and force plate data. The data was combined for different surface and player conditions so any variations were ignored. However, this was less important in the context of the variables analysed as it was the general trends and ranges over which the athletes performed which were relevant.

4.5 Conclusions

The aim of this chapter was to analyse a movement from a set of subject data previously collected to understand the relevant variables and the boundaries that exist in regard to both rotational and translational traction devices. Although they cannot be taken as concrete boundaries, they are a useful guideline. It was found that in general, the subjects performed their movements consistently amongst trials which give confidence when using mechanical tests as they are designed to be consistent between trials.

A list of target conditions are set out below:

*Vertical ground reaction force* – There was an initial vertical peak at touchdown, which was an average of $1.9 \pm 0.5$ bodyweights (BW). The literature review (section 2.3.4.3) reiterated this with a number of studies showing a maximum load of between 1.5 and 3 BWs. However, it could be considered that where slipping is most likely and when the surface is most pushed to its limit is towards the end of the movement as the player turns and pushes off the surface. The vertical ground reaction force is between 1 and 1.5 BW at this point (70-80 % of the stance phase). This would be more replicable load for the mechanical devices.
The GRF is difficult to replicate on a mechanical device without making it difficult to operate or by compromising portability. Having a device that does match an average body mass (75 kg) does have benefits for measuring more biofidelic results.

**Contact time** - The average contact time for the subjects was 0.47 ± 0.03 seconds for the stop and turn movement. When using the rotational traction device, this equates to 0.63 seconds, however the distance moved is much further compared to the subject data. This may add to the justification that the initial movements may be a better indicator of the mechanism involved in the traction mobilised by subjects.

**Rotational angle** - The results showed the low rotation of the foot parallel to the floor, with the average rotation only being 5.71 ± 1.76°. This reinforces the initial movement potentially being a better indicator of traction compared to using a later measure such as peak torque, as it is questionable whether a subject rotates 30-40°.

**Rotational velocity** - The rotational velocity calculated for the subjects was 6.41 ± 6.31 °/s, which was much lower than the velocity used for the FIFA rotational traction device (72 °/s). However, it is worth noting that the velocity was much higher at the start and end of the movement. A range of velocities were tested for both the rotational and translational traction devices, with the velocities having an effect on the results. Therefore, this needs to be something that is considered when designing methods for the mechanical tests.

**Rotational acceleration** – During the FFP, the rotational acceleration for all the players averaged 248 ± 92 °/s². The acceleration peaked before levelling out once the foot became fully planted. Due to this reason, it may be more appropriate to match an acceleration profile or limits rather than a target velocity to be able to ensure that the initial movements are biofidelic.

**Vertical touch down velocity** - The vertical touch down velocity was calculated as -0.89 m/s. This is comparable to the FIFA rotational device which has a vertical velocity of -1.08 m/s. However, this is not applicable using the translational traction device as the test begins with the shoe/plate placed on the surface.

The results have established the variables that show similar boundary conditions to the mechanical test devices used and the variables that are dissimilar. It is desired that they would help to further inform mechanical devices to ensure they are as closely matched to human boundaries as possible, however there are limitations when designing mechanical devices as discussed in Chapter five.
CHAPTER FIVE - DEVELOPMENT OF MECHANICAL TEST EQUIPMENT

5.1 Introduction

As mentioned in previous chapters, two mechanical test devices have been used to understand the mechanisms of traction by testing both rotational and translational traction. The FIFA rotational traction device is widely used to characterise both natural and artificial pitches, and has been developed further to allow for additional data capture. This development is based on literature, subject testing discussed in Chapter four, and preliminary testing. A translational traction device was also developed and constructed. The methods established for completion of the mechanical test devices were created with the aim of supporting the mechanism hypotheses set out in Chapter three. The following chapter outlines the development of both mechanical traction devices, the testing methods and the analysis completed on the data collected from the test devices.

5.2 Development of rotational traction device

As mentioned in Section 2.3.5.1.1, the FIFA standard rotational traction device is simplistic with a number of limitations. These include the output of one value of peak torque and the inability to gain immediate feedback post completion of a trial, to determine the velocity of the previous trial. In light of this, the decision was made to modify the device to reduce these limitations and allow for a wider range of analysis when implementing the device.

5.2.1. Addition of sensors

The modification included the addition of instrumentation which was incorporated to provide measurement of the torque and angle throughout the rotation of the test disc. It was ensured that these sensors did not impede the movement of the device. A strain-gauge torque sensor was mounted below the existing torque wrench. The rotational sensor, using a Hall Effect potentiometer, was mounted below the strain gauge torque sensor. These sensors can be seen attached to the rotational traction device in Figure 5.1.
The strain-gauge torque sensor was calibrated against a digital torque wrench. The digital torque wrench gave a lower error compared to the analogue torque wrench.

The rotational sensor comprises of a Hall Effect sensor. A Hall Effect sensor works with a transducer which varies its output voltage in response to an external magnetic field. The output given by the sensor is the function of magnetic field density around the device. When the magnetic flux density around the sensors exceeds a set threshold, the sensor can detect it and this generates an output voltage. The Hall Effect potentiometer (measuring rotation) was calibrated by dividing the voltage across it by the number of degrees of rotation in the manufacturer’s specification which was cross checked against a protractor. From these calibrations, the sensitivity values of the sensors were entered into Labview, the user interface software used during testing. The outputs of these sensors were sampled at 250Hz with each sensor displaying its own measurement, plotted on a graph against time using LabView. The trials were then saved as a CSV file before being imported to Microsoft Excel to allow for analysis and interpretation. Note that a discrete value of peak torque from the torque gauge was still available following these modifications (Figure 5.2).
5.2.2 Portability of device

The initial modification meant the device was no longer portable due to the addition of a desktop computer. However, the device was further modified with the addition of a power source, charged from the mains, which provided power for each sensor and subsequently transferred the measurement to a laptop via a USB cable. This portability allowed for the device to be taken onto outdoor pitches to collect a much wider range of data. Figure 5.3 below shows the input box with connections to the sensors and a laptop.

Figure 5.3 Schematic of the modified rotational traction device with added instrumentation and power source/laptop for portability.
5.2.3 Rotational traction device troubleshooting

Following the addition of sensors to the rotational traction device, several initial problems were discovered. These issues were addressed in the study and are discussed in the following section.

5.2.3.1 Rotational give

With the addition of the sensors, there was a small amount of give in the connection between the torque wrench and the fixture below. This refers to the amount that the torque wrench rotates freely before any or only a small amount of traction is mobilised. The extra movement has the potential to affect the results, particularly the identification of the start point, which is particularly important when looking at the initial mobilisation of traction. To solve this, the frame was tightened with the addition of two screws to the connection between the main frame and the added instrumentation fixture (Figure 5.4) to attempt to stabilise the structure further.

![Diagram showing the added sensors to the rotational traction device and the two added screws to reduce give.]

Figure 5.4: The added sensors to the rotational traction device and the two added screws to reduce give.

The amount of rotational give was reduced from up to 11° to approximately 0.1° which can be considered negligible during testing and analysis.
5.2.3.2 Rate of rotation

With the addition of the sensors, the rate of rotation could be calculated after a trial was completed to identify whether the desired velocity of 12 rev/min (FIFA, 2010) was achieved. The results demonstrated the difficulty in reaching a set velocity and keeping it constant when rotating the torque wrench. Three velocities were chosen to test; 12, 8 and 4 rev/min. Figure 5.5 shows a trial from each velocity that was tested. It was found that similar peak torques were reached for 12 and 8 rev/min, although peak torque was reached at a higher rotation for 12 rev/min compared to 8 rev/min. The trial for 4 rev/min was found to be lower. The two stiffness values were calculated (defined in section 5.6.1) with similar results found for all three velocities. These results suggest that the rate of rotation did not have an effect on the results until peak torque was reached, where the lowest velocity produced a significantly lower value for peak torque compared to the two higher velocities. This suggests that it may be feasible to have a range of velocities for rate of rotation compared to one value. This would allow for a more user friendly and achievable method, compared to the current FIFA standards.

Figure 5.5: Three rotational velocities testing rate of rotation using the rotational traction device.
5.3 Development of translational traction device

The following section outlines the development and construction of a mechanical test device to measure translational traction. This includes the desired specification for the device, the construction of the device and any required troubleshooting.

5.3.1 Fulfilment of specification criteria

As stated in Chapter three, there was no device available to measure and test translational traction, therefore the decision was made to design and construct one. A list of criteria was set with the desired specification for the device. These are outlined below:

- The device should fix to the Instron 3365 uni-axial tensile machine situated in the laboratory at Loughborough University Sport Technology Institute;
- It should measure the displacement of stud movement into the infill to understand if full stud penetration is occurring and how this contributes to the horizontal force;
- The horizontal force developed over a period of time/distance should be measurable;
- The test foot/plate should be interchangeable;
- Be able to change the surface sample being tested to be able to place any sample in the device and allow for conditioning between trials;
- The normal load should have the ability to be altered.

Before the device was constructed, the above were considered while coming up with a design. The schematic shown in Figure 5.6 represents the design of the developed rig. The diagram shows a side view of the Instron uni-axial tensile machine. It shows how the frame was fixed to the machine and how the tray was attached to allow for horizontal movement. It also highlights the mechanism for moving the test foot/plate vertically and the ability to add mass to the top of the device.
Following on from the design of the rig, construction was completed, with details of the various components outlined in the following section.

5.3.2 Construction of device

The device was constructed over the course of a number of months with the outcome corresponding with the schematic shown in Figure 5.6. The following section breaks down the construction of the device and details the various components making up the complete device.

The frame was designed to rest with two height adjustable legs on the floor, also attaching to the Instron 3365 uni-axial tensile machine by four screws to keep the device securely in place.
The tray measured 500 x 500 mm in size. This size was chosen to allow enough room for a shoe to move at least 100 mm through the surface, and to also allow for edge effect as this may affect results collected. The tray is attached to the frame by four rail guides placed on two rails, either side of the tray. A metal cable is attached to the underside of the tray which subsequently attaches to the crosshead - the moveable component of the uni-axial device. To allow for horizontal movement of the tray, a pulley was fixed directly below the crosshead for the cable to be fed around (Figure 5.8). With bearings placed either side of the pulley, it was ensured that rotation of the pulley involved as little friction as possible to ensure smooth movement of the tray.

Figure 5.7: The bottom part of the frame, with the tray, attached to the Instron uni-axial tensile test equipment before construction of the full rig was completed (left) and method of attaching two bolts from frame to Instron (right).

Figure 5.8: Pulley placed adjacent to the tray with cable fed from tray, for attachment to Instron crosshead.
The frame was constructed around and above the tray/foot plate, as seen in Figure 5.9 (left). The mechanism to control the central column involved two linear actuators (annotated in Figure 5.9) that are able to move the central column up and down, including the mass placed on top of the device, by approximately 100 mm. The actuators drop the foot down onto the surface, causing the foot and weight to be free to move vertically during normal operation, thereby ensuring a constant normal load. Four bearings are placed either side of the central column (two at the top, two at the bottom) which aim to reduce the friction of the vertical shaft as it moves up and down freely.

The desired mass is placed on top of the rig, with a shaft allowing for the safe placement of weights. A maximum mass of 70 kg could be placed on the rig. The central column runs from where the weights are placed, down to where the foot plate is situated. At the bottom of the central column is the connection for the fixed foot. A detachable plate is connected to the central column by two pins. This allows the attachment to be disconnected and rotated in 10 degree increments before being fixed by the pins. This aims to represent a foot impacting the surface at an angle and translating horizontally through the surface.

At the end of the detachable connection is a space for interchangeable fixtures to be attached to the rig, depending on the testing being completed e.g. shoe last, stud plate. This will be discussed in the following section.
5.3.2.1 Variations of stud plate

As mentioned above, an advantage of the test device is the ability to design, construct and attach any plate/shoe with an interchangeable mechanism (Figure 5.11). This was achieved with a gap in the vertical central column, where attachments could be slotted in and fixed securely with a bolt and washer.

For this project, a last with an attached shoe was not used, to take away any possibility of the shoe material affecting the results (e.g. bending stiffness). However, this would be possible for future projects and highlights the scope for the test device.

A flat aluminium plate was used for testing (shown above in Figure 5.11) which allows for the studs to be screwed in and attached underneath. A square plate measuring 120 mm x 120 mm was constructed with nine stud holes (three by three). This was to control where...
the studs are relative to each other e.g. directly behind or next to, to better understand the mechanisms involved in traction. The studs were spaced 45 mm apart to match the spacing of the rotational traction stud plate. The force was placed through the centre of the square.

![Figure 5.12: Square stud plate with nine stud holes and fixture for attachment to central column.](image)

5.3.2.2 Measuring vertical stud penetration

To measure the distance that the studs displace vertically into the surface, a vertical displacement sensor was added to the device as seen in Figure 5.13 below. As the actuators are moving and the stud plate is placed onto the surface, the protruding plate comes into contact with the vertical displacement sensor, which outputs a measure to Labview, a user friendly interface software (connected via a cable to a laptop) and measures any vertical displacement by the central column as the stud plate and studs move horizontally through the surface.

![Figure 5.13: Vertical displacement sensor at the top of the translational traction device.](image)
The data from the vertical displacement sensor was synched to the horizontal force data produced by the Instron tensile machine. On the software (Bluehill) used to control the Instron 3365, an extra movement was added near the end of the instructions. This was an increase in speed for one second which would act as a marker for the vertical displacement sensor. This had the intention of triggering the vertical displacement sensor, which along with the point on the Instron software, could be matched to each other to know the point that the studs and plate penetrated vertically into the surface. This could consequently tell if the studs moved up or down as the stud plate moves horizontally through the surface.

![Flowchart of instructions for a trial using the uni-axial tensile machine.](image)

5.3.2.3 Calibration platform

In order to determine the vertical displacement of the studs and stud plate into the infill, a value for the top of the infill needed to be calculated. To achieve this, a calibration platform was designed and built. The platform consisted of an aluminium disc, with three points of contact created using flat head bolts. Three points were chosen to minimise the number of contact points with the surface which ensured the rubber infill was disturbed as little as possible. A bubble level was attached to the top of the platform to ensure the surface was level when any measurements were taken.

![Calibration platform for placement on surface.](image)
The distance between the bottom of the stud plate and the top of the calibration platform was measured using a Vernier calliper (a in Figure 5.16). The total height of the calibration platform was a known height (b). The value for the position of the vertical displacement sensor (taken from Labview software) was noted, with the values of a and b subtracted from the position of the vertical displacement sensor. This value can then be used for the vertical displacement sensor to act as an offset to give the top of the surface a value of 0. Any penetration of the stud and stud plate into the infill can therefore be determined.

Figure 5.16: Method for determining top of the surface (a = distance between bottom of stud plate and top of calibration platform, b = height of calibration platform).

5.3.3 Translational traction device troubleshooting

A number of improvements and changes had to be made to the translational traction device due to it being a new design, which initially needed a degree of trial and error to ensure problems were minimised. The methods of troubleshooting are described in the following section.

5.3.3.1 Rails underneath tray

A set of rails were initially attached to the rig, however these produced a large amount of friction when the tray moved across them. The rails were replaced with a higher specification of rail with a near frictionless horizontal movement. With the old rails, a correction method would have been necessary to account for the friction from the rails. This would have involved performing a test where the frictional force in the rails were known, and discounting this from any horizontal force produced with the foot on the surface. However, with the new rails with a much lower friction, a correction method was not deemed necessary as it would not compromise the data. It was decided that when a higher normal load was being placed on the surface, the friction on the rails was negligible.
The friction in the newest rails can be seen in Figure 5.17. This represents a total mass of 90 kg on the rails (including the mass of the tray), with the tray then moved 50 mm. There was no foot on the surface for this testing. Compared to the forces produced with a foot on the surface, the forces shown in figure 5.17 are much lower. The oscillations (which were reduced with new rails) were due to the initial movements of the tray, and are likely because of the stiff cable attached between the tray and the crosshead of the Instron uni-axial tensile machine. As mentioned above, a correction method was not deemed necessary because of the low forces produced by the rails. When compared to a trial with the foot on the surface at comparable vertical loads, the force produced by the rails was only small, therefore it will have little effect on the overall force produced.

![Figure 5.17: The force produced by the rails with a total mass of 90 kg on the rails (including the mass of the tray), with the tray moved 50 mm.](image)

### 5.3.3.2 Cable

The cable connecting the tray to the crosshead of the Instron tensile machine was tested to investigate the effect of keeping the cable taut or loose while testing. It was found that when leaving the cable loose at the start of a trial, then adding mass to the tray to represent a set mass and the foot on the surface, a large force was produced. However, with the cable taut the force was reduced by approximately half. With the loose cable, it took approximately four millimetres to reach the desired velocity; with a taut cable it only took...
approximately two millimetres. It was decided to consistently keep the cable taut throughout testing as this has an effect on the force produced and it is desirable to reach the target velocity as quickly as possible.

5.3.3.3 Bearings

After initial testing, the pulley which allowed for movement between the tray and the crosshead on the Instron rotated inconsistently and required a new bearing. Therefore, this was replaced to correct the problem. The smooth and frictionless movement of the pulley is essential during testing, otherwise the force produced will be affected and the trials will be inconsistent.

5.3.3.4 Velocity of Instron

A range of velocities were chosen to test the effect they had on the force produced. The mechanical crosshead on the tensile machine was programmed to move at four different velocities: 250; 500; 700 and 1000 mm/min. These were completed on the same specification of artificial turf, being conditioned after each trial to ensure consistency. Three trials were completed at each velocity. It was found that 250 mm/min produced a lower force, whereas the three other velocities produced comparable forces. As expected, there were small discrepancies due to the varying nature of the surface. The maximum speed of 1000 mm/min was chosen for the testing completed using the Instron tensile machine.

