EFFECT OF MECHANICAL BEHAVIOUR OF ARTIFICIAL TURF ON PLAYER-SURFACE INTERACTION IN SOCCER

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ABSTRACT

This study aimed to extend the knowledge on player and surface loading by contributing new data in relation to a greater range of movements, relevant in-game scenarios and on carefully controlled third generation artificial turf surfaces. This was done by selecting soccer relevant movements and in-game scenarios for a player movement study with the help of a player focus group and questionnaire. Furthermore, four surfaces were created with surface hardness and rotational traction values at the upper and lower limits of the standards set by FIFA.

The study showed that both the surface hardness and rotational traction properties can affect the human movement dynamics, though these effects were mainly present during the stop and turn manoeuvre. During the stop and turn manoeuvre the soft and high traction surfaces conditions led to increased frontal plane moments as well as increased average ground reaction forces during mid-stance. In combination with decreased ground contact times it appeared that the players were able to decelerate / accelerate faster and generate a larger force on the soft and high traction surfaces. During peak push off it appeared that the players were able to generate a larger force on the hard surfaces, which also led to a significant increase in plantar flexion moment.

While some parameters showed an effect for surface hardness and / or rotational traction across all four surface conditions, for others such as the knee valgus, hip extension and hip internal rotation moment showed only a significant effect between two of the four surfaces. At the same time the other surfaces showed either no effect or the opposite effect. This suggests that the effects of the surface hardness can be influenced by the rotational traction properties, and vice versa.

Regarding the jumping / heading manoeuvre the effects of the surface conditions were limited. This may have been related to the high demands of the movement, or to limitations of the mechanical measurement methods.

In addition to the effects of surface properties on human movement dynamics the study also showed that the mechanical measurement methods may not be representative of the human loading. The impact force conditions of the advanced artificial athlete were substantially different to that of the stop and turn and jumping / heading manoeuvre. Whereas for the rotational traction test the study showed that the rotation of the foot during the ST was substantially less than the minimum 45° required by the FIFA guidelines.

Regarding the inclusion of in-game scenarios the study showed that both the simulated opponent used for the stop and turn manoeuvre, and heading a ball during a maximal vertical stop jump manoeuvre can affect the human movement dynamics. During the stop and turn with a simulated opponent the frontal plane moments in the lower limbs were significantly increased. However, this increase in joint loading could not be related to any changes in movement strategy. During the landing after heading a ball during a maximal vertical stop jump the players used a different landing strategy by landing in a more upright position and increasing the ankle plantar flexion ankle just before lading. This allowed for a larger change in the ankle plantar / dorsi flexion angle to absorb the impact of the landing. In addition to this, the heading manoeuvre also led to a significant increase in the frontal plane joint moments of the lower limbs.

For future studies it is recommended that a combination of surface properties is used to gain insight into how these affect each other regarding the effects they have on human movement dynamics. In addition, they should provide detailed information on the surface design as well as the properties. Regarding the quantification of the properties it is recommended that in addition to industry standards the surfaces are also quantified using conditions closer to those expected within the study. It is also recommended that future studies incorporate in-game scenarios in order to gain more insight into the effects of interventions that simulate actual match situations.

Keywords: Third Generation Synthetic Turf Surface, Surface Hardness, Rotational Traction, Mechanical Property Behaviour, Soccer, In-game Scenarios, Stop and Turn, Vertical Stop Jump, Heading, Simulated Opponent

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TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1: Introduction

Chapter 2: Literature Review

Chapter 7: Player Movement Study

LIST OF TABLES

Chapter 2: Literature Review

Chapter 3: Research Philosophy

Chapter 4: Player Perception

Chapter 5: Pressure Insoles

Chapter 6: Surface Design

Chapter 7: Player Movement Study

NOMENCLATURE AND ABBREVIATIONS

FIFA	International Federation of Association Football
SBR	Styrene-butadiene-rubber
g	Gram
kg	Kilogram
N	Newton
kN/m	kilo Newton per metre
N/mm	Newton per millimetre
Hz	Hertz
Fz, Fy, Fx	Force coordinates related to forces platform (Figure 7.5)
AAA	Advanced Artificial Athlete
GRF	Ground reaction force
vGRF	Vertical ground reaction force
m/s	Metre per second
FR	Force reduction
3G	Third generation artificial turf
mm	Millimetre
cm	Centimetre
km	Kilometre
s	Seconds
UV	Ultraviolet
%	Percentage
°	Degree
§	Section
>	Greater than
h	hour
LED	Light-emitting diode
2D	Two-dimensional space
3D	Three-dimensional space
~	Approximately
m^2	Square metre
e.g.	Example given