5.4 Test setup

The following section outlines the specifications of the two surfaces used and how a surface is constructed, prepared and conditioned for the desired setup.

5.4.1 Sample Preparation

As mentioned in Chapter two, one of the gaps in knowledge is the lack in communication of surface systems. The below section highlights the basic specification of the surfaces used, with more detailed specifications referenced in Appendix A.
Two different specifications of surface have been used during testing, with the quantities taken from carpet manufacturer’s specifications (Appendix A). Although the specifications are similar, they represent an older and newer pitch on the Loughborough University campus with small differences such as the fibre length and the size of the rubber infill particles.

1. 3rd generation multi-purpose long-pile artificial turf, sourced from a recent new-build facility at Loughborough University, named Holywell. A 25 mm rubber shockpad was used, with 60 mm monofilament polyethylene fibres, 15 kg/m² of sand and 15 kg/m² of rubber crumb. The majority of testing was completed using this surface system. The rubber infill was finer than the specification below (named as PEC surface throughout thesis, as per name on Loughborough University campus).

![Diagram of Holywell surface specification](image)

Figure 5.18: Diagram of Holywell surface specification.

2. 3rd Generation football/rugby long-pile artificial turf was used which was identical to the surface used on the PEC rubber crumb pitch on Loughborough University campus. A 25 mm rubber shockpad was used, with 65 mm monofilament polyethylene fibres, 20 kg/m² of sand and 12 kg/m² of rubber crumb.

![Diagram of PEC surface specification](image)

Figure 5.19: Diagram of PEC surface specification

A sample of any given specification was constructed by first cutting out a piece of carpet measuring the desired size, depending on whether rotational or translational traction was being tested. The volume of sand required was then weighed out and evenly placed in the carpet by hand two or three kg at a time. The infill height was regularly measured during this process to ensure the sand was level throughout. The level was checked using an infill
height gauge and measured in ~20 locations across the sample. Three measurements were taken in each position and an average was taken. This method was repeated with the rubber infill, and again the height was measured throughout to ensure a level surface. A piece of shockpad, of the correct specification, measuring the same size as the carpet was also cut out and placed beneath the carpet. The sample was then raked and rolled to the required number of rolls using the hand roller. The specification and method for the roller is stated in the FIFA handbook of test methods (2015). FIFA did state that it should be rolled between 50 and 250 times (FIFA, 2012), one roll being forwards and back on the same path, however this has more recently been changed to state that 50 rolls should be performed (FIFA, 2015). Any variance in number of rolls or volume of material is stated. It is important to keep the construction of the samples as consistent as possible so any variations in results are not due to the construction and omits that extra variable. This can be helped by only having one person constructing the samples and by ensuring the method is consistent throughout.

With the rotational traction testing (testing using a one by one metre sample), five tests were completed on each sample, moving the device to a fresh piece of turf for each trial, before being reconditioned for the next piece of testing. When using the translational traction device, three trials were completed on each sample, reconditioned between trials. With a new batch of testing, a new sample was constructed to ensure any changes that may have occurred in the material are replaced. After testing was completed, the measuring of the infill height was repeated.
5.5 Test methods

The following section outlines the methods for each specific set of testing with changing variables. It will be stated if the tests are completed on rotational device, translational device, or both. The testing has been split into shoe and surface properties.

5.5.1 Shoe properties

5.5.1.1 Change in stud type

Studs can be differentiated by length, surface area and material. The studs in Table 5.1 were chosen as they represent a range of lengths, cross-sectional areas and shape. It will be determined whether these affect the traction developed. It is hypothesised that the longer studs will penetrate the infill further, and this larger frontal area will cause a higher resistance.

Table 5.1: Stud dimensions and cross-sectional areas of studs tested. FB = football studs, R = rugby studs.

<table>
<thead>
<tr>
<th>Stud dimensions</th>
<th>D₁ (mm)</th>
<th>D₂ (mm)</th>
<th>L (mm)</th>
<th>Cross-sectional area of stud profile in frontal plane (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 mm FB</td>
<td>12</td>
<td>18</td>
<td>13</td>
<td>175.5</td>
</tr>
<tr>
<td>16 mm FB</td>
<td>12</td>
<td>18</td>
<td>13</td>
<td>211.5</td>
</tr>
<tr>
<td>15 mm R</td>
<td>6</td>
<td>20</td>
<td>15</td>
<td>195</td>
</tr>
<tr>
<td>18 mm R</td>
<td>9</td>
<td>20</td>
<td>18</td>
<td>261</td>
</tr>
<tr>
<td>21 mm R</td>
<td>7</td>
<td>20</td>
<td>21</td>
<td>283.5</td>
</tr>
</tbody>
</table>

5.5.1.2 Stud penetration

The translational traction device had a vertical displacement sensor added to be able to measure the displacement of the studs and stud plate into the infill. This allows the penetration and compression of the infill to be determined from the studs/stud plate. This has not been investigated in detail in the past. Severn (2010) and Clarke (2011) measured vertical displacement using one of their test devices, however there was a varying vertical force throughout the trials which made it unreliable. The vertical displacement was measured for all trials to determine any differences and whether any patterns emerged to
aid the understanding of the mechanisms. For example, the effect that differing normal loads have on the vertical penetration.

5.5.1.3 Number of studs/stud configuration

Regarding the rotational traction device, Severn (2010) looked at the number of studs and the distance from the centre of the circular disc on the rotational device as described in the literature review. For the testing in this study, the studded disc was kept consistent throughout with only the type of stud changing, as shown in the previous section. The translational traction device is designed to have an interchangeable attachment. One attachment is designed as a square stud plate to which nine studs may be attached.

Variation in stud configuration using translational device

This set of testing aimed to look at the effect of the studs relative to each other and the effect this had on the forces produced. A number of configurations were chosen, as shown below in Figure 5.20. Codes A-G were assigned for future reference. The front (F) and back (B) of the plate are also annotated, with the front (F) being equivalent to the ‘toe’ of a shoe and the back (B), the ‘heel’.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="circles.png" alt="" /></td>
<td><img src="circles.png" alt="" /></td>
<td><img src="circles.png" alt="" /></td>
<td><img src="circles.png" alt="" /></td>
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<td><img src="circles.png" alt="" /></td>
<td><img src="circles.png" alt="" /></td>
</tr>
</tbody>
</table>

Figure 5.20: Stud configurations A-G with filled circles showing the placement of the studs. F = front of plate, B = back of plate.

These configurations were chosen to represent a range of situations. Testing with only the stud plate and no studs was chosen to show the effect the stud plate alone has on the force, and consequently with the addition of studs it should be easier to identify any differences additional studs make. Studs were placed adjacent to each other in a number of positions so that when the studs were moving through the surface, it could be observed whether there was any difference between the studs being behind each other or parallel to each other.
This can also be repeated with two and three studs to observe how this affects the mechanism.

The testing was carried out on the Holywell surface (Section 5.4.1) with 200 completed rolls. The configurations were initially tested using 13 mm football studs, dimensions shown in Table 5.1. The football studs are constructed from plastic. This was then repeated with 21 mm rugby studs to represent an extreme situation in comparison to 13 mm football studs. The dimensions are also shown in Table 5.1. The rugby studs are constructed from aluminium and are likely to have different frictional properties to the plastic football studs. Both stud types were tested under a vertical load of 45 kg and 70 kg. These two normal forces were tested to identify whether this made a difference to the trends that were observed. 45 kg was chosen to mirror the normal load used on the rotational traction device. 70 kg was used to represent the average mass of a player. The forces developed were measured, along with the vertical displacement and the infill depth.

5.5.2 Standard setup for translational and rotational device

From the testing described above, it was decided that a standard setup should be chosen to complete the remaining testing on the translational and rotational traction devices. When testing on the translational device, 45 kg was chosen as the normal load as this is the same as the rotational traction device. Configuration E (Figure 5.20) was chosen as it is a simple configuration which gave a repeatable result and will allow for comparison between changes in variables. The chosen setup will always be stated when the method is outlined. The rotational device is set at a mass of 46 ± 2 kg which aims to represent half the body weight of a player. The mass is unable to be increased due to space constraints. The standard 13 mm football studs (Table 5.1) were also used throughout testing.

Velocity of the devices

With the translational traction device, the velocity of the tray depends on the velocity of the Instron uni-axial tensile machine. The maximum velocity possible is 0.0167 m·s⁻¹ (equivalent to 1000 mm/min). As part of the initial testing and troubleshooting, a range of velocities were tested to determine how the velocity affects the force produced (Section 5.3.3.4). This concluded that a velocity of 1000 mm/min was chosen for the completion of testing.
When using the rotational traction device, the FIFA guidelines state that the torque wrench should be rotated at 12 rev/min (equivalent to 72°/s). Section 5.2.3.2 investigates a range of velocities, with the FIFA recommended velocity chosen for the testing. With the added sensors this immediate feedback is available and the velocity can be identified after a trial to ensure it is the desired velocity, with the trial repeated if this velocity is not achieved.

5.5.4 Surface properties

The following section outlines testing completed with changing surface properties.

5.5.4.1 Rubber infill density

The literature review (Section 2.4.1.2) highlighted that density of the infill had an effect on the traction due to the compaction of the infill causing a higher resistance. Severn (2010) looked at the density of infill but limited it to a maximum of 200 rolls, or 0.55 g/cm³. Additionally, only a value for peak torque was output. A set of testing was designed to change the density of the infill by rolling the surface to represent different stages of compaction. These were 0, 50, 100, 200, 300 and 500 rolls. The FIFA standard did state (FIFA, 2012) that the surface should be rolled between 50 and 250 times, however has since been changed to recommend 50 rolls (FIFA, 2015). It is useful to test outside of this range to observe whether there is a threshold which is reached before the density has no effect. The samples were rolled using the hand pulled roller (FIFA, 2015) and it was ensured that a new sample was used for each density to ensure the properties of the infill were not affected by the previous test completed using the device.

**Rotational**

One by one metre of carpet was used when testing with the rotational traction device. The standard setup of 13 m football studs and 45 kg normal force were used. Five trials were performed for each level of compaction, ensuring that the trials were performed in different positions to avoid disturbance of the infill. Testing was completed on both surface specifications (Section 5.4.1 and Appendix A).

Testing was completed on an outdoor pitch of the same specification. Comparison was made between the field and lab results to determine whether the lab results were in the region of the results collected from the outdoor pitch.
13 mm football studs were used in configuration E with a normal load of 45 kg. The vertical displacement of the studs and infill depth will also be measured. This testing was only completed on the Holywell surface specification (Section 5.4.1 and Appendix A).

5.5.4.2 Change in number of carpet fibres
It has been reported that the carpet and infill work together to produce a resistive force. This is achieved by the fibres reinforcing the infill. To test this, and to test the effect the number of fibres have on both rotational and translational traction, a test was developed to omit fibres from the sample, keeping the infill and the other properties in the sample consistent. Previously, Severn (2010) looked at fibre density by testing three different sample specifications with varying number of fibres per sqm. However, this project aims to use the same specification of surface, cutting out the fibres by hand, allowing a controlled experiment by cutting a set number of fibre tufts. This will also provide a continuous set of data as opposed to only a value of peak torque.

The effect of the fibres was investigated to determine how the force/torque changes with the reduction of the fibres in the system. The infill was also isolated to further understand the forces produced and the mechanism of traction.

Four different carpet densities were used for testing. These included:
- The original carpet (tuft density of 8400 m²)
- Half density (tuft density of 4200 m²)
- Quarter density (tuft density of 2100 m²)
- Rubber crumb infill by itself (Sand by itself was also tested for interest).

Illustrations of these conditions are shown in Figure 5.21.
The carpet fibres were cut out at the bottom of the fibres, ensuring the numbers of fibres cut were consistent to ensure it was as close to the desired number as possible.

The piece of carpet used for testing measured 500 x 500 mm to fit the tray on the translational traction device; however the same piece was used for the rotational traction testing. The same specification of infill was used for each sample (Holywell sample – Section 5.4.1), with 15 kg/m² of sand and 15 kg/m² of rubber infill. It also included a 25 mm shockpad underneath the carpet. The surface was rolled 200 times to compact the infill and ensure consistent conditioning of the samples.

When isolating the infill for the rotational traction testing, a metre squared box was used to hold and confine the infill. With the sand only condition, 20 mm of sand was placed in the tray to ensure the bottom of the tray was not reached if full stud penetration was achieved. The sand was raked after every test and the height was measured to ensure a consistent surface. 10 mm of sand was then removed and 30 mm of rubber crumb added for the rubber infill condition. The infill was compacted evenly by foot. The standard roller could not be used to compact the infill due to the free flowing nature of the infill. With the
translational traction testing, the same method was used; however the infill was placed straight into the 500 x 500 mm tray attached to the rig.

5.5.5 Suspending studs in contact with infill

The translational traction device is able to move the central column, with the stud plate attached, vertically using the pneumatic actuators. These allow the stud plate to be set at any height while being suspended and without movement.

To determine the horizontal force produced when the studs were isolated in the infill, without the influence of the stud plate, the 13 mm football studs were placed 10 mm into the infill, with no normal load on the surface and a space between the bottom of the stud plate and the top of the surface. The tray was then translated 75 mm horizontally to measure the force.

5.6 Data analysis

5.6.1 Analysis of stiffness regions

During initial testing completed on the modified rotational traction device, two stiffness regions were identified as a result of the added sensors. When torque was plotted against rotational angle, the graphs typically illustrated an initial steep gradient (1), followed by a longer more gradual increase (2). The gradient for region one was identified from the start of movement (after the initial give in the torque wrench was taken into account), until the point where the gradient began to decrease. This was deemed as between 0 and 3°. Region two was taken as a larger section in the latter stages of the movement between 10 and 25°. These two regions can be seen in Figure 5.22.
These two regions were kept consistent throughout all analysis as the regions were seen on all trials and this would allow for comparison. The gradients were calculated using a polynomial curve fitting (function name: polyfit) in MATLAB (Version 7.10 R2010a). 

From the rotational testing, the translational testing was subsequently completed, with two similar stiffness regions identified on the force against displacement graphs. It was desirable that these regions would be similar/comparable to the regions found in the rotational traction analysis to allow for comparison in trends.

For region one (identified between 0 and 3°), this was calculated as lying between 0 and 2.42 mm when the displacement of the bottom of the rotational traction device was measured. This was found to be a very small displacement, and when looking at data collected from the translational traction device, five millimetres seemed more appropriate as it was an obvious initial steeper gradient and consistent amongst all tests. For region two, the angle between 10 and 25° was calculated as the equivalent of between 8.05 and 20.13 mm in terms of displacement. It was decided that between 10 and 25 mm would be more appropriate as a longer gradient is more desirable when completing a polynomial curve fitting. However, there is some validity in these regions as they are comparable. Figure 5.23 shows a typical graph with the two gradients highlighted.
Livesay et al. (2006) used a similar test device to the rotational traction device using the forefoot of a grass and turf shoe to complete preliminary testing and found two stiffness regions, which agrees with the two regions shown above. The first region was characterised by an initial steep increase in torque with applied rotation of the shoe (between 0 and 2º), with the second region being where there was a linear increase in torque with additional rotation (between 2 and 10º) before peak torque was reached. Although the first stiffness region is comparable, the second region was calculated by considering larger displacements/angles in this study, which may help inform the mechanism of traction.

**5.6.2 Vertical displacement on translational traction device**

Attached to the translational traction device is a vertical displacement sensor (as described in Section 5.3.2.2), measuring the vertical movement of the studs and stud plate into the surface. The vertical displacement sensor outputs displacement and time from LabView into Microsoft Excel for further analysis. This data was matched to the force data collected from the Instron which is shown in Figure 5.24.

At the end of the tray movement, the Instron was programmed to increase in speed for one second to provide a marker for data synchronisation. These points were matched to
calculate the point that the tray started to move. This point is not shown in Figure 5.24 as it was not visible on the graph without expanding the scale.

The top of the surface was measured using a calibration platform, as described in Section 5.3.2.3. The top of the surface was identified as 0. This 0 marker is shown as 0 on the Y axis.

Two values were calculated:
- The first being the distance that the studs moved into the surface as the actuators moved the stud plate and the mass downwards (A on Figure 5.24).
- The second value is the maximum distance that the studs moved into the surface as the tray moves (B on Figure 5.24).

As the studs were 13 mm long, this is shown on Figure 5.24 as the dotted line and highlights the full penetration of the studs. In the results shown in Chapter six, A and B have been normalised to zero. Figure 5.24 is a representative graph from all trials completed.

Figure 5.24 – Example graph showing a force and vertical displacement trial aligned to show the vertical displacement measurements.
Chapter five outlined the development of the mechanical test devices with the addition of sensors to the rotational traction device and the construction of the translational traction device. Troubleshooting of the devices was necessary, particularly with the translational traction device as the device had not been used previously. It allowed for replacements to be made and boundaries to be tested.

The test methods were outlined with changes in show and surface variables described. The setup of the mechanical devices were also outlined and justified. The analysis for both the stiffness regions and the vertical displacement sensor were detailed with the methods used for the remainder of the testing.

The following chapter shows the results for all the testing completed, as a result of the methods set out in this chapter.
CHAPTER SIX – RESULTS

This chapter documents the results collected from the two mechanical test devices previously discussed.

6.1 Change in stud type – rotational traction

The initial testing completed used the modified rotational traction device described in Section 5.2. This involved testing five different stud types including 13 and 16 mm football studs and 15, 18 and 21 mm rugby studs. The aim was to determine whether the differing stud types had an effect on the force and stiffness produced, and whether the stud geometry/cross-sectional area is an influencing factor.

Figure 6.1 shows a typical torque against rotation graph of a 13 mm football stud. The graph shows the initial build-up of resistance at the start of the movement (stiffness region one) followed by an increasing torque (stiffness region two) as the test disc continues to rotate until peak torque is reached, after which the resistance reduces.

![Figure 6.1](image)

Figure 6.1: A typical torque against rotation graph using the rotational traction device with 13 mm football studs at a rotational velocity of 12 rev/min.

The stud dimensions and cross-sectional area for the five stud designs are shown in Table 6.1 below. This shows the increasing cross-sectional area with increase in stud length within stud types. It is also worth mentioning the materials of the two studs, with the rugby studs constructed from aluminium and the football studs constructed from plastic.
Table 6.1: Stud dimensions for the five chosen stud types. FB = Football, R = Rugby.

<table>
<thead>
<tr>
<th>Stud dimensions</th>
<th>D₁ (mm)</th>
<th>D₂ (mm)</th>
<th>L (mm)</th>
<th>Cross-sectional area of stud profile in frontal plane (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 mm FB</td>
<td>12</td>
<td>18</td>
<td>13</td>
<td>175.5</td>
</tr>
<tr>
<td>16 mm FB</td>
<td>12</td>
<td>18</td>
<td>16</td>
<td>211.5</td>
</tr>
<tr>
<td>15 mm R</td>
<td>6</td>
<td>20</td>
<td>15</td>
<td>195</td>
</tr>
<tr>
<td>18 mm R</td>
<td>9</td>
<td>20</td>
<td>18</td>
<td>261</td>
</tr>
<tr>
<td>21 mm R</td>
<td>7</td>
<td>20</td>
<td>21</td>
<td>283.5</td>
</tr>
</tbody>
</table>

Figure 6.2 shows the peak torque and the angle that peak torque was reached at against the cross-sectional area when using the rotational traction device. It is apparent that within stud types (football and rugby), the peak torque increases with an increase in cross-sectional area. When combining stud types (as in Figure 6.2), the cross-sectional area does not have an effect on the peak torque or angle of peak torque with no clear pattern observed. The only significant difference ($p \leq 0.05$) was between 195 and $211$ m² (15 mm rugby stud and 16 mm football stud) and 195 and $283.5$ m² (15 mm rugby stud and 21 mm rugby stud) for peak torque results. No significant differences ($p \leq 0.05$) were found between values for the angle that peak torque was reached at.

**Figure 6.2**: Peak torque and angle of peak torque over the five stud types (Mean ± for five repeated tests). Statistical significance is shown where * indicates $p \leq 0.05$. Solid bars = rugby studs, dashed bars = football studs.
Figure 6.3 shows the stiffness values for regions one and two with an increase in stud cross-sectional area. Stiffness region one observes a general trend of increasing stiffness with an increase in cross-sectional area. This is clearer when observing the two lengths of football studs. However, no significant differences (p ≤ 0.05) were found between the five stud types. Stiffness region two saw no increase in stiffness with an increase in the cross-sectional area.

![Graph showing stiffness values](image)

Figure 6.3: Rotational stiffness values for the two regions; the start of movement (stiffness 1), and further through the movement (stiffness 2), as indicated in Figure 5.22, for each stud design (Mean ± SD over five test positions). Solid bars = rugby studs, dashed bars = football studs.

**Infill height**

Table 6.2 below shows the infill height measured for each surface sample used, after the surface was rolled 200 times. A different sample was constructed for each stud type and infill height was measured at five different positions. The infill height for each set of testing was consistent with heights of between 35.0 and 36.1 mm indicating good consistency in the surface samples used.
Table 6.2: Infill height over the five samples used in testing (Mean ± SD). The infill height was measured in five positions on each sample.

<table>
<thead>
<tr>
<th>Infill height (mm)</th>
<th>13 mm FB</th>
<th>16 mm FB</th>
<th>15 mm R</th>
<th>18 mm R</th>
<th>21 mm R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36.1</td>
<td>36.0</td>
<td>35.3</td>
<td>35.7</td>
<td>35.0</td>
</tr>
<tr>
<td>SD (mm)</td>
<td>0.6</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

6.2 Change in stud configuration using the translational traction device under different conditions

As described in Section 5.4.1.2, using the developed translational traction device, a set of testing was designed to investigate the effect of changing stud configuration on the forces and stiffness values produced. Seven different stud configurations were investigated under four testing conditions of varying stud length and normal load. The first section documents the results found with the standard setup using a normal load of 45 kg and 13 mm football studs. Subsequently, the normal load was increased to 70 kg with the same 13 mm football studs. The final two testing conditions were with 21 mm rugby studs, under the two normal loads of 45 and 70 kg. The results show the force produced for each configuration, the stiffness values calculated and the vertical displacement of the studs and stud plate into the infill.

6.2.1 45 kg normal load and 13 mm football studs

The first testing condition was completed using 13 mm football studs and a normal load of 45 kg on the translational traction device. Figure 6.4 shows the results with an increase in studs parallel to the front of the stud plate. Alternatively, Figure 6.5 shows the results with an increase in studs perpendicular to the front of the stud plate. Both figures include the results with the stud plate (A) and the results from one stud (B) and four studs (G). The initial vertical penetration of the stud plate is shown in Figure 6.7. The two stiffness regions, calculated from the rate that force was developed (Section 5.5.1), are illustrated in Figure 6.8.
The results with no studs attached to the stud plate (A) show that there is a resistance produced by the stud plate on its own. The force increases to a peak of ~310 N at ~40 mm before levelling out. With the addition of one stud (B), after ~8-9 mm, a consistently higher force of ~50 N between 15 – 40 mm is produced compared to no studs, however the force continues to increase to ~440 N, unlike the results with no studs where the force stabilised. Configurations C and D use two and three studs parallel to the front of the stud plate, respectively. As expected, the maximum force produced with two studs is higher than one, with configuration D (three studs) higher again, represented in Figure 6.6 with the maximum force values. Configuration C follows a similar pattern to B with the continued increase in force, however produces a higher force, up to ~540 N. With configuration D, the force continues to increase gradually until ~60 mm at 630 N where the force reduces.

Configurations E and F use two and three studs perpendicular to the front of the stud plate, respectively (Figure 6.5). Configuration E reaches a peak at ~45 mm, before the force reduces, and then increases further after ~55 mm. This decrease in force may be due to the stud behind reaching the path of the preceding stud. For configuration F, a peak is reached at ~40 mm with ~510 N, before levelling out for ~15 mm then reducing in force. As with E, the reduction in force is hypothesised to be due to the studs being directly behind one another; therefore they reach the path of the stud in front, where the infill has been cleared. Unlike E (with two studs), the force does not increase again which may be due to the extra stud, causing more of the infill to disperse.

The final stud configuration (G) tested was using four studs (two by two). The force increases to ~470 N before flattening out at ~30 mm for 25 mm, before increasing again.
Figure 6.4: Force against displacement for illustrated stud configurations with an increase in the number of studs parallel to the front of the stud plate under 45 kg of mass with 13 mm football studs.

Figure 6.5: Force against displacement for illustrated stud configurations with an increase in the number of studs perpendicular to the front of the stud plate under 45 kg of mass with 13 mm football studs.
Figure 6.6 shows the average maximum force found for the stud configurations along with the displacements that the maximum force were reached at. It shows that with an increase in the number of studs parallel to the front of the stud plate, the maximum force increases further compared to the studs perpendicular to the stud plate i.e. configurations C and D compared to E and F. Significances for the maximum force are shown in Table 6.3 with significances for the displacement of peak force shown in Figure 6.6. The displacements of maximum force varied between configurations.

![Diagram of stud configurations and force-displacement data](image-url)

Figure 6.6: Maximum force and displacement of maximum force over the seven stud configurations. Statistical significance is shown for displacements of maximum force where * indicates $p \leq 0.05$. 
Table 6.3: Significant differences for maximum force from Figure 6.6.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B, C, D, E, F, G</td>
</tr>
<tr>
<td>B</td>
<td>A, C, D, G</td>
</tr>
<tr>
<td>C</td>
<td>A, B, D, E</td>
</tr>
<tr>
<td>D</td>
<td>A, B, C, E, F</td>
</tr>
<tr>
<td>E</td>
<td>A, C, D, F, G</td>
</tr>
<tr>
<td>F</td>
<td>A, D, E</td>
</tr>
<tr>
<td>G</td>
<td>A, B, E</td>
</tr>
</tbody>
</table>

Figure 6.7 shows the vertical penetration of the infill under the loaded stud plate prior to translation. The length of the stud has been subtracted as they fully penetrated the surface. The data shows the displacement of the stud plate with zero on the y axis being the top of the infill, measured before every trial, as described in Section 5.3.3.2. The results show that when no studs were present (A), the plate penetrated furthest into the infill. The pattern then shows that as the number of studs increased, the plate did not penetrate as far, which may be due to the increased surface area. However, stud configuration G, with four studs was the exception as this moved between 1.25 and 1.35 mm into the infill. It is worth noting the stud plate only penetrated to a maximum displacement of 1.60 mm.

These displacements are likely to affect the force produced by the studs and stud plate as translation is occurring due to the higher resistance caused by the stud plate and the effect on the compression of infill around the studs/stud plate. The vertical penetration of the stud plate as the translation occurred was also measured, however the displacements were found to be very small at ~ 0.5 mm.
Figure 6.7: Vertical compression of the infill under the loaded stud plate prior to translation. 0 indicates the top of the infill prior to loading. Significant differences are shown where $p \leq 0.05$.

Table 6.4: Significant differences for vertical compression results from Figure 6.7.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significant ($p &lt; 0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D, E, F</td>
</tr>
<tr>
<td>B</td>
<td>D, E, F</td>
</tr>
<tr>
<td>C</td>
<td>None</td>
</tr>
<tr>
<td>D</td>
<td>A, B</td>
</tr>
<tr>
<td>E</td>
<td>A, B</td>
</tr>
<tr>
<td>F</td>
<td>A, B</td>
</tr>
<tr>
<td>G</td>
<td>None</td>
</tr>
</tbody>
</table>

Figure 6.8 shows the two stiffness region values identified in Section 5.5.1. Stiffness one shows the similarities between stud configurations. This indicates that the number of studs and the stud orientation has little effect on this initial stiffness as no significant differences were found.
Stiffness two indicates that the different stud configurations do have an effect on the stiffness produced. The results show that the number of studs has more of an effect than the stud orientation. This can be seen by looking at the similarities in configuration C and E (both two studs) and configurations D and G (three studs). It is also worth identifying that the configuration with four studs (G) produces the highest stiffness two value, with configuration A (no studs) producing the lowest. This indicates that the number of studs, and therefore the cross-sectional area of the studs is a key influence on this region between 10 and 25 mm. However the standard deviations should be acknowledged. Significant differences between the configurations for stiffness two are shown in Table 6.5.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
</table>

![Graph](image_url)

Figure 6.8: Results from stiffness region one and two over the seven stud configurations.
Table 6.5: Significances for stiffness region two from Figure 6.8.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D, F, G</td>
</tr>
<tr>
<td>B</td>
<td>D, F, G</td>
</tr>
<tr>
<td>C</td>
<td>G</td>
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<tr>
<td>D</td>
<td>A, B</td>
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<td>E</td>
<td>G</td>
</tr>
<tr>
<td>F</td>
<td>A, B</td>
</tr>
<tr>
<td>G</td>
<td>A, B, C, E</td>
</tr>
</tbody>
</table>

6.2.2 70 kg normal load and 13 mm football studs

Following on from the 45 kg normal load, it was subsequently increased to 70 kg to see the effect this normal load had on the force produced. The testing was repeated with the 13 mm football studs over the seven stud configurations.

Figure 6.9 shows the results with an increase in studs parallel to the front of the stud plate with Figure 6.10 showing the results with an increase in studs perpendicular to the front of the stud plate. Both figures include the results with only the stud plate (A) and the results from one stud (B) and four studs (G).

With the increase in normal load, the results show a difference in the patterns of force produced compared to 45 kg. All stud configurations followed a similar pattern of gradually increasing in force, before reaching a peak and subsequently reducing in force. When comparing this to the 45 kg normal load results, they had more variable trials with changing configurations.

Configuration A shows a higher force produced compared to 45 kg, due to the higher normal load and the higher stud plate vertical displacement into the infill (3.70 mm compared to 1.60 mm). A higher force is seen to be produced when the studs were parallel to the front of the stud plate compared to the studs perpendicular to the stud plate, for example, comparing C to E (two studs). Similar to the 45 kg condition, stud configuration D produced the highest force.
Figure 6.9: Force against displacement for illustrated stud configurations with an increase in the number of studs parallel to the front of the stud plate under 70 kg of mass with 13 mm football studs.

Figure 6.10: Force against displacement for illustrated stud configurations with an increase in the number of studs perpendicular to the front of the stud plate under 70 kg of mass with 13 mm football studs.
Figure 6.11 shows the maximum force for each configuration along with the displacement of maximum force. It highlights the highest force developed being configuration D. The displacements that the maximum forces were reached at were similar, with no significant differences found. The significant differences for maximum force are shown in Table 6.6.

When comparing the peak forces produced, the forces under 70 kg were much higher than 45 kg, however a similar pattern was followed with an increase in force with the number of studs. A higher force was also produced when the studs were parallel to the front of the stud plate compared to the studs perpendicular to the stud plate. The results show that stud orientation had more of an effect on the maximum force, compared to the number of studs.
Table 6.6: Significant differences for results of maximum force from Figure 6.11.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significance (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B,C,D,E,F,G</td>
</tr>
<tr>
<td>B</td>
<td>A,D,G</td>
</tr>
<tr>
<td>C</td>
<td>A,D</td>
</tr>
<tr>
<td>D</td>
<td>A,B,C,E,F,G</td>
</tr>
<tr>
<td>E</td>
<td>A,D,G</td>
</tr>
<tr>
<td>F</td>
<td>A,D</td>
</tr>
<tr>
<td>G</td>
<td>A,B,D,E</td>
</tr>
</tbody>
</table>

Figure 6.12 shows the vertical compression of the infill under the loaded stud plate prior to translation. It shows that the studs have fully penetrated the infill (with 0 indicating this), and the stud plate also displacing the infill. The displacement was approximately two millimetres further into the infill than the 45 kg normal load, causing compression of the infill and contributing to the higher forces when translation occurs. No significant differences (p ≤ 0.05) were found between stud configurations with similar results observed. These similar results suggest that the number of studs and stud orientation may not contribute to a variation in the vertical displacement of the stud plate.

Figure 6.12: Vertical displacement of the infill under the loaded stud plate prior to translation. Zero indicates the top of the infill prior to loading.
Figure 6.13 shows the values for the two stiffness regions. Stiffness one shows the similarities between stud configurations. A significant difference was found between stud configuration A and F, with all other stud configurations producing no significant differences. The values produced were higher than with the normal load of 45 kg (Figure 6.8) which shows that normal load does have an effect on the initial movement.

Table 6.7 show the significant differences over stud configurations for stiffness value two. It suggests that a higher number of studs (two or more) produce similar stiffness values for the displacement between 10 and 25 mm, with stud orientation having no effect. The stud configuration with no studs (A) or one stud (B) produced lower values in stiffness region two, which suggests having a lower number of studs produces less force.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
</table>

![Stiffness Diagram](image)

Figure 6.13: Results from stiffness regions one and two over the seven stud configurations. Statistical significance is shown where * indicates p ≤ 0.05
Table 6.7: Significant differences for stiffness region two results from Figure 6.13.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significance (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B,C,D,E,F,G</td>
</tr>
<tr>
<td>B</td>
<td>A,D,F,G</td>
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<tr>
<td>C</td>
<td>A</td>
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<td>D</td>
<td>A,B</td>
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<td>E</td>
<td>A</td>
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<tr>
<td>F</td>
<td>A,B</td>
</tr>
<tr>
<td>G</td>
<td>A,B</td>
</tr>
</tbody>
</table>

6.2.3 45 kg normal load and 21 mm rugby studs

The testing was repeated with 21 mm rugby studs to determine how a higher cross sectional area will affect the force produced with changing stud configurations. This was completed with the same vertical normal load of 45 kg.

Figure 6.14 shows the results with an increase in studs parallel to the front of the stud plate with Figure 6.15 showing the results with an increase in studs perpendicular to the front of the stud plate. Both figures include the results with only the stud plate (A) and the results from one stud (B) and four studs (G).

As with Section 6.2.1, configuration A (no studs) gave a similar result with a peak force reached at ~ 340 N at ~45 mm before the force levelled out. Similar to the results with 13 mm studs, the force produced with stud configuration B continued to gradually increase, however a maximum was reached at approximately 60 mm before stabilising. This suggests that no further resistance is being developed from the infill and fibres, with the stud and stud plate shearing through the infill. The force produced was larger than testing with 13 mm football studs under the same normal load due to a higher cross-sectional area being in contact with the infill, causing a higher resistance.