SD	Standard deviation
rev/min	Revolutions per minute
ST	Stop and turn
JH	Jumping / Heading
RT	Rotational traction
PRE	Pre-movement phase
WA	Weight acceptance phase
MS	Mid-stance phase
PO	Push-off phase
FP	Final push off phase
IMP	Impact phase
KNF	Knee flexion phase
FIN	Final phase
COM	Centre of mass
BW	Body weight
HAhi	Hard – high traction surface
HAlo	Hard – low traction surface
SOhi	Soft – high traction surface
SOlo	Soft – low traction surface

1. INTRODUCTION

1.1 Introduction

Since the introduction of artificial turf in the 1960's it has gone through substantial developments. In some sports like field hockey it has been accepted as a replacement for natural grass and the majority of top level matches are played on artificial turf (FIH, 2008). However, in other sports like soccer a lot of players and teams still prefer natural grass and concerns exist about the effects of artificial turf on the game characteristics, like ball bounce, and injury risk. Also players complain about aches after playing on artificial turf and in some cases players have missed matches due to fear of injuries (Schalke04, 2011). In addition to this, teams are not always happy to play on artificial turf, Real Madrid even demanded that a natural grass layer was installed on top of an artificial turf pitch before playing a friendly match (Reuters, 2009). Finally, coaches and soccer players often have a negative attitude towards artificial turf. For example, during the 2012 European championships Ruud Gullit, former player (A. C. Milan) and coach (Chelsea F.C.), explicitly stated on Dutch television (Studio Sportzomer, 21 June 2012) that he was opposed to the use of artificial turf in soccer and in his opinion all soccer players are.

Despite the reluctance of some players and teams, artificial turf has been gaining popularity in soccer since the introduction of the so-called 'third generation' (3G) artificial turf, which uses sand and rubber infill that makes the playing characteristics closer to that of natural grass. Over the years more top teams, like Tottenham Hotspur, are making use of artificial turf on their training facilities and some clubs in the top national divisions in Europe have an artificial pitch as their match surface, such as Heracles Almelo in the Netherlands. Besides this some international matches, such as the Russia versus England match in the Euro 2008 qualification, have been played on artificial turf.

While the popularity and acceptance of artificial turf is increasing little is known about the effects different surface properties, and more specifically the standards set by FIFA, have on the musculoskeletal loading of the players. Some studies have been done with the inclusion of artificial turf surfaces or using different soccer boots (Kaila, 2007; Queen et al., 2007; Stefanyshyn et al., 2010). However, most of these studies fail to provide any information about the surface properties. This means that while FIFA has set several guidelines and two quality certifications it is unknown how these values affect the loading on the body, as well as how much variation exists within the limits set by FIFA.

On top of the limited knowledge on how the surface properties affect the musculoskeletal loading, previous biomechanical studies are also limited primarily to in-line running (Arampatzis et al., 1999; Eils et al., 2004; Farley & Gonzalez, 1996; Meijer et al., 2007), and to a lesser extent on cutting and turning manoeuvres (Besier et al., 2001; McLean et al., 2004; Wannop et al., 2010; Stefanyshyn et al., 2010) and vertical jumps / landings (Chappell et al., 2005; Decker et al., 2003; Kellis & Kouvelioti, 2009; Oliver et al., 2008), despite the large range of movements identified in other studies (Bloomfield et al., 2004). In addition to this movements are often performed under controlled lab conditions, whereas the loading on the body during a match situation may be different as suggested in previous research (Reilly, 1997; McLean et al., 2004; Chan et al., 2009). Therefore the use of in-game conditions could be a valuable addition to gain insight into how the body is loaded during actual match situations.

1.2 Aims and Objectives

The aim of the research performed for this PhD was to extend the knowledge on player and surface loading by contributing new data in relation to a greater range of movements, relevant in-game scenarios and on carefully controlled surfaces. In order to achieve this aim the following research questions were formulated:

A: How do varying surface properties of artificial turf in soccer affect the movement dynamics of players during soccer relevant movements?