Stud configurations C and D also had a gradual increase in force, but peaked before reducing in force. D produced the highest force, similar to the results from 13 mm football studs. The two stud configurations peaked at ~ 60 mm whereas three studs peaked at ~ 68 mm. This may be due to the infill failing earlier with the lower number of studs. Both configurations moved further into the infill than with the 13 mm football studs which will have contributed to the higher force produced.
Stud configuration E continued to increase in force before reaching 50 mm at 700 N and reducing in force and stabilising at 480 N. Similarly, configuration F increased in force before stabilising at 50 mm and staying consistent at 680 N. The forces produced were higher than the forces produced with the 13 mm studs. Stud configuration E was similar to 13 mm with a peak being reached, however was later in the displacement. It is hypothesised that this could be due to the stud reaching the path of the proceeding stud. Configuration F had an extra stud which may cause more of the infill to disperse, suggesting that there is more room for the studs and stud plate to move with added resistance coming from the infill or the fibres, hence why the force stabilises.

The force developed with stud configuration G (four studs) continued to increase after a displacement of 30 mm, however the gradient varied as the stud plate moved through the infill (Figure 6.14).
Figure 6.14: Force against displacement for illustrated stud configurations with an increase in the number of studs parallel to the front of the stud plate under 45 kg of mass with 21 mm rugby studs.

Figure 6.15: Force against displacement for illustrated stud configurations with an increase in the number of studs perpendicular to the front of the stud plate under 45 kg of mass with 21 mm rugby studs.
Figure 6.16 shows the average maximum force produced from each stud configuration along with the displacement that the maximum force was reached at. It shows the increase in the peak force with an increase in the number of studs. The force was highest for the studs parallel to the front of the stud plate, when compared to the studs perpendicular to the front of the stud plate. As illustrated before, in Figures 6.14 and 6.15, the maximum force with the 21 mm studs (Figure 6.16) was higher than the maximum force produced by the 13 mm studs due to the higher contact area of the 21 mm studs. The significant differences for the maximum forces are shown in Table 6.8 with the significant differences for displacement of maximum force shown in Figure 6.16.

<table>
<thead>
<tr>
<th>Stud configuration</th>
<th>Maximum force (N)</th>
<th>Displacement of maximum force (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
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<tr>
<td>C</td>
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<td>D</td>
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<td></td>
<td></td>
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<tr>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.16: Maximum force and displacement of maximum force over the seven stud configurations. Statistical significance is shown for displacements of maximum force where * indicates $p \leq 0.05$. 
Table 6.8: Significant differences for maximum force results from Figure 6.16.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B, C, D, E, F, G</td>
</tr>
<tr>
<td>B</td>
<td>A, C, D, F, G</td>
</tr>
<tr>
<td>C</td>
<td>A, B, D, E, F, G</td>
</tr>
<tr>
<td>D</td>
<td>A, B, C, E, F, G</td>
</tr>
<tr>
<td>E</td>
<td>A, C, D, G</td>
</tr>
<tr>
<td>F</td>
<td>A, B, C, D, G</td>
</tr>
<tr>
<td>G</td>
<td>A, B, C, E, F</td>
</tr>
</tbody>
</table>

Figure 6.17 shows the vertical compression of the infill under the loaded stud plate prior to translation. It shows that the studs have fully penetrated the infill, with the stud plate also displacing the infill a variable amount. Stud configurations A, B, D and G show a similar displacement to 13 mm, with C, E and F displacing the infill further. There were no significant differences found between stud configurations, showing that with the longer studs, the number of studs or orientation had no effect. This indicates that a change in the number of studs and the orientation of the studs did not contribute to a variation in the displacement of the stud plate.
The two stiffness values are shown in Figure 6.18. As with the 13 mm studs, the stiffness one values are comparable. However, significant differences (Table 6.9) show that configuration G is significantly different to configuration A, B, E and F which suggests the higher number of studs had an effect on the initial resistance to movement. The values for stiffness two are higher with the 21 mm studs compared to 13 mm studs under the same normal load. This shows that the stud length does have an effect on the stiffness being developed between 10 and 25 mm. This is due to a larger cross-sectional area being in contact with the infill, causing a higher resistance as they plough through. Similar to the 13 mm football studs, the results appear to show that the number of studs have more of an effect than the stud orientation.
Figure 6.18: Results from stiffness region one and two over the seven stud configurations.

Table 6.9: Significant differences for stiffness one and two results from Figure 6.18.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Stiffness 1 Significant (p &lt; 0.05)</th>
<th>Stiffness 2 Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>G</td>
<td>C,D,E,F,G</td>
</tr>
<tr>
<td>B</td>
<td>G</td>
<td>D,F,G</td>
</tr>
<tr>
<td>C</td>
<td>None</td>
<td>A,D</td>
</tr>
<tr>
<td>D</td>
<td>None</td>
<td>A,B,C,E</td>
</tr>
<tr>
<td>E</td>
<td>G</td>
<td>A,D</td>
</tr>
<tr>
<td>F</td>
<td>G</td>
<td>A,B</td>
</tr>
<tr>
<td>G</td>
<td>A,B,E,F</td>
<td>A,B</td>
</tr>
</tbody>
</table>
6.2.4 70 kg normal load and 21 mm rugby studs

The final set of testing involved using the same 21 mm rugby studs, but with the increased normal load of 70 kg. Figure 6.19 shows the results with an increase in studs parallel to the front of the stud plate with Figure 6.20 showing the results with an increase in studs perpendicular to the front of the stud plate. Both figures include the results with only the stud plate (A) and the results from one stud (B) and four studs (G). As expected, this condition produced the highest force. The force developed with stud configuration B continued to increase throughout the translational movement, at a lower rate than the other configurations due to the lower number of studs. Stud consideration C, D and G all continued to increase in force throughout the movement as seen in Figure 6.19. This shows that the resistance is building as the studs plough through the infill compacting and compressing the rubber infill. No peak was reached which may be due to the infill and fibre zone not failing over the 75 mm distance shown. Figure 6.20 shows the similarities in configuration E and F with a peak reached at around 65 mm before reducing in force. This shows that with the configurations perpendicular to the front of the stud plate, the infill and fibre zone in front of the studs are failing.
Figure 6.19: Force against displacement for illustrated stud configurations with an increase in the number of studs parallel to the front of the stud plate under 70 kg of mass with 21 mm rugby studs.

Figure 6.20: Force against displacement for illustrated stud configurations with an increase in the number of studs perpendicular to the front of the stud plate under 70 kg of mass with 21 mm rugby studs.
Figure 6.21 shows the maximum force and displacement of maximum force. Table 6.10 highlights the significant differences found for both variables. A similar pattern is achieved with the peak force, where the increase in the number of studs produces a higher peak force. However there is less variation between the orientations of the studs, with no significant differences found for two or more studs. The peak forces are developed much later on in the displacement of the tray compared to the lower normal loads. This suggests that under a higher load, the infill and fibre zone in front of the studs take longer to fail.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Stud Configuration A" /></td>
<td><img src="image2" alt="Stud Configuration B" /></td>
<td><img src="image3" alt="Stud Configuration C" /></td>
<td><img src="image4" alt="Stud Configuration D" /></td>
<td><img src="image5" alt="Stud Configuration E" /></td>
<td><img src="image6" alt="Stud Configuration F" /></td>
<td><img src="image7" alt="Stud Configuration G" /></td>
</tr>
</tbody>
</table>

![Graph](image8)

**Figure 6.21:** Maximum force and displacement of maximum force over the seven stud configurations.
Table 6.10: Significant differences for both maximum force and displacement of maximum force results from Figure 6.21.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Maximum force Significance (p &lt; 0.05)</th>
<th>Displacement of maximum force Significance (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B, C, D, E, F, G</td>
<td>B, C, D, E, F, G</td>
</tr>
<tr>
<td>B</td>
<td>A, C, D, G</td>
<td>A, E</td>
</tr>
<tr>
<td>C</td>
<td>A, B</td>
<td>A, E</td>
</tr>
<tr>
<td>D</td>
<td>A, B</td>
<td>A, E, F</td>
</tr>
<tr>
<td>E</td>
<td>A</td>
<td>A, B, C, D, G</td>
</tr>
<tr>
<td>F</td>
<td>A</td>
<td>A, D</td>
</tr>
<tr>
<td>G</td>
<td>A, B</td>
<td>A, E</td>
</tr>
</tbody>
</table>

Figure 6.22 shows the vertical compression of the infill under the loaded stud plate prior to translation. It shows that the studs have fully penetrated the infill, with the stud plate also displacing the infill.

The displacements were comparable, with no significant differences between stud configurations. The stud plate displaced the infill a comparable amount to the 13 mm football studs under 70 kg. This shows that the number of studs and stud orientation had no effect on the displacement of the stud plate. The normal load placed through the mechanical device had the obvious effect on the displacement of the studs and stud plate.
Figure 6.22: Vertical displacement of the infill under the loaded stud plate prior to translation over the seven stud configurations. 0 indicates the top of the infill prior to loading.

Figure 6.23 shows the two stiffness values. The first stiffness region showed no significant differences between stud configurations, suggesting that the number of studs and stud orientation had no effect on the initial movement. They were also seen to be comparable to the 13 mm studs under the same normal load. This shows that, similar to 45 kg, no significant differences were found between stud types, indicating that the stud length had no effect on the initial movement.

Figure 6.23 shows the stiffness values for the second region. The values are higher than all previous conditions tested. This corresponds with the hypothesis that both longer studs and higher normal load produce a higher force due to both the larger cross-sectional area in contact with the infill, and the higher displacement of the stud plate into the surface, causing higher compression under the stud plate. Table 6.11 show the significant differences over stud configurations. It suggests that a higher number of studs (two or
more) produce similar stiffness values for the displacement between 10 and 25 mm, with stud orientation having no effect.

Table 6.1: Significant differences over the stiffness two region results from Figure 6.23.

<table>
<thead>
<tr>
<th>Stud Configuration</th>
<th>Significance (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B,C,D,E,F,G</td>
</tr>
<tr>
<td>B</td>
<td>A,D,F,G</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>A,B</td>
</tr>
<tr>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>F</td>
<td>A,B</td>
</tr>
<tr>
<td>G</td>
<td>A,B</td>
</tr>
</tbody>
</table>
6.3 Density of infill

6.3.1 Translational testing (Holywell)

The density of the infill was increased to investigate the effect it has on the force and stiffness produced. The surface was rolled to a set number, before the infill height was measured to determine the rubber infill net bulk density (Section 2.4.1.2). 13 mm football studs were used in stud configuration E, using the translational traction device. The specification of the pitch can be seen in Appendix A.

Figure 6.24 shows the number of rolls performed (see Section 5.4.1), with the corresponding rubber infill net bulk density and the air void percentage. It shows the increase in net bulk density and the decrease in air void percentage with an increase in the number of rolls on the surface, as the particles become more packed.

![Graph showing rubber infill net bulk density and air void percentage against the number of rolls completed on the surface samples.](image)

Figure 6.25 shows the horizontal force produced for the six different infill net bulk density surfaces tested using the translational traction device.

A similar pattern for all densities is seen where the force increases before a peak is reached, reducing in force, then increasing again. This is with the exception of the lowest density, where the force continued to increase until ~ 70 mm, where it plateaued. The results show that, in general, a higher force was produced with lower infill densities, particularly when
looking at the initial peak reached between 37 and 48 mm. All densities showed a similar force produced up to 30 mm, with the exception of the lowest density (0.42 g/cm$^3$) which showed a lower force produced.

Figure 6.25: Horizontal force produced over six surface densities using the translational traction device.

Figure 6.26 shows the peak force and displacement of peak force with an increase in the rubber infill net bulk density. The peak force represents the first peak that is reached. It shows a general trend of decreasing peak force with an increase in density, which corresponds to Figure 6.25 above. As the density is increased, the peak force was reached sooner and it is hypothesised that with the lowest density, this is due to the force continued to increase due to how loose the infill was. This is discussed in Chapter seven.
Figure 6.27 shows the vertical compression and compaction of the infill under the loaded stud plate prior to translation, assuming full penetration of the studs. It also shows the maximum vertical compression as translation of the stud plate occurs. The stud plate compressed the infill furthest (Figure 6.27) with the lowest density infill condition, which may contribute to the higher force produced. This high displacement is due to the higher number of air voids, allowing the studs to fully penetrate the infill and the stud plate to move a further ~3.5 mm into the infill. The higher number of air voids allows for more compression of the infill and penetration under the normal load. The stud plate penetrated the infill less with 0.48 g/cm$^3$ than with the lowest density (0.42 g/cm$^3$) but more than the other four densities which showed values of similar displacements. Once translation of the stud plate was occurring, the lowest infill density (0.42 g/cm$^3$) displaced the most infill with a further displacement of two millimetres. With the higher densities, the stud plate displaced the infill a similar distance. This may also contribute to the higher force produced by 0.42 g/cm$^3$ condition.
Figure 6.27: Vertical displacement of the infill under the loaded stud plate prior to translation (Blue), and as the stud plate moves through the infill (Red).

Figure 6.28 shows the two stiffness region values for the increasing rubber infill net bulk density. At the lowest net bulk density of rubber infill (0.42 g/cm$^3$), the stiffness one value was significantly lower than the higher densities. There was a small increase in the stiffness values with increasing density, however there were no significant differences found. This suggests that other than the lowest density, the rubber infill net bulk density has no effect on the initial resistance to movement.

The second stiffness region shows the comparability between the values, with no significant differences found. This is evident with the similar gradients between 10 and 25 mm in Figure 6.25, with the rubber infill net bulk density having no effect on the rate that force was produced.
6.3.2 Rotational traction testing (Holywell)

Subsequent to the translational traction device, the testing was repeated using the rotational traction device. Figure 6.29 shows the torque developed over the six different rubber infill net bulk densities. The net bulk densities calculated were the same as the testing completed in Section 6.3.1 due to the samples being constructed with identical methods and specifications.

The results show that there is no clear pattern with the torque produced when the density increases. With all densities tested, the torque increased before a peak torque was reached, with the torque subsequently decreasing. Figure 6.29 only shows one trial from each infill density tested, however, the mean and standard deviations are shown in the results following Figure 6.29.
Figure 6.29: Torque developed using 13 mm football studs over a range of surface densities on the Holywell surface using the rotational traction device at a rotational velocity of 12 rev/min.

Figure 6.30 show the average peak torque and the average angle of peak torque. The peak torque shows a small increase as the rubber infill net bulk density increases. However, the angle of peak torque gives variable results with no clear trend. The high standard deviations show that the results were inconsistent across the five repeat trials for each net bulk density.
Figure 6.30: Peak Torque and angle of peak torque over an increase in rubber infill net bulk densities (Mean ± SD over five repeat trials).

Figure 6.31 shows the average stiffness values over the two regions as the rubber infill net bulk density increased. Significant differences are shown in Table 6.11. Stiffness one increases with an increase in net bulk density, particularly when comparing the first and last densities. Stiffness two shows a small increase with net bulk density.
Figure 6.31: Stiffness over the two stiffness regions with an increase in rubber infill net bulk density using the rotational traction device (Mean ± SD over five repeat trials).

Table 6.12: Significant differences from stiffness region one and two results from Figure 6.31.

<table>
<thead>
<tr>
<th>Rubber infill net bulk density (g/cm³)</th>
<th>Stiffness 1 Significant (p &lt; 0.05)</th>
<th>Stiffness 2 Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.42</td>
<td>3, 4, 5, 6</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>4, 6</td>
</tr>
<tr>
<td>3</td>
<td>0.49</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.51</td>
<td>1, 2</td>
</tr>
<tr>
<td>5</td>
<td>0.52</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0.58</td>
<td>1, 2</td>
</tr>
</tbody>
</table>
Field testing comparison (Holywell)

The results below show three sets of testing over different periods of time on an outdoor pitch with the same specification as the Holywell surface. The first was just after it was laid, before it had been played on (November 2014 - A), the second was four months later (March 2015 - B), with the third being a year later to monitor the changes (April 2016 - C). The results show the testing completed on six positions across the pitch, taken as the FIFA positions (FIFA, 2015).

Figure 6.32 shows the peak torque values over the six positions across the three testing periods. It shows the varying results over the space of 17 months with a range of 10 Nm. When comparing it to Figure 6.30 which had the same specification with varying rubber infill densities, the peak torque values were in the region of the higher density surfaces.

Figure 6.32: Peak torque values for three sets of testing over six FIFA positions, tested on the outdoor Holywell pitch using the rotational traction device.

Figure 6.33 shows the two stiffness values over the three testing sessions completed. It shows the range in values across the different time periods, as found with the peak torque values. When comparing the results to Figure 6.31, similar to peak torque, the results were
in the region of the higher density surfaces. This suggests that the infill on the outdoor pitch has been compacted with use.

Figure 6.33: Stiffness regions one and two (initial region and later region) for three sets of testing over six FIFA positions, tested on the outdoor Holywell pitch using the rotational traction device.
6.3.3 Rotational traction testing (PEC)

The above testing was also repeated on a second surface specification (Appendix A). The same method was repeated with a varying number of rolls completed, with the method for the roller shown in Section 5.4.1. Figure 6.34 shows the number of rolls performed, with the corresponding rubber infill net bulk density and the air void percentage. It shows the increase in net bulk density and the decrease in air void percentage with an increase in the number of rolls on the surface, the same pattern as with the other surface specification.

![Figure 6.34: Rubber infill net bulk density and air void percentage over an increasing number of rolls using the PEC surface.](image)

Figure 6.35 shows the torque developed with an increasing rubber infill net bulk density. There is a clear distinction between the lowest and highest densities, compared to the densities in between. The densities between 0.40 and 0.49 g/cm³ show a similar torque produced. It is worth noting that there are two values showing 0.49 g/cm³ have been rounded with the highest density (solid black line) having the highest density.
Figure 6.35: Torque developed using 13 mm football studs over a range of surface densities on the PEC surface using the rotational traction device at a rotational velocity of 12 rev/min.

Figure 6.36 shows the peak torque and angle of peak torque over the varying rubber infill net bulk densities. It shows the increase in peak torque with the increase in the rubber infill density, as well as clearly showing a decrease in the angle of peak torque. This is similar to the results produced by the translational tester for angle of peak torque (Section 6.3.1). It is hypothesised that as the infill density increases the resistance is building up quicker and the infill/fibre zone in front of the studs is failing quicker, hence the peak force been reached sooner with a higher density.
Figure 6.36: Peak torque and angle of peak torque over increasing rubber infill net bulk densities (Mean ± SD over five repeat trials).

Figure 6.37 shows the average stiffness over the two regions. Stiffness one shows a similar magnitude of values, other than the highest density, although the standard deviation is high. Stiffness two increases gradually with an increase in rubber infill net bulk density.

Figure 6.37: Average stiffness over stiffness regions one and two with an increasing rubber infill net bulk density using the rotational traction device (Mean ± SD over five repeat trials).
The following two figures, 6.38 and 6.39 compare results from the two surface specifications for the rotational traction testing. Figure 6.38 shows the peak torque against the rubber infill net bulk density. It shows an overlap in the densities; however the Holywell surface is seen to be greater in general when compared to the PEC surface. The range was 0.42 – 0.58 g/cm³ for the Holywell surface with a range of 0.57 – 0.75 g/cm³ for the PEC specification. Figure 6.38 also shows the higher peak torque reached with the PEC surface. This may be due to the smaller rubber infill particles in the Holywell specification (Appendix A). This would allow for more air voids and tighter compaction of the particles. This may also account for the higher peak torque developed with the PEC surface due to there being less space for the rubber to displace, hence the higher resistance as the studs plough through the infill.

![Figure 6.38: Comparing peak torque with an increase in rubber infill net bulk density for two surface specifications using the rotational traction device.](image)

Figure 6.39 shows the values for the two stiffness regions over the two surface specifications. It shows the comparable stiffnesses between surfaces, and the general pattern of increasing stiffness with an increase in the rubber infill net bulk density.
6.4 Effect of changing numbers of carpet fibres

6.4.1 Translational testing

The number of carpet fibres was altered to investigate the effect of reducing the number of carpet fibres on the force and stiffness developed. The carpet was also omitted to leave the rubber and sand in solitude. The following section documents the testing completed with the translational traction tester. 13 mm football studs were used in stud configuration E with a normal load of 45 kg.

Figure 6.40 shows the force produced for the different carpet conditions. It shows that the highest force produced was with the half number of carpet fibres which increased in force until a peak was reached at ~65 mm. The full carpet density peaked at 45 mm, before reducing in force, then increasing again after 55 mm. The quarter density continued to increase in force, but at a lower rate than half density.

The result for sand in solitude shows a force was reached at ~ 110 N before stabilising and oscillating. This oscillation may be due to a stick and slip action caused as the stud plate is displacing the sand. The rubber infill condition reached a peak at 10 mm before reducing in force.
Table 6.13 shows the values for peak force and the displacements that the peak force values were reached at.

![Graph showing peak force and displacement](image)

**Figure 6.40:** Horizontal force produced using full, half and quarter density carpet fibres, and rubber and sand in solitude using the translational traction device.

Table 6.13: Peak force and displacement of peak force for each surface condition (Mean ± SD over three repeat trials)

<table>
<thead>
<tr>
<th></th>
<th>Full density</th>
<th>Half density</th>
<th>Quarter density</th>
<th>Rubber</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak force (N)</td>
<td>472.3 ± 7.5</td>
<td>565.5 ± 59.3</td>
<td>513.1 ± 36.3</td>
<td>160.2 ± 3.5</td>
<td>135.5 ± 11.6</td>
</tr>
<tr>
<td>Displacement of peak force (mm)</td>
<td>73.2 ± 1.9</td>
<td>63.3 ± 1.4</td>
<td>74.5 ± 1.8</td>
<td>14.2 ± 0.3</td>
<td>68.3 ±2.1</td>
</tr>
</tbody>
</table>

Figure 6.41 shows the average stiffness values for the two identified regions. Stiffness one and two can be seen to be comparable for the three different carpet fibre conditions, with a small decrease as the number of fibres decreases. The rubber only condition has a lower stiffness one value with the sand only condition producing a higher value. The stiffness two values were close to zero for both the rubber and sand conditions. The negative value of stiffness region two illustrated by the rubber only condition represents the decrease in force.
shown in Figure 6.40 due to it being a negative gradient. Table 6.14 show the significant differences for both stiffness one and two.

![Chart showing stiffness values for the two regions; the start of movement (1), and further through the movement (2) for each surface condition (Mean ± SD over three repeat trials).]

Table 6.14: Significant differences for stiffness region one and two from results on Figure 6.41.

<table>
<thead>
<tr>
<th>Carpet density</th>
<th>Stiffness 1</th>
<th>Stiffness 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Full density</td>
<td>Significant (p &lt; 0.05)</td>
<td>Significant (p &lt; 0.05)</td>
</tr>
<tr>
<td>2 Half density</td>
<td>4,5</td>
<td>4,5</td>
</tr>
<tr>
<td>3 Quarter density</td>
<td>4,5</td>
<td>4,5</td>
</tr>
<tr>
<td>4 Rubber only</td>
<td>1,2,3,5</td>
<td>1,2,3,5</td>
</tr>
<tr>
<td>5 Sand only</td>
<td>1,2,3,4</td>
<td>1,2,3,4</td>
</tr>
</tbody>
</table>

Figure 6.42 shows the rubber infill net bulk density for each condition. The three carpet fibre conditions are shown before the surface was rolled, and after 200 rolls. It shows the increase in rubber infill net bulk density with less carpet fibres. The rubber infill only condition was compacted by foot, with the net bulk density shown.
Figure 6.43 shows the air void percentage for the same results as Figure 6.42. It shows the lower air void percentage with the lower number of carpet fibres after 200 rolls of the surface.

Figure 6.42: Rubber infill net bulk density for each surface condition with 0 and 200 surface rolls.

Figure 6.43: Air void percentage for each surface condition with 0 and 200 surface rolls.
Figure 6.44 shows the vertical displacement of the infill under the loaded stud plate prior to translation. The results are shown for both stud configuration A (no studs) and E (two studs perpendicular to the front of the stud plate). It shows the higher penetration into the infill with a reduction in the number of carpet fibres.

Figure 6.45 shows the vertical displacement of the stud plate as translation occurs. It shows the minor vertical displacements for the varying number of carpet fibres. With the rubber and sand in solitude, the stud plate ploughs through a high volume of the sand/rubber, causing the high vertical displacements.

Figure 6.44: Vertical displacement of the infill under the loaded stud plate prior to translation for each surface condition. Results are shown for two stud configurations; A (no studs) and E (two studs).
Figure 6.45: Vertical displacement as translation of the stud plate occurs for each surface condition. Zero indicates the point at which the studs are at rest before the tray moves. Results are shown for two stud configurations; A (no studs) and E (two studs).
6.4.2 Effect of change in number of carpet fibres - Rotational traction testing

The experiment was then repeated using the rotational traction device. Figure 6.46 shows the torque produced over the varying carpet densities. It shows the full density carpet producing the highest torque, with the half and quarter density carpets producing a similar torque to each other. The rubber only torque reaches a torque of ~ 7° before stabilising. The sand only condition reached a peak at 5 Nm before reducing to ~ 4 Nm and stabilising. Table 6.15 shows the values of peak torque and the angles that these peak torques were reached at.

![Figure 6.46: Torque produced over each surface condition for one trial using the rotational traction device at a rotational velocity of 12 rev/min.](image)

Table 6.15: Peak torque and angle of peak torque for each surface condition (Mean ± SD over five repeat trials).

<table>
<thead>
<tr>
<th>Surface Condition</th>
<th>Peak Torque (Nm)</th>
<th>Angle of peak torque (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full density</td>
<td>47.2 ± 2.7</td>
<td>43.6 ± 4.1</td>
</tr>
<tr>
<td>Half density</td>
<td>26.2 ± 1.1</td>
<td>37.9 ± 4.3</td>
</tr>
<tr>
<td>Quarter density</td>
<td>27.9 ± 2.1</td>
<td>37.6 ± 1.7</td>
</tr>
<tr>
<td>Rubber</td>
<td>7.9 ± 0.8</td>
<td>11.5 ± 2.2</td>
</tr>
<tr>
<td>Sand</td>
<td>5.1 ± 0.8</td>
<td>5.9 ± 3.1</td>
</tr>
</tbody>
</table>
Figure 6.47 shows the two stiffness values for the different surface conditions. The stiffness one values were similar between the three varying fibre density carpets. The rubber and sand only conditions gave a much lower value of stiffness. When comparing stiffness two, the lower fibre numbers gave a lower stiffness value. Rubber and sand only gave values close to zero due to the torques flattening and staying consistent. Significant differences for both stiffness regions are shown in Table 6.16.

![Figure 6.47: Average stiffness values for the two regions; the start of movement (1), and further through the movement (2) for each surface condition (Mean ± SD over five repeat trials).](image)

Table 6.16: Significant differences for stiffness region one and two from Figure 6.47.

<table>
<thead>
<tr>
<th>Carpet density</th>
<th>Stiffness 1 Significant (p &lt; 0.05)</th>
<th>Stiffness 2 Significant (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Full density</td>
<td>4,5</td>
<td>2,3,4,5</td>
</tr>
<tr>
<td>2 Half density</td>
<td>4,5</td>
<td>1,4,5</td>
</tr>
<tr>
<td>3 Quarter density</td>
<td>4,5</td>
<td>1,4,5</td>
</tr>
<tr>
<td>4 Rubber only</td>
<td>1,2,3</td>
<td>1,2,3</td>
</tr>
<tr>
<td>5 Sand only</td>
<td>1,2,3</td>
<td>1,2,3</td>
</tr>
</tbody>
</table>
6.5 Suspending studs in contact with the rubber infill

The translational traction device is able to move the stud plate vertically using the pneumatic actuators. These allow the stud plate to be set at any height while being suspended and without moving.

Figure 6.48 show the force produced when the 13 mm football studs were placed 10 mm into the infill, with no normal load on the surface and a space between the bottom of the stud plate and the top of the surface while using the translational traction device, before being moved 75 mm horizontally. The results show the low force produced over the changing number of studs. The configuration with one stud showed no resistance from the infill, with the force produced being from the rails. The configurations with two and three studs perpendicular to the front of the stud plate showed a small increase in the force developed, however it was still almost negligible. With the three studs parallel to the front of the stud plate, the force produced reached a peak of 40 N being reached at approximately 40 mm. Due to the low forces, an extreme example of nine studs were chosen to investigate whether this had a large influence on the force. A larger force was produced with a peak of 80 N being reached. This shows that the number of studs does have an influence on force mobilised, however the majority of the force is produced by the stud plate.
Figure 6.48: Force produced with an increasing number of studs and varying stud configurations with 13 mm football studs placed 10 mm into the rubber infill using the translational traction device.
CHAPTER SEVEN – DISCUSSION

The following chapter includes the discussion from the results collected and presented in Chapter six. It involves refinement of the hypotheses previously outlined based on the mechanisms of traction. This refinement is based on the results collected, along with reinforcement from the literature presented in Chapter two.

7.1 Forces developed during movement

The mechanism for rotational and translational traction was found to be similar, allowing for combination of the two movements. The following section details the forces produced in both the vertical and horizontal directions which are referred to throughout the discussion.

Vertical direction

Figure 7.1 shows the forces in the vertical direction as the stud plate impacts the surface. It shows the normal force from above as the mass impacts the surface (1). There are also a number of frictional forces resisting the studs and stud plate which contribute to the overall force. There is also an infill resistance from the plate as it penetrates the surface (2). An infill resistance is present at the bottom of the studs (which applies to all studs) as the studs penetrate the surface and compact the infill (3). There will also be an amount of infill resistance at the sides of the studs. There will also be infill resistance at the side of the stud plate (4) as the stud plate penetrates the infill.

Figure 7.1: Diagram of stud plate and studs vertically impacting the surface, with annotated forces. Normal force (1), infill resistance underneath stud plate (2), infill resistance with the studs, shown as black border around studs (3) and infill resistance with the side of the stud plate (4).
**Horizontal direction**

As the studs and stud plate begin to move, a number of forces are being produced in the horizontal direction. The applied force is shown (1) and is the direction the stud plate and studs are moving in. As the force is applied, there are a number of resistive forces in the opposite direction. There is an infill resistance with the bottom of the stud plate as it moves through the surface system (2). There is also an infill resistance with the sides of the stud (3) and a resistance force from the infill (4). The base of the studs also has a resistance with the infill (5). These forces are shown for one stud but can be applied to all of them.

![Diagram of stud moving horizontally with the forces annotated.](image)

**7.2 Effect of varying stud type**

A selection of stud types with varying cross-sectional area (Table 6.1) were tested using the rotational traction device with corresponding results shown in Section 6.1. These included football (13 and 16 mm) and rugby (15, 18 and 21 mm) studs. The football studs were constructed from plastic and the rugby studs were constructed from aluminium. The normal load stayed consistent throughout this set of testing, at the set mass of 45 ± 2 kg.

Figure 7.1 illustrates the forces involved during the vertical impact of the stud plate onto the surface, however does not show the behaviour of the infill, described below.

It was hypothesised that as the studded test plate (fully loaded to 46 kg) was dropped from the specified height of 60 mm, the initially undisturbed surface system has subsequently been disturbed by the impact from the stud plate. The initial stud penetration into the infill causes a zone of stiffer infill around the studs. Vertical impact from the stud plate will also
cause a layer of stiffer infill underneath the stud plate as it confines the infill. This area of stiffer infill is caused by the displacement and compression of the infill as the studs and the stud plate ploughs through it, causing a shearing force. The density of the infill increases as the infill particles become more tightly packed and move into available air voids (Severn, 2010).

The forces involved during horizontal movement of the stud plate are shown in Figure 7.2. Early movement of the stud plate shows a higher stiffness being developed over the first 4° of rotation. This initial region of higher stiffness is referred to in the results as stiffness region one. An initial stiffness is desired by players performing a movement to ensure they are generating force instantly by gripping the surface and ensuring the player is stable and in control. This coincides with why stiffness region one is higher than the second stiffness region. Stiffness region one observed a general trend of increasing stiffness with an increase in cross-sectional area however, no significant differences were seen in the data. This suggests that the early behaviour (the initial 4°) is only marginally affected by the size, shape or material of the stud. It is feasible that the normal force is the dominant factor influencing the initial resistance developed, hence why there are no significant differences. The surface had been rolled to a rubber infill net bulk density of 0.62 g/cm³ (after 200 rolls) which in previous literature is considered a ‘dense’ condition. Literature (Severn, 2010; Anderson, 2007) suggests that the infill is compressing, causing the torque being mobilised by the rotational traction device. The fibres provide reinforcement which may also contribute to the high resistance.

Once the stud disc reaches approximately 4-5°, the studs are past this ‘stiffer’ zone and into an undisturbed infill and fibre mix, although this may partly be disturbed due to the stud plate causing vertical compression of the infill upon impact. This section represents stiffness region two, found to produce similar results with an increase in the stud length. This suggests that the size, shape or material of the studs have no effect on the stiffness between 10-25°. The resistance builds up as the infill continues to be displaced while the studs plough through the infill, causing a shearing force. The infill continues to compress as the rubber infill particles are displaced and move into available air voids.

Figure 7.3 illustrates the hypothesised regions of higher stiffness around the six studs on the stud plate. It indicates the regions of stiffer infill, with a higher density around the studs. There is a space between regions where infill is undisturbed (region two). Evidence of this
was shown in Section 2.7 with work completed by Driscoll (2012) where photo elastic images were produced showing the stress patterns achieved during a running movement in studded outsoles.

![Image of regions of stiffer infill around the six studs underneath the stud plate on the rotational traction device.](image)

**Figure 7.3:** Regions of stiffer infill around the six studs underneath the stud plate on the rotational traction device.

The peak torque is reached at the point immediately before the infill/fibre zone in front of the stud/s fails. This may be due to the shear strength of the material being achieved and/or the stud reaching a point close to the path of the preceding stud during rotation. The path of the preceding stud is illustrated in Figure 7.3 and is considered the undisturbed infill.

Within stud types (football and rugby), the peak torque increased with an increase in cross-sectional area (Figure 6.2). When combining stud types, the cross-sectional area does not have an effect on the peak torque or angle of peak torque with no clear pattern observed. The only significant difference ($p \leq 0.05$) was between 195 and 211 m$^2$ (15 mm rugby stud and 16 mm football stud) and 195 and 283.5 m$^2$ (15 mm rugby stud and 21 mm rugby stud) for peak torque results. No significant differences ($p \leq 0.05$) were found between values for the angle that peak torque was reached at.

The longest studs for each stud type produced a similar magnitude of peak torque, even though they had varying cross-sectional areas. It is possible that either the normal force had more of an effect than the cross-sectional area, or the differing material of the studs had an effect, influencing the friction between the infill material and the studs. The diameter of the bottom of the stud (nearest the stud plate – $D_2$ in Table 6.1) was larger for the 21 mm rugby stud compared to the 16 mm football stud. The angle of peak torque for the rugby studs was lower compared to the football studs (although not significant) which may be due to
the stud reaching the path of the stud ahead at an earlier angle, where infill had already been disturbed and therefore affected the peak torque. Clarke (2011) found that the shape of the stud had an effect on the vertical penetration into the infill (Figure 2.21). This may also be justification for why there was less differentiation between stud cross-sectional areas, as the vertical penetration would affect the peak torque achieved. However, it was not possible to measure the vertical displacement using the rotational traction device.