B: How do in-game scenarios affect the movement dynamics of players during soccer relevant movements?

To answer these research questions the following objectives were formulated:

1: Review current knowledge on: surface design, standards and test methods; player movements in soccer; and the effects of surface properties and in-game scenarios on player kinematics and loading during soccer-specific movements.

2: Select relevant surface properties and range of properties, movements and develop suitable in-game scenarios to form the basis of an experimental investigation into the effects of surface properties on player kinematics and loading.

3: Design artificial turf systems that represent the range of surface properties identified in Objective 2.

4: Design an experimental study to measure the player kinematics and kinetics on the different surfaces and in-game scenarios.

5: Measure the effects of controlled surface properties and in-game scenarios on player kinematics and loading during selected soccer movements (as identified in Objective 2).

6: Evaluate the results from Objective 5 with respect to the effects of surface properties on player movement and loading, and the relevance of in-game scenarios under lab testing conditions.

The first objective was achieved with the help of a thorough literature review. Details on the approach to meet the remaining objectives and choices made are presented in the research philosophy (Chapter 3).

1.3 Thesis Structure

The chapters in this thesis are related to each other and some cross referencing will take place in the varying chapters. A preview of each chapter is given with a brief description and flow chart (Figure 1.1) presents how the different chapters are interlinked.

Chapter 1: Introduction

Provides an introduction to the thesis as well as an overview of the background of the research topic and the aims and objectives set.

Chapter 2: Literature Review

Contains a thorough review of the current literature covering the different factors related to the research topic including: artificial turf surfaces (including surface standards and testing), injuries in soccer, and movements (including types of movements and biomechanical effects of surface properties and in-game scenarios on human movement dynamics).

Chapter 3: Research Philosophy

Discusses the approach taken to achieve the aims and objectives presented in §1.2, hypotheses for the player movement study, and a statement on the contribution to knowledge.

Chapter 4: Player Questionnaire / Focus group

Presents the findings of a player questionnaire and focus group conducted with soccer players of Loughborough University teams on the relevance of various movements and in-game scenarios in soccer and the experienced loading on the body during these. Furthermore, it discusses their preference on surface properties and perception and attitude while playing on different surfaces.

Chapter 5: Evaluation of Pressure Insoles

Presents the findings of a study on the repeatability, reliability and durability of pressure insoles during running and an evaluation on whether they could be a valuable contribution to the player movement study.

Chapter 6: Surface Design

Discusses the design process of the different surfaces used in the player movement study, as well as the results of tests to evaluate how to maintain the surface properties when being disturbed.

Chapter 7: Player Movement Study

Presents the results of how the surface hardness and rotational traction properties of an artificial turf surface, and in-game conditions affect the human movement dynamics of soccer players during a stop and turn and landing after a jumping / heading movement. The main findings of this are drawn together in §7.4.

Chapter 8: Conclusion

Formulates a final conclusion from the discussion in Chapter 8, highlights the limitations of the current study and offers recommendations for future work.