Villwock et al., (2009a), completed a similar test with a mechanical test device using real boots and looked at the rotational stiffness between the start of the test and up until 75% of the peak torque. The mean stiffness values found using an artificial surface most comparable to the one in this study were 3.1 Nm/deg and 3.4 Nm/deg, with two different models of seven studded football boots. This is within 10 and 15% of the mean stiffness region one value in this study (3.7 Nm/deg) where stiffness was first developed.

Livesay et al., (2006) found that peak torque and rotational stiffness scaled linearly with compressive load by performing five trials at five different compressive loads, with a maximum load of 511 N. This is comparable to the load used in this study. A comparison can be made between the two regions of rotational stiffness found in the study by Livesay et al., (2006) which used 12.7 mm cleated boots, and the two regions for rotational stiffness assessed in this study. The initial stiffness in region one found in Livesay et al., (2006) was 3.1 Nm/deg, compared to 3.7 Nm/deg found in this study. The second linear region (between 2 and 10º for Livesay et al., 2006 and corresponding to region two in this study) was approximately 1.0 Nm/deg in Livesay et al., (2006), compared to 1.32 Nm/deg found in this study. It is worth noting that the surface used - consisting of polyethylene fibres and 100% rubber infill - was not identical to the one used in this study, which may have affected the results.

These results have begun to understand and outline the complex interaction between the studs, stud plate and the surface system while using the rotational traction device. The knowledge can be taken forward to investigate the effect of number of studs and changing stud configuration and normal force on the horizontal force produced. It can be assumed that the basic mechanism will be similar between the mechanical devices; however this will be discussed in Section 7.3.
7.3 Change in stud configuration using the translational traction device under different number of configurations of studs and normal loads.

Following development of the translational traction device, application of the rig is demonstrated through a number of investigations. The following set of testing investigated the effect of stud configuration on the horizontal force produced. The testing was completed using the translational traction device, as described in Section 5.5.1.3. Four testing conditions were utilised, involving changes in stud type (13 mm football studs and 21 mm rugby studs) and changes in normal force (45 and 70 kg).

The overall mechanism involved during the use of the translational traction device is similar to the rotational traction device described in Section 7.2. As with the mechanism hypotheses in Section 3.4, the movement can be split into two sections; the initial vertical placement of the stud plate onto the surface, and the horizontal displacement of the tray. As described in Section 7.2, a model of the forces produced as the central column is lowered vertically and the stud plate is placed onto the surface is shown in Figure 7.1, taken from hypotheses in Section 3.4.

The results presented in Section 6.2 confirm that vertical penetration is occurring as the stud plate is loaded onto the surface. This involves the infill being displaced, as well as compression around the studs and underneath the stud plate, causing the zone of stiffer infill around them, as discussed in Section 7.2. This increases the density of the infill due to compression decreasing the number of air voids and packing the infill particles closer together, as hypothesised in Section 3.3.4.

As the tray moves, a different set of forces are acting between the surface system and the studs/stud plate, as illustrated in Figure 7.2. Not shown on the diagram is the friction produced by the rails, however this was consistent throughout all testing and had previously been shown to have little effect (Section 5.3.3.1).

As with the rotational traction device, the results indicated that an initial higher gradient was identified (corresponding to stiffness region one) which is hypothesised to be caused by the zone of stiffer infill from the initial vertical load. The studs and stud plate plough horizontally through the higher density infill, causing a shearing force and therefore, a higher resistance.
Following on from stiffness region one, the force continues to increase, however with a decreased gradient, corresponding to stiffness region two. This is in accordance with the hypothesis that the studs and stud plate have passed through the zone of stiffer infill, causing the stiffness to decrease as the studs plough horizontally into an undisturbed infill mix. Resistance builds up as the infill is compressed and the fibres resist infill displacement and shearing. As the displacement increased, depending on the differing stud configurations or normal force, the horizontal force followed varying patterns, as discussed in the following sections.

### 7.3.1 Change in stud configuration

Seven different stud configurations were tested with varying numbers and positions (illustrated in Figure 7.4) The stud penetration was measured during completion of the tests, with the vertical displacement of the stud plate into the infill illustrated (Figure 7.4). The vertical penetration of the stud plate did not produce significant differences between stud configurations when comparing between the four sets of testing. This was with the exception of the set of testing involving the 13 mm football studs and 45 kg normal force, which indicated a trend of decreasing displacement as the number of studs was increased. Hypothetically, this is due to the higher number of studs resulting in a larger surface area being in contact with the infill, thus causing a higher resistance from the infill particles as the studs plough vertically through it and therefore not displacing the infill as far.

The results found that without any studs attached to the stud plate, a horizontal force was produced. It is hypothesised that this horizontal force exists due to the stud plate having displaced the infill, therefore causing a zone of stiffer infill around the plate, whilst compressing and confining the infill underneath. Once translation of the stud plate occurs and the plate ploughs through the infill, a shearing force is produced. Resistance of movement comes from the compression of infill around the stud plate and friction from underneath the stud plate.

The values calculated for stiffness region one were, in the majority of cases, comparable between stud configurations (Figure 7.5) as the infill is being compressed. This indicates that the orientation of the studs have no effect on the initial displacement. The second stiffness region showed differing values between stud configurations. The values showed a pattern of
similar magnitude of results with the same number of studs, for example configurations C and E which both have two studs, although in different orientations. Although the differences were not significant, the trends were noticeable.

A number of the configurations reached a peak horizontal force before reducing in force. It is hypothesised that this is due to the infill/fibre zone in front of the studs failing. This was evident with higher numbers of studs or when placed under a high normal force (70 kg). This was due to the shear strength of the material being achieved.

The results found that a higher maximum horizontal force was produced with a higher number of studs parallel to the front of the stud plate. With an increase in the number of studs perpendicular to the front of the stud plate (B, E and F) - under both normal forces and stud lengths - a similar magnitude of results of horizontal force was achieved after a displacement of approximately 70-75 mm. However, a higher number of studs produced a higher horizontal force/stiffness value in region two (10 – 25 mm of tray displacement) prior to this displacement.

The studs parallel to the front of the stud plate had the largest effect on the force produced due to the shearing force as ploughing occurs. This may have implications on boot design as the studs that first come in contact with the surface during a translational movement will have the greatest effect on the force developed.

7.3.2 Change in stud type

The two stud types tested were 13 mm football studs (constructed from a plastic material) and 21 mm rugby studs (constructed from aluminium).

Both the 13 mm football studs and the 21 mm rugby studs fully penetrated the infill for all sets of testing with varying stud configurations and normal forces. This resulted in a higher force being produced with the longer studs. This corresponds to the hypothesis of a higher vertical penetration causing a higher horizontal force. This is due to the higher surface area being in contact with the infill, therefore producing a larger resistive force as the studs plough through the infill. This corresponds with work completed by Clarke (2011) who stated that as the length of the stud increases, the ploughing traction will became a more dominating contributor to the overall traction.
With the same vertical normal force, the stiffness one values were comparable between the two stud types as shown in Figure 7.5. This indicates that the stud length had no effect on the initial movements of the stud plate and studs. The results from the second stiffness region showed higher values for the larger 21 mm rugby studs (Figure 7.6). As above, this is due to the higher surface area of the studs causing a higher resistance as they plough through the infill, producing a higher shearing force. When linking this to player-surface interaction and boot design, it shows that the type of stud may not have an effect on the initial movements a player makes. However, if a movement requires a higher displacement, it may have more of an effect. A surface which has a lower density, or potentially a wet surface may require more traction to be developed to ensure the shoe grips the surface and does not cause injury.

7.3.3 Change in normal load

The vertical normal force (force 1 on Figure 7.1) had the largest effect on the results produced. Figure 7.2 shows the higher vertical displacement of the stud plate with an increase in the vertical normal load. This contributed to the higher horizontal force produced with 70 kg due to the higher compression of the infill around the studs and stud plate after loading of the stud plate onto the surface. The values for the first stiffness region show an approximately 10 N/mm difference between vertical normal loads. Figure 7.3 shows the influence the normal force has on the initial movement.

With the higher normal force, the results showed a difference in the patterns of force produced. All stud configurations followed a similar pattern of gradually increasing in force, before reaching a peak and subsequently reducing in force. In comparison, the 45 kg normal force results had more variable trials with changing configuration. With regards to the maximum forces produced, these were much higher under 70 kg compared to 45 kg, however a similar force pattern was observed as the number of studs was increased.

The values for the second stiffness region (Figure 7.6) show the comparability between the 70 kg normal force and the 13 mm football studs, and the 45 kg normal force and 21 mm rugby studs with regards to changing stud configurations. This indicates that between 10 and 25 mm, the higher normal force may have the same effect as the longer studs. The
setup consisting of the 70 kg normal force and 21 mm rugby studs produced consistently higher values for the second stiffness region compared to the other combinations of normal force and stud length.

As expected, the largest normal force with the longest studs produced the highest horizontal forces. A similar force was produced for stud configurations above one stud which show that at higher vertical loads, an increase in the number of studs (up to four studs) or stud orientation have no effect on the horizontal force produced. A maximum force was either not reached or reached much later in the displacement compared to the lower normal force. This suggests that the infill/fibre zone in front of the studs did not fail.

![Figure 7.4](image)

**Figure 7.4:** Vertical displacement of stud plate under load prior to translation for all four conditions tested.
Figure 7.5: Stiffness region one values for four conditions tested.

Figure 7.6: Stiffness region two values for four conditions tested.
7.4 Changing infill density

The following testing investigated the change in rubber infill net bulk density and the effect this had on the torque and force produced when tested using the rotational and translational traction devices.

7.4.1 Translational traction (Holywell)

The results in Section 6.3 illustrate that as the number of rolls performed on the surface increased, the net bulk rubber infill density increased and the air void percentage decreased. This represents the compaction that has taken place through permanent change in particle packing, reducing the volume of air voids. The maximum rubber infill net bulk density achieved over 500 rolls was $0.58 \text{ g/cm}^3$ which is comparable to the value achieved with the Proctor method by Severn (2010) of $0.59 \text{ g/cm}^3$. The stiffness one values above a rubber infill net bulk density of $0.48 \text{ g/cm}^3$ (the second highest density) showed no significant differences which suggest the density has no effect during the initial four mm of movement, other than with the loosest density state. Severn (2010) reported that surface systems that were initially ‘dense’ resulted in more of the displacement being ascribed to compression, whereas initially ‘loose’ surface systems resulted in the displacement being ascribed to compaction. Therefore, it can be postulated that with the lowest density of $0.42 \text{ g/cm}^3$ (air void percentage: 63%), the studs are displacing the rubber particles into the available air voids, resulting in a lower stiffness value compared to the higher densities of surface with a correspondingly lower air void percentage. The higher rubber infill net bulk density surface systems (above $0.48 \text{ g/cm}^3$) showed similar magnitude of results for stiffness value one. This may have been the threshold for when the displacement was compression of the infill, therefore explaining the similarity in results.

The stiffness two values showed comparability between the rubber infill net bulk densities, with no significant differences found suggesting that the rubber infill net bulk density had no effect on the rate that force was produced between 10 and 25 mm of tray displacement. It was hypothesised that displacement of the infill is causing compression of the infill as the air voids will be filled.
As the density increased, the peak force was reached at an earlier displacement. It is hypothesised that with the lowest density the force continued to increase for a number of reasons. The stud plate penetrated the infill furthest with the lowest density infill condition. This high penetration is due to the higher number of air voids, allowing the studs to fully penetrate the infill and the stud plate to move a further ~3.5 mm into the infill. The higher number of air voids allows for more compaction of the infill under the normal load as the rubber particles move to fill air voids. The high vertical penetration of the stud plate may contribute to the highest peak force achieved at ~70 mm. This coincides with work completed by Clarke (2011) who found that a surface with a low density of rubber infill allowed for a greater penetration of the studs, which caused the outsole plate to move vertically, compressing the fibres and infill around the studs.

The loose condition of the surface and the elastic nature of the rubber infill material resulted in the compression of the infill as the displacement increased, however a peak shear resistance was reached much later at the lower surface densities. The density is likely to control the amount of strain tolerated by the rubber infill before failure occurs. The fibres also resist infill displacement and shearing, contributing to the resistance.

As the initial rubber infill net bulk density increases, the peak horizontal force is reached at an earlier displacement. The infill compresses less with higher density infill conditions due to the lower air void content. Therefore, it is hypothesised that as the infill compresses and a shearing force was produced, a peak shear resistance is achieved earlier with the higher density infill state. It is also worth noting that the peaks are reached at ~45 mm displacement (other than with the lowest density) which is the length of the stud spacing between the two studs (stud configuration E).
7.4.2 Rotational traction (Holywell)

The change in rubber infill net bulk density was also tested using the rotational traction device, using two different surface specifications to analyse the effect this had on the results produced.

The results illustrating torque produced by the rotation of the mechanical device displayed no clear pattern with an increase in the rubber infill net bulk density. This is in contrast to the testing carried out using the translational traction device, discussed in Section 7.4.1.

A general pattern of increasing peak torque with an increase in rubber infill net bulk density was identified; however the high standard deviations resulted in no significant differences being found. There was also no pattern regarding the angle at which peak torque was reached, with no significant differences found. This is in contrast to the results found with the same surface specification using the translational test device which indicated a clear pattern with the increase in bulk density.

Stiffness one showed a pattern of increasing stiffness with an increase in the rubber infill net bulk density, however the densities higher than 0.49 g/cm$^3$ showed significant differences with the two lowest densities. This demonstrates that with the higher density where the infill particles are closely packed together, the initial torque developed is higher as the infill is being compressed. With the lower densities, the studs are displacing the rubber particles into the available air voids which is producing a lower stiffness value compared to the higher densities which produced a similar magnitude of results.

Stiffness two showed a small increase with the increase in rubber infill net bulk density. This is due to the higher resistance caused by the rubber infill particles being closely packed with less air voids. As the studs are moving through the infill, it is being compressed and the fibres are resisting infill displacement and shearing.

When comparing the above results to field testing completed on an identical specification, observations can be made. Field testing was repeated three times over a period of 17 months, beginning with testing completed subsequent to construction of the pitch and before use, hence the variety in results between sets of testing. The results from the outdoor pitch showed values in the region of the higher density surface systems from the laboratory testing. This corresponds to the infill being compacted over time from player-surface interaction, as well as by the action of maintenance equipment.
7.4.2.1 PEC surface

Testing completed with a second surface specification using the rotational traction device indicated a clear pattern showing an increase in peak torque with an increase in rubber infill net bulk density. This was in contrast to the results collected by the translational traction device as a higher net bulk density produced a lower peak force. There is also a decrease in the angle of peak torque with an increase in the rubber infill bulk density, which demonstrates that peak torque was reached earlier with a higher infill bulk density, compared to the lower densities. This is similar to the results produced by the translational traction tester.

Similar to Section 7.4.2, the density of the rubber infill controls the amount of strain tolerated before failure occurs. It is hypothesised that as the infill density increases, the peak shear resistance occurs earlier as the maximum compression of the rubber infill under load is reached.

As discussed in Section 7.4.1, with the loose infill, more of the displacement is likely to be compaction, whereas with the denser infill conditions, more of the displacement will be compression due to the lower number of air voids available. Upon the stud plate impacting the surface, it is hypothesised that the lower density infills are compacting, reducing the number of air voids. However, the higher densities may not change upon impact due to the low number of air voids into which the infill particles can move. Once rotation of the device begins, this may result in similar surface properties around the studs (within the first four degrees), hence the similar magnitude of results shown in stiffness one, with no significant differences observed.

Stiffness two shows a small increase in stiffness with an increase in the rubber infill net bulk density. As the studs move into an undisturbed infill mix, the varying densities have more of an effect. The higher densities produce a larger stiffness due to the greater shearing forces as the studs compress the infill, causing resistance. The lower densities produce lower shearing forces due to the displacement being through compaction as the rubber particles move into available air voids.
7.4.3 Comparisons between two surface specifications

A higher rubber infill net bulk density was reached for the PEC specification, compared to the Holywell specification. A higher peak torque was also observed for the PEC surface. Severn (2010) found that with larger infill particles, the displacement of the infill decreased as the infill was compressed. This causes a stiffer sample. The PEC rubber infill particles are larger than the Holywell particles. The peak torque and stiffness value two were higher for the PEC surface, compared to Holywell which may be due to the larger infill particles causing a stiffer sample as they are compressed under displacement. Conversely, Villwock et al., (2009b) found that a finer infill caused a higher rotational traction peak value, which was justified as being due to the fineness of the infill which caused a more compacted structure of infill. The stiffness one values were similar between the surface specifications, which indicates that the size of the infill particles does not have an effect on the initial rotation. This testing shows that the initial state of the surface has an effect on the mechanism of traction and how a player reacts to the surface.

7.5 Change in number of carpet fibres

To investigate the influence of carpet fibres on the torque/horizontal force produced, testing involving decreasing the number of carpet fibres was completed. Severn (2010) investigated a number of different carpet types with range in height and density. The effect was found to be minimal, however it was less extreme compared to the carpet fibres omitted in this study. The only noticeable result was with the carpet with a high volume of fibres having a lower quantity of infill in the sample, and therefore the initial net bulk density of the rubber infill density.

7.5.1 Translational traction testing

It was hypothesised that with a full carpet density, a higher horizontal force would be produced due to a higher number of fibres causing more resistance against the studs and stud plate. However, it was observed that the full density trial peaked at ~45 mm before decreasing, then increasing again at 55 mm. In contrast, the half and quarter density trials showed a continuous increasing force. This may be explained by acknowledging the vertical
displacement of the stud plate. The stud plate displaced further into the surface with a carpet of half density. An even greater infill displacement by the stud plate is seen with the quarter density carpet. It is hypothesised that a higher number of fibres causes confinement of the infill resulting in reduced stud penetration.

The half density carpet produced a higher horizontal force than quarter density, despite the higher vertical penetration of the studs and stud plate in the quarter density carpet. It is hypothesised that this is due to the higher number of fibres providing reinforcement of the infill and causing a horizontal resistance between the fibres and the studs. It is also worth noting that with full carpet density, a peak was reached at 45 mm, equivalent to the spacing between the two studs, suggesting that the stud behind was reaching the path of the stud in front and therefore the force is reduced due to the previously disturbed infill.

The rubber infill net bulk density increased as the number of fibres decreased (after 200 rolls). As the fibres were being omitted, there was more space for the rubber infill, hence the lower percentage of air voids and the decreased infill height with the same number of rolls. The stiffness values for regions one and two for each carpet density showed that for full, half and quarter density, the stiffness decreased as the number of fibres decreased for both one and two. Although the density is lower for full density and thus may be expected to have a lower stiffness, it is hypothesised that it is the higher number of reinforcing fibres causing this higher resistance for the two regions chosen. However, as mentioned earlier, the force for the half and quarter carpet densities keeps on increasing unlike the full density carpet which displays a fluctuating force profile.

With the rubber only condition, the two studs (configuration E) fully displaced the rubber infill, with the stud plate also moving five mm into the infill. It may be expected that the studs would penetrate the infill further with only rubber infill compared with carpet fibres present due to the loose state of the infill. However, it may be due to how the infill particles were compacted together. With the sand only condition, the two studs did not fully displace the sand. This is lower than the other conditions due to the stiffness and non-compressibility of sand. As the tray began to translate, the initial stiffness one value of the rubber infill was lower than the initial stiffness of the conditions with carpet fibres present. This is due to the loose nature of the infill and the ease of mobility with the lack of carpet fibres. The sand's initial stiffness one was the highest of all conditions, due to the rigidness of the material, as stated previously.
7.5.2 Rotational traction device

The results using the rotational traction device showed the full density carpet producing the highest torque, with the half and quarter density carpets producing a similar torque to each other.

The reduction in fibres means the infill is freer to move around providing less resistance. This is not apparent in stiffness region one as the values found for full, half and quarter density were similar with no significant differences found. This small, early rotation is not enough for the change in the number of fibres to have an effect. As the stud disc continues to rotate, this difference in force becomes obvious with the full carpet density having a higher stiffness value two and reaching a higher peak torque. The similar results for half and quarter density suggest this difference in the number of fibres made little or no difference to the force produced.

The rubber only condition produced a lower traction measurement. With a lack of fibres, the rubber infill was able to flow freely and not cause much resistance. The sand only condition produced a lower traction force than the rubber only condition. This may be due to the free flowing and compressible properties of the rubber compared to the free flowing and rigid properties of sand.

7.6 Suspending studs in contact with infill

To measure the effect of the stud plate on the results, the translational traction device was utilised to measure the horizontal force produced with the studs placed a set displacement into the infill. This included having no normal load on the surface, with a space between the bottom of the stud plate and the top of the infill.

The results in Figure 6.48 showed the low force produced with an increasing number of studs. The configuration with one stud showed no resistance from the infill, with the force produced being from the rails (previously shown in Section 5.3.3.1). With an increase in the number of studs a small increase in the horizontal force was identified, however for two and three studs, it was almost negligible. A higher force was produced with the studs parallel to the front of the stud plate. The highest force produced was with nine studs attached to the
stud plate. These results showed that the number of studs and the stud orientation does have an influence on the force mobilised, however the majority of the force is produced by the stud plate.

A higher cross-sectional area of stud was also tested, with an increase in the horizontal force found. This indicates that the higher cross-sectional area does have an effect on the traction mobilised. It is hypothesised that this is due to the higher surface area being in contact with the rubber infill, causing increased ploughing traction and increased friction between the studs and surface.

7.7 Summary of mechanical devices

7.7.1 Rotational traction device

The mechanism involved in a rotational movement was hypothesised and presented throughout the results discussed in this chapter. Two stiffness regions were observed on all trials collected. This allowed for comparison between values.

The results showed, in general, an increasing peak torque with an increase in the rubber infill net bulk density. This was more obvious with the PEC surface system. An increased stiffness value two was also observed with an increase in the rubber infill net bulk density, however stiffness one had little effect.

The number of fibres had an effect on the torque produced, however no difference was seen with half or quarter the number of fibres. When rubber and sand were tested in isolation, the torque produced was very low due to the lack of stabilising fibres.

7.7.2 Translational traction device

The translational traction device was successfully designed and constructed, as documented in Chapter five. The discussion has aimed to dissect the results and define the mechanisms that are present during a horizontal movement. The mechanisms found were similar to the rotational traction device and highlighted the influence of the fibres, the change in infill density, and the effect changing stud configuration, stud length and normal load had on the horizontal force produced.
It has been determined that the normal load had the largest effect on the horizontal force with the stud configuration/stud length less determinable under the higher load. However, under the lower load, the effects could be better determined with changes in shoe or surface properties being recognised.
CHAPTER 8 – CONCLUSIONS

8.1 Introduction

The aim of the research documented in this thesis was to make a contribution to knowledge with regard to the mobilisation of traction and apply this to the understanding of shoe-surface interactions. This has been achieved through the objectives set out in Section 1.2.2. The following chapter highlights the key conclusions and findings from the completed PhD regarding the mechanical test devices, the testing completed and the refined mechanisms. The limitations of the study are also set out, along with any potential future work that has arisen from the PhD. Finally, any implications from the research that can be taken forward have been outlined.

8.2 Conclusions

The following section presents a summary of the conclusions determined over the course of the PhD. They have been split into a number of sub-sections.

Development of mechanical test devices

- The rotational traction device was successfully developed to include additional sensors to record the torque and rotation throughout a complete trial (Objective five).
- A translational traction device was successfully designed and constructed (Objective five) which fulfilled the specification requirements set out.
  - The device held many advantages such as the ability to alter the normal force, being able to measure the vertical displacement into the surface, having a flexible foot attachment and having the ability to test any surface sample.
  - The device was designed to ensure edge effect around the perimeter of the tray did not influence the testing being carried out.
The player movement study (Chapter four) highlighted a number of boundary conditions in regard to both rotational and translational traction devices (Objective two). Although it was not possible to use all boundary conditions for the mechanical devices, it highlighted the variables and boundaries that exist, as well as the difficulty in replicating player-interaction movements.

**Collection of data**

- Two stiffness regions were identified in both rotational and translational data collections. Initial movement (stiffness region one) may be a better indicator of traction compared to using a later measure such as peak torque, as it is questionable whether a subject rotates 30-40° during movements. The literature review and subject testing (Chapter four) showed that a player may only rotate at an angle of 10° or less.
- Stiffness region two helped to understand the behaviour at the shoe-surface interaction on the run up to the peak value. Later observations were also made, even if a player may not rotate/translate to that rotation or displacement.

**Summary of results**

Effect of stud length (Rotational traction device):

- The early movement showed a steeper gradient which represented a stiffer material over the first four degrees. The gradient then reduced, however the torque continued to increase until peak torque was achieved.
- Stiffness region one observed a general trend of increasing with an increase in cross-sectional area, however stiffness region two saw no pattern.
- Within stud types (Football and Rugby), a trend of increasing peak torque with an increase in stud length was observed. When all stud types were combined, there was no pattern with an increase in cross-sectional area.

Changing stud configuration under various conditions (Translational traction device):
• A change in the stud length produced a higher horizontal force due to the higher contact area with the infill as they fully penetrated the infill. However, the stud length did not have an effect on stiffness region one which may be predominantly affected by normal force.

• The vertical normal load had the largest effect on the horizontal force produced with changing stud length and stud configuration. This was discussed as being partly due to the vertical displacement of the stud plate which was deeper under a higher load.

• The force produced was often affected by preceding studs due to disturbance of the infill; however, the studs nearest the front were found to be the dominant producers of the horizontal force.

• The stud plate was found to have a large effect on the overall force produced. This was determined by suspending the studs into the infill and measuring the horizontal force. The studs in isolation did produce a force; however, it was very small in comparison to the stud plate. A higher number of studs produced a higher contribution of horizontal force due to the studs causing resistance with the surface system.

• The stud plate has an edge effect as it moves through the infill, therefore increasing the force.

Surface properties:

*Translational traction*

• A change in the number of carpet fibres across the sample was investigated to observe the effect the fibres had on the overall traction developed during movement.

• Testing completed using the translational traction device observed a higher vertical stud penetration into the infill with a lower number of carpet fibres due to the higher number of fibres proving reinforcement of the infill upon loading of the surface.

• The carpet with half the number of fibres produced a higher horizontal force than the carpet with a quarter of the fibres despite the higher vertical penetration of the
studs and stud plate in the quarter density carpet. This is due to the higher number of fibres providing reinforcement of the infill and causing a horizontal resistance between the fibres and the studs.

- The rubber infill net bulk density increased as the number of fibres decreased (after 200 rolls were completed). As the fibres were being omitted, there was more space for the rubber infill, hence the lower percentage of air voids and the decreased infill height with the same number of rolls.

- The stiffness values for regions one and two for each surface system showed that for full, half and a quarter number of fibres, the stiffness decreased as the number of fibres decreased. Although the density is lower for full density, and thus may be expected to have a lower stiffness, it is hypothesised that it is the higher number of reinforcing fibres causing this higher resistance for the two chosen regions.

- By increasing the number of rolls on the surface, the rubber infill net bulk density increased, with the percentage of air voids decreasing.

- A lower surface density caused the studs and stud plate to penetrate further into the infill. This is due to a higher number of air voids available as the stud plate/studs plough through the infill, compacting it together.

- The peak force decreased with an increase in the rubber infill net bulk density. With the higher density of infill, the available air voids will already be filled causing a high compaction of infill. Therefore shear failure occurs earlier, as the infill is compressed.

- The stiffness one value increased with an increase in the rubber infill net bulk density. Under lower densities, compaction of the infill particles was occurring as they were pushed into available air voids. With a higher infill density, the infill was being compressed due to a lower number of available air voids. This resulted in a higher stiffness system.

**Rotational traction**

- The results using the rotational traction device showed the full density carpet producing the highest torque, with the carpets with half and quarter number of
fibres producing a similar torque to each other. The reduction in fibres means the infill is freer to move around, therefore providing less resistance.

- Stiffness region one values for full, half and quarter number of carpet fibres were similar with no significant differences found. This small, early rotation is not enough for the change in the number of fibres to have an effect.

- As the stud disc continues to rotate, this difference in force becomes obvious with the full carpet surface having a higher stiffness value two and reaching a higher peak torque. The similar results for half and quarter number of fibres suggest this difference in the number of fibres made little or no impact on the force produced.

- In general, there was an increase in peak torque with an increase in the rubber infill net bulk densities (on both surface specifications).

- Field data was compared to the laboratory data and concluded that it was in the higher region of the surfaces with a change in density.

**Rubber and sand only conditions**

- When testing rubber and sand in isolation, the results for both rotational and translational testing observed the free flowing nature of both materials in isolation. The forces/torques produced were low without the carpet fibres providing reinforcement. This highlighted the tole and importance of the fibres in the surface system.

**Mechanisms of traction**

- The mechanisms of traction have been detailed in Chapter seven with the change in surface and shoe properties when using the rotational and translational traction devices.

- A movement was split into the vertical and horizontal direction to illustrate the forces that are occurring between the studs/stud plate and the surface. The infill resistance was highlighted between the various components.

- In the analysis of the results, it was observed that the stud/stud plate penetration had a large effect on the traction developed and was key to the production of horizontal force. This influenced the compression of the infill during penetration of
the studs, as well as compaction of the infill where air voids were available. The displacement of penetration also has an effect on the edge of the stud plate as this causes resistance during movement through the infill.

- The results indicated the effect the properties had on the two stiffness regions identified. The 1st region may be a better indicator of traction compared to any peak values due to realistic boundary conditions identified in Chapter four. However, the second region was a useful indicator of trends that occurred.

### 8.3 Limitations of study and further work

This study contains a number of limitations. Some of them have already been discussed throughout the thesis; however the key limitations are detailed in the following section. Primarily, a limitation is only using two surface systems, of which the specifications were very similar. A justification for this approach is that they represent recent and popular specifications used in football, rugby and American football. Further work would include testing a wider range of surface specifications to further understand the effect of surface properties on the force/torque produced, for example different carpet fibre lengths.

The mechanical test devices used have been a useful asset for understanding the mechanism of traction; however both the rotational and translational mechanical devices still hold a number of limitations.

A limitation of the developed rotational traction device is the lack of a vertical displacement sensor. An attempt was made to rectify this limitation; however there was difficulty in finding a point for the top of the surface. It is likely that this limitation is not a permanent one and could be solved and the solution incorporated into future testing. Another limitation of the rotational traction device is the inability to increase the normal force above 46 ± 2 kg without rendering the device no longer portable or user friendly enough to be used outside of laboratory testing.

The translational traction device is unable to be transported outside of the laboratory due to the attachment to the uni-axial tensile machine inside the lab. However, it has the
advantage of allowing adjustments to be made to the normal force, and alterations to be made to the surface that is being tested.

A limitation of the testing completed using the translational traction device involved the use of a square fronted plate, as results indicated that this produced a high force. A boot outsole was not chosen, as any possibility of the shoe material affecting the results (e.g. bending stiffness) was considered unacceptable. However, it is also fair to assume that a boot outsole produces force.

Although the intention of the study was to gauge an understanding of the effect of increasing number of studs and stud orientation, a limitation was the small number of studs used. It may have been more realistic to use a higher number of studs that more closely reproduces the number of studs found on a typical boot, however the number and configurations were chosen to allow for control over the spacing.

Limitations regarding the laboratory set-up and testing protocol are mentioned in Chapter four (analysis of subject data). In reference to the analysis completed for this thesis, a limitation is that only one movement was analysed from the study previously carried out by El Kati (2012). However, the other movement was not deemed as relevant for investigating traction.

Another limiting element was the finding that horizontal impact velocity has an effect on the movement being carried out. This is a limitation of the mechanical test devices, as they do not include a horizontal impact element. The analysis of the subject data also acknowledged that it may be more appropriate to use an acceleration profile or acceleration limits for the use of the rotational traction device. This would be in place of the rotational velocity target currently set by governing bodies. This would make the mechanical test device more closely reproduce sport-specific movements.

The traction testing using the translational device for both change in rubber infill net bulk density and change in carpet fibre numbers only used one configuration during testing. The chosen configuration was E (two studs perpendicular to the front of the stud plate). It was chosen as it gave repeatable results in preliminary testing and it was decided that a simple configuration would be best to determine the interaction between the studs and the surface system. However, this may be seen as a limitation as it is not realistic, nor comparable to the rotational traction stud pattern.
The translational traction device was a newly developed device, which has been utilised to successfully collect the data needed for the thesis. However, the possibilities for future testing are wide ranging, with the device not yet reaching its full potential. There are a number of components which were not operated in the testing completed so far. These include the ability to alter the plate fixture for interaction with the surfaces. Although shoe outsoles have been used on a previous study (external to this study), the next logical step would be to attach a shoe last with the ability to change the shoe. The device also allows for rotation of the fixture, allowing for the horizontal force to be measured with the shoe at a variety of angles (to potentially investigate a cutting movement).

A future possibility for testing may involve the use of a six degrees of freedom robot, situated in the Sport Technology Institute laboratories at Loughborough University. This would allow for a wider range of sport-specific movements to be tested, as well as the potential for testing higher velocities. With the addition of a force plate, the forces over three axes could be collected.

8.4 Implications of research

There are a number of implications that can be taken forward from the research completed. These are presented below.

- One of the key conclusions of the PhD is the importance of characterising the surface by stating the specification used. This has often been missed during previous studies, however it has been shown that the properties of a surface have a key effect on the traction mobilised. Therefore it is important that the details of the surface are presented to allow for comparison.

- Although stated from the start of the thesis, the importance of using player-testing data to reinforce mechanical testing completed has been reinforced. This has been difficult to comply with for all boundary conditions due to restraints, but having an understanding of the player-surface interaction is essential.

- The results have shown how much the properties of a surface affect the forces produced, even with small changes such as the number of fibres or a change in density. This is crucial for surface manufacturers to understand. For example, if too
few carpet fibres were used, this would increase the chance of slippage due to a lack of reinforcement within the surface system.

- By altering the density of the surface, the results show the potential for increasing force/torque with an increase in the compaction of the infill, which may lead to locking of the shoe during rotational movements. This confirms the importance of maintaining a surface to ensure the risk of injury is kept to a minimum.

- The normal force was found to have the largest effect on the force produced. It is important a player generates enough normal force during a movement to achieve the traction required to perform the specific interaction. Otherwise the player risks injury or loss of performance during the desired movement.

- It could be argued that the normal force is the most important factor due to the large effect the normal force had in the testing completed. However, a surface with a high density or a high number of carpet fibres or a shoe with long studs/a high number of studs will increase the chances of an injury occurring, so the properties of the surface and the shoe must not be ignored.