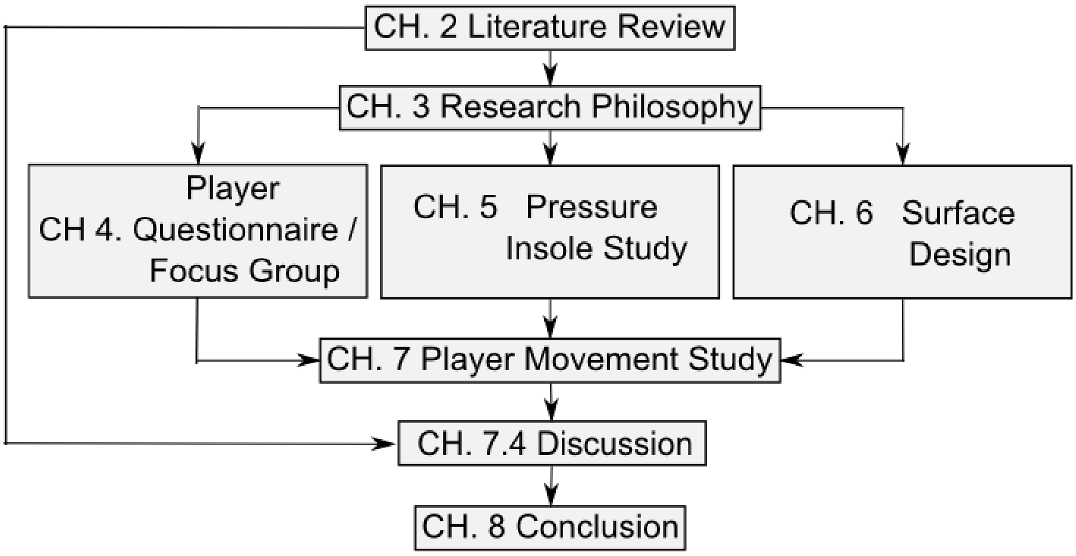

Figure 1.1. Flow chart presenting how the chapters of this thesis are interlinked with each other

1.4 References

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2. Literature Review

2.1 Introduction

The first objective set in Chapter 1 for this thesis involved reviewing the current knowledge on: surface design, standards and test methods; player movements in soccer; and the effects of surface properties and in-game scenarios on player kinematics and loading during soccer-specific movements. This chapter meets this objective and for this the chapter is divided into three main sections: surfaces (§2.2), injuries in soccer (§2.3), and movements (§2.4).

The aim of §2.2 was to gain insight into the different types of artificial turf that currently exist, the criteria set by FIFA, the mechanical measurement methods, and how the properties of the surface can be modified. This formed the basis for creating surfaces with different properties, and for the approach to measuring and monitoring these properties (detailed in Chapter 3). Section 2.3 had the aim to gain insight into what body locations are commonly injured in soccer and risk factors that have been identified to increase the injury risk. This gave an indication of which body parts are loaded the most in soccer, whereas the risk factors identified also helped with the approach to the experimental design of the player movement study (Chapter 3). The aim of §2.4 was to gain insight into the range of movements in soccer that have been identified and classified in previous studies, as well as the effects that surface properties and in-game scenarios may have on the movement dynamics and human loading, and the player dynamics during selected movements. This knowledge assisted in selecting movements and in-game scenarios for the player movement study and with formulating hypotheses (detailed in Chapter 3).

The key gaps in knowledge are then discussed in §2.5. This includes the presentation of an approach for moving the research forward in this area of player-surface interaction and forms the basis for the research philosophy set out in Chapter 3.

2.2 Surfaces

2.2.1 Introduction

Sport surfaces can be divided into natural and artificial surfaces. Natural surfaces like grass or snow are created by suitable preparation of an area and are common in many outdoor sports. Artificial surfaces like artificial turf or an athletics track are constructed with human prepared materials and can normally be found in indoor sports like basketball or the track events in athletics (Nigg & Yeadon, 1987).

Artificial turf was first introduced in a professional sport setting in the Astrodome in Texas (1966), which consisted of a synthetic grass carpet made from nylon fibres. After a few years the nylon fibres were replaced by polypropylene which was softer and more comfortable. This design is now referred to as ‘first generation’ artificial turf. In the late 1970’s ‘second generation’ artificial turf was introduced, which had longer tufts that were spaced more widely apart and it had a sand infill to provide firmness and stability for the players. The main advantage of ‘second generation’ artificial turf was that the playing surface was more even than natural grass which gives better ball control. This was especially of use in field hockey and led to an increase in speed of the game. For soccer the playing characteristics and ball behaviour on the ‘second generation’ artificial turf were deemed too different compared to playing on natural grass.

In the 1990’s ‘third generation’ (3G) artificial turf was developed. This new generation had longer fibres which again were spaced further apart. They were also made of polyethylene which is softer and kinder to the skin and a rubber infill was added to the sand already used in the second generation turf. These changes brought the characteristics of the game closer to the characteristics on natural grass and therefore 3G surfaces were deemed more suitable for soccer (FIFA, 2004).

2.2.2 Artificial Turf Systems

An artificial turf system consists of a surface system (infill, carpet, shockpad) and a foundation (asphalt, geotextile and sub-base) (Figure 2.1) (Fleming, 2011). The foundation is important for the stability of the surface system as well as other properties of the artificial turf system such as water drainage. However, as the remainder of this thesis focuses on the surface system only this part of the artificial turf system will be discussed in the rest of this chapter.

Considering the surface system there are many different types of artificial turf for which the main differences include the infill and the carpet (pile height and density). Six different kinds of artificial turf have been identified and are presented in Table 2.1, which serve different sports. Third generation artificial turf is the type used in soccer and is also the type of artificial turf that is referred to in the remainder of this chapter / thesis unless otherwise stated.

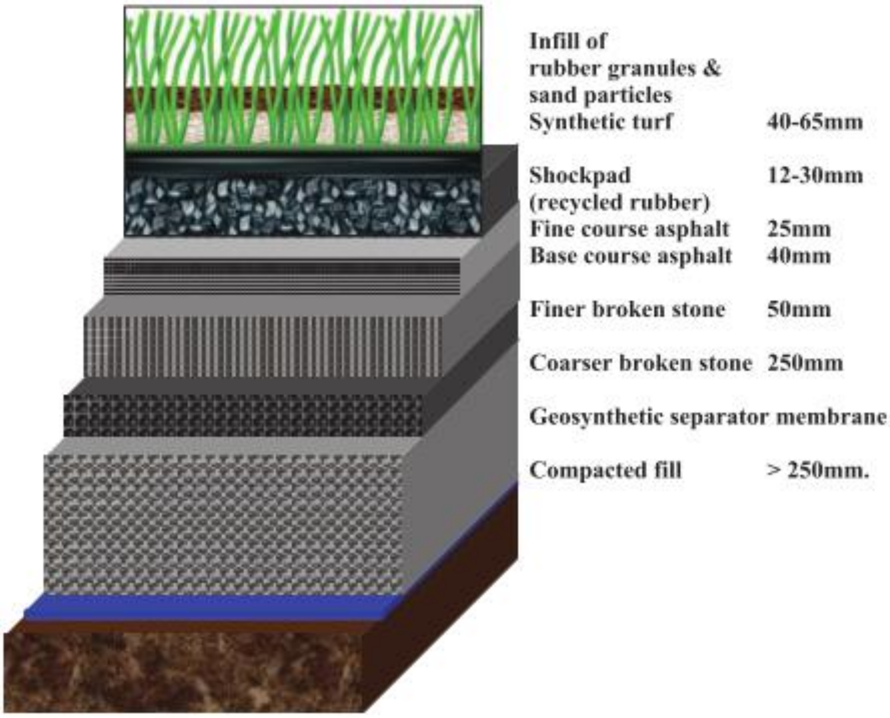

Figure 2.1. Cross-section of typical construction profile for third generation artificial turf systems including the surface system (infill, carpet, shockpad) and foundation underneath (Fleming, 2011).

Table 2.1. The characteristics of the different types of artificial turf (SAPCA, 2009).

Type of artificial turf	Type of infill	Characteristics	Sport
Non-filled	-	High pile density	
Water-based	-	Water is base for stability and changes playing characteristics	Hockey
Sand-filled	Sand	Widest tufting method, sand within 3mm of fibre tips	
Sand-dressed	Sand	Shorter and denser pile than sand-filled	
Needle-punch	Sand	8 – 16 mm thick carpet with fine sand filling	
Third generation (3G)	Sand & Rubber	Longest pile up to 65 mm, combination of rubber/sand infill up to $^{2}/_{3}$ of pile height	Soccer

All 3G pitches use a combination of sand and rubber infill to modify the playing characteristics and provide stability to the carpet. However, a wide variation is possible when it comes to the materials used for the carpet, infill and shockpad. The carpet has a pile height of up to 65 mm of which $^{2}/_{3}$ includes the sand and rubber infill. The tufts keep the infill in place and can be made of different materials, such as polypropylene and polyethylene**,** different shapes, straight curled and twisted, and different fibres, such as monofilament or fibrillated fibres (Figure 2.1). The rubber infill provides some of the shock absorption and can either be mixed with the sand or incorporated with the sand in layers. Different types of rubber / elastomeres infill exist; styrene-butadiene-rubber (recycled tyres) is most commonly used, but specially developed infill is also available such as Terra XPS^{TM}, Coolfill^{TM}, Flexsand^{TM} and TenCate I-sport^{TM} (Figure 2.3).

To modify the shock absorption properties and ball behaviour of the surface a shockpad can be placed underneath the carpet. Shockpads