- The stud configuration was found to have had an impact on the traction mobilised with the position of the studs relative to each other affecting the horizontal force produced. Shoe manufacturers could learn from determining the most important studs and whether there are any redundant studs which perform no use during movements.

- The penetration of the studs and stud plate was found to have a large effect on the amount of force developed. Therefore, it is important to include this measurement in future devices.

- The mechanisms determined from the results collected have helped to improve the understanding of the mechanism of interaction between the shoe and the surface and the high number of variables involved. This research can be taken forward to apply to a full boot interaction. The complex number of variables and interactions make this difficult, however by breaking the movement down, this allows for a better understanding.
8.5 List of publications arising from the Research Project


conference on Science Technology and Research into Sport Surfaces (STARSS). Loughborough University, UK.

- Clarke, James, (2011). Understanding the Performance and Comfort of Soccer Boots. PhD, Department of Mechanical Engineering, University of Sheffield.


• Kirk, Robert, (2008). Traction of Association Football Boots. PhD, Department of Mechanical Engineering, University of Sheffield.


• SAPCA (2009). The sports and play construction association website. Available at: www.sapca.org.uk.


# Holywell surface

## Technical Data Sheet

### Product name
- **LigaTurf RS+ CoolPlus 260 16/4**

### Application
- Professional

### Description
- 3rd generation football turf with sand-rubber infill; Polytan Monofilament with ENTANGLEMENT technology; 100 % Polytan PE formulation with CoolPlus function; straight without curling, single extrusion uncut, without fibrillation

### Yarn data
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<tr>
<th>Materials</th>
<th>100 % Polytan PE</th>
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<tr>
<td>Filament/film</td>
<td>Monofilament</td>
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<tr>
<td>Number of filaments</td>
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</tr>
<tr>
<td>Thickness app.</td>
<td>360 µm</td>
</tr>
<tr>
<td>Average thickness app.</td>
<td>210 µm</td>
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<tr>
<td>Yarn fineness app.</td>
<td>13000 dtx</td>
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<tr>
<td>Cross section area app.</td>
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### Construction data
| Pile height app.    | 60 mm            |
| Machine gauge       | 3/4 "            |
| Stitch density app. | 160 /m           |
| Number of tufts app. | 8400 /m²        |
| Number of filaments app. | 100800 /m²   |
| Fibre weight app.   | 1470 g/m²        |

### Backing construction
- Primary backing 1 100 % PP woven fabric, UV stabilised
- Primary backing 2 100 % PP support layer
- Coating: Latex, antibacterial and antifungal, waterproof
  - Coating weight app. | 1000 g/m²
- Perforation, hole spacing app. | 140 mm
- Perforation, hole diameter min. | 3 mm

### Product data
- Production technology: Tufting velours
- Maximum width: 4 m
- Maximum length: depending on installation width
- Total height app.: 62 mm
- Total weight app.: 2690 g/m²

### General data
- Turf colour: olivegreen
- Line colour: white or yellow, other colours on request
- Elastic layer: -

### Maintenance
- Details for maintenance see Polytan maintenance brochure

---

In order to maintain our surfaces to the highest and most up to date technical standards, we reserve the right to modify the product data. We advise that the technical values regarding yarn- and construction data as well as weight indications are approximate values and could vary due to technical reasons by +/- 10 %. (March 2013)

---

Polytan Sportfeldbaue GmbH
Geerbering 3, 89996 Burghheim
info@polytan.com, www.polytan.de

130402-LigaTurf RS+ CoolPlus 260 16-4 ol
PM

212
Technical Data Sheet

Product name  LigaTurf RS+ CoolPlus 260 16/4

Application  Professional

Quality data

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<th>Unit</th>
<th>Norm</th>
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<td>Tuft pull out force app.</td>
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<tr>
<td>Tensile strength axial MD app.</td>
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<td>Tensile strength longitudinal MD app.</td>
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<tr>
<td>Colour fastness</td>
<td>7 - 8 Blue scale</td>
<td></td>
</tr>
<tr>
<td>Weathering fastness</td>
<td>5 Grey scale</td>
<td></td>
</tr>
</tbody>
</table>

System design

Elastic layer

Polytan EL min.
Polytan ET min.

Turf infill-base

Sand  hydro classified, clean dried silica sand
Diameter round app.  0.3 - 0.8 mm

Turf infill-upper

Rubber granules  SBR, RPU, EPDM, BonfPro

Installation data

Carpet installation  floating
Seals  glued with Polytan wet-
component-adhesive

Certificates

- 

In order to maintain our surfaces to the highest and most up to date technical standards, we reserve the right to modify the product data. We advise that the technical values regarding yarn- and construction data as well as weight indications are approximate values and could vary due to technical reasons by +/- 10 %. (March 2013)
## Technical Data Sheet

### Product name

**LigaTurf RS+265 18/4**

### Application

**Professional**

### Description

Football turf with sand-rubber infill; Polytan Monofilament; 100 % Polytan PE formulation, straight without curling, single extrusion uncut, without fibrillation

### Yarn data

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<th>Materials</th>
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<th>Norm</th>
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<th>Number of filaments</th>
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<tbody>
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<td>360 µm</td>
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<td>Weight app.</td>
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### Backing construction

- **Primary backing 1**: 100 % PP woven fabric, UV stabilised
- **Primary backing 2**: 100 % PP stabilising fabric
- **Coating**: Latex, antibakteral and antifungal, waterproof

### Product data

- **Production technology**: Tufting velours, zig - zag
- **Maximum width**: 4 m
- **Maximum length depending on installation width**: 67 mm
- **Coating weight**: 1000 g/m²
- **Total weight**: 3000 g/m²

### General data

- **Turf colour**: green
- **Line colour**: white or yellow, other colours on request
- **Elastic layer**: Polytan EL layer in-situ

### Maintenance

Details for maintenance see Polytan maintenance brochure

---

Polytan artificial turf products exceed all technical values of the minimum requirements of the DIN V 18035/7. In order to maintain our surfaces to the highest and most up to date technical standards, we reserve the right to modify the product data. We advise that the technical values regarding yarn thickness and dtex, as well as the weight, are approximate values and could vary due to technical reasons by +/- 10 %. (April 2008)
## Technical Data Sheet

### Additional information

#### Product name

**LigaTurf RS+265 18/4**

#### Application

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<td>Tensile strength longitudinal MD app.</td>
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<td>7 - 8 Blue scale</td>
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<tr>
<td>Flammability</td>
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#### System design

- **Elastic layer**
  - Polytan EL min.: mm in-situ, on engineered base
  - Polytan TE min.: mm in-situ, on dynamic base

- **Turf infill-base**
  - Sand: hydro classified, clean dried silica sand
  - Diameter round app.: 0.3 - 0.8 mm
  - Sand filling app.: 13 kg/m² Laboratory data

- **Turf infill-upper**
  - Granules SBR (0.5 - 2.0) app.: 17 kg/m² Laboratory data
  - Granules RPU (0.5 - 1.5) app.: 0 kg/m² Laboratory data
  - Granules Bion Pro (0.5 - 2.0) app.: kg/m² Laboratory data
  - Granules Bion Pro (0.5 - 1.2) app.: kg/m² Laboratory data

#### Installation data

- **Carpet installation** floating
- **Seals** glued with Polytan wet-adhesive or two component-adhesive

#### Certificates

- EN 15330-1: FIFA 2 Star Accreditation

---

Polytan artificial turf products exceed all technical values of the minimum requirements of the DIN V 18039-7. In order to maintain our surfaces to the highest and most up to date technical standards, we reserve the right to modify the product data. We advise that the technical values regarding yarn thickness and die, as well as the weight, are approximate values and could vary due to technical reasons by +/- 10 %. (April 2008)

---

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APPENDIX B

Particle size distribution for rubber infill (PEC)

July 2015

MI 0.8mm – 2.5mm Granulated Rubber

Product Description

MI 0.8mm – 2.5mm granulated rubber is predominantly used as infill for artificial pitches; can also be applied to other products in a loose or bonded form.

Particle Grading

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</tbody>
</table>

Particle Size Distribution

Test Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber Hydrocarbon Content</td>
<td>BS 7014:13</td>
<td>50.89%</td>
</tr>
<tr>
<td>Azobenzene Extract</td>
<td>BA 182:1407</td>
<td>5.76%</td>
</tr>
<tr>
<td>Carbon Black Content</td>
<td>BS 7014:14</td>
<td>25.35%</td>
</tr>
<tr>
<td>Ash Content @550°C</td>
<td>BS 1202:97</td>
<td>5.75%</td>
</tr>
<tr>
<td>Sulphur Content</td>
<td>BS 1202:98</td>
<td>50.70</td>
</tr>
<tr>
<td>Pinpointed Hardness</td>
<td>BS 1802:81</td>
<td>60.75</td>
</tr>
<tr>
<td>Uncompacted Bulk Density</td>
<td>BS EN 1110/3</td>
<td>0.434 g/cm³</td>
</tr>
</tbody>
</table>

Particle Shape & Bulk Density

<table>
<thead>
<tr>
<th>Sample</th>
<th>Particle Shape</th>
<th>Classification</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Irregular</td>
<td>A3</td>
<td>0.44</td>
</tr>
<tr>
<td>2</td>
<td>Irregular</td>
<td>A3</td>
<td>0.44</td>
</tr>
<tr>
<td>3</td>
<td>Irregular</td>
<td>A3</td>
<td>0.43</td>
</tr>
<tr>
<td>Mean</td>
<td>Irregular</td>
<td>A3</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Packaging

Available in bulk bags or 25kg bags

#PremiumGranulatedRubber

Comply with & are distributed in accordance with PAS 100:2012 Quality Standard. For further information on packaging & storage please refer to PAS 100:2012.
**Data Sheet:**

**Product name:** GENAN Rubber Granulate Fine 1) - Medium 1) - Coarse & Rubber Powder 2)

**Producer:**
- Genan GmbH
- Birkenallee 80
- D - 16515 Oranienburg
- Genan A/S
- Jegindevej 16
- DK - 8800 Viborg

**Classification:**
- ASTM D 5603 - 01 / Grade 1 and 5

<table>
<thead>
<tr>
<th>Properties</th>
<th>Test methods acc. ASTM</th>
<th>Specification values acc. ASTM</th>
<th>Typical values GENAN Granulate &amp; Powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>J.</td>
<td>J.</td>
<td>1.10-1.20 g/cm³ 5)</td>
</tr>
<tr>
<td>Dicke / Masseichte</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td>D 5003, 8</td>
<td>J.</td>
<td>app. 500 kg/m³ 6)</td>
</tr>
<tr>
<td>Schützgewicht / Rümmelg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ashes</td>
<td>D 297, 34-37</td>
<td>&lt;= 8%</td>
<td>&lt;= 5%</td>
</tr>
<tr>
<td>Asche / Asf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetone extractables</td>
<td>D 297, 17-19</td>
<td>6-22%</td>
<td>app. 11-17%</td>
</tr>
<tr>
<td>Carbon black content 2)</td>
<td>D 297, 38-39</td>
<td>29-38%</td>
<td>app. 32-36%</td>
</tr>
<tr>
<td>Kautschuk-Kohlenwasserstoff</td>
<td>D 297,11</td>
<td>&gt;= 42%</td>
<td>&gt;= 42%</td>
</tr>
<tr>
<td>Loss on heating (2h@105°C) 3)</td>
<td>D 1509</td>
<td>&lt;= 1%</td>
<td>&lt;= 1%</td>
</tr>
<tr>
<td>Verlust bei Erwärmen / tab ved opvarmning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural rubber 3)</td>
<td>D 297, 52-53</td>
<td>10-35%</td>
<td>app. 30%</td>
</tr>
<tr>
<td>Free metal content 4)</td>
<td>D 5003, 7.3.2</td>
<td>&lt;= 0.1%</td>
<td>&lt;= 0.002% w/w</td>
</tr>
<tr>
<td>Freie Metalle / frit metal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free fibre content 4)</td>
<td>D 5003, 7.4</td>
<td>&lt;= 0.5%</td>
<td>&lt;= 0.001% w/w</td>
</tr>
<tr>
<td>Freie Textilfasern / frit tekstil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free mineral content 4)</td>
<td>D 5003, 7.3.1</td>
<td>J.</td>
<td>&lt;= 0.002% w/w</td>
</tr>
<tr>
<td>Freie Mineraler / frit mineraler</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

1) Includes Mix products FINE + MEDIUM-Mix / Inkl. Mischprodukt FEIN + MITTEL-Mix / Inkl. blandet produkt FIN + MODEL-Mix
2) In some tyres silica SiO₂ is used as part-replacement for carbon black
3) In one or more types the SiO₂ is used as part-replacement for carbon black
4) App. Water content / ca. Vassinehalt / ca. vandinhold
5) GENAN values only for rubber powder produced out of our rubber granulate in our fine grinding process
6) GENAN values only for rubber powder produced out of our rubber granulate in our fine grinding process
7) As the product is made off a large number of different types of material, GENAN can not give any exact values of the elastomeric composition of the material. The following can be used as a guideline:
   - NR (Natural Rubber) app. 30%
   - SBR (styrene-butadiene rubber) app. 40%
   - BR (butadiene rubber) app. 20%
   - IR (Isoprene rubber) app. 10%
8) Depend on material size / Affändig av materialgrösse / afhängig von materialgrößen

**Health and safety:**
- Not a dangerous substance when handled in accordance with good industrial hygiene and safety practice
- Kein gefährliches Produkt bei Beachtung industrieller hygienischer- und Sicherheitspraktiken
- Ingen farlig produkt ved anvendelse af de industrielle hygiejne- og sikkerhedspraktikker

These product specifications have been prepared to the best of our knowledge, and we shall not be liable for any insufficiency of inaccuracy in such information in any case whatsoever.

Dette data sheet er udarbejdet på grundlag af vor bedste viden, og vi hæfter ikke for manglende og/eller ukorrekte oplysninger somme eventuelle ændringer heraf.

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Version: GB=DK / 3

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APPENDIX C – STEP-BY-STEP OF MECHANICAL DEVICES

Step-by-step method of rotational test device

Below is a run through of the steps that must be achieved when completing a trial on the rotational traction device.

1. Ensure correct studs are in bottom of stud plate on device.
2. Make up the desired sample. A sample of any given specification was made up measuring 1000 x 1000 mm.
3. Place the device on the surface with weights of 46 ± 2 kg attached above the stud plate.
4. Use the 60 mm depth gauge to measure the distance that the weights are lifted and dropped.
5. Ensure the sensors are attached to the rotational device and connected to the laptop as discussed in 5.2.1.

6. Put the desired settings in Labview, including the calibration settings and capture rate.

7. Press start on the laptop to begin the collection of data from the sensors.

8. Lift the weights to a height of 60 ± 5 mm and drop onto the surface.

9. The torque wrench is then rotated by at least 45° trying to keep the rate of rotation at a constant speed of 12 rev/min. The intended rotational for every trial was 180°.

10. Save the trial on the laptop.

11. Move the device onto a new piece of surface for next trial.
Step-by-step method of translational traction device

1. Make up the desired sample. A sample of any given specification was made up by first cutting out a piece of carpet of 500 x 500 mm. It was then ensured that this sample fit in the tray attached to the rig, and cut down to size if required.

2. Place the shockpad in the tray, followed by the surface sample. It was ensured that the shockpad was fixed to the tray and the carpet was fixed to the shockpad to guarantee no movement took place. To ensure for stability, strong double sided tape was placed on the bottom of the tray to attach to the piece of shockpad. Double sided tape was then placed on top of the shockpad for attachment to the bottom of the carpet. This was to ensure that under high loads, the carpet did not move.

3. Place desired weights on top of the device. The appropriate mass could be added to the top of the rig. Due to the height of the rig and the mass of the weights (20 kg), this was completed using a ladder to fulfil the health and safety requirements.

4. Fix the foot plate being used onto device by slotting it into the bottom of the central column and fixing with a nut and bolt.

5. Ensure a laptop is attached to the vertical displacement sensor and Labview is set up. Change the settings, including the sensitivity, the capture time and capture rate.

6. Use the calibration platform described in section 5.3.2.3 to complete the calibration of the vertical displacement sensor. This is completed using the following steps.
- The platform is placed in the middle of the sample, underneath the foot plate, and ensured the infill is level, using the bubble level. If uneven, the surface was raked.

- A reading can be taken at a point, with the foot above the platform/surface. The distance between the top of the platform and the bottom of the foot could be measured using Vernier callipers.

- The height of the platform can then be added to this number. The stud height can then be subtracted.

- This gives a distance between the top of the surface and the bottom of the studs. If this height is taken from the original number from the vertical displacement sensor, this gives us a value that can be offset to give the top of the surface a value of 0.

- When any testing is completed, it will be clear in the results how far the studs penetrate the surface and move up and down as the foot is pulled through the surface.

7. Measure the infill height using an infill height gauge.

8. Set appropriate program on Instron using Bluehill software.

9. Ensure the tray is pulled out to the maximum position so that when the foot plate is placed on the surface, it is in the correct position.

10. Lower the linear actuators to place the foot plate on the surface, ensuring weight is fully on the surface for a constant normal load.

11. Press record on the Labview software on laptop to start vertical displacement sensor recording.

12. Press start on Bluehill Instron software on desktop computer to begin movement of the tray.

13. Wait for tray to move and for foot plate to complete movement through the surface.

14. Lift the foot plate off the surface using the linear actuators.

15. Save the data from vertical displacement sensor.

16. Measure infill height again to measure the change in height during the test.

17. Recondition the surface.

18. Repeat trial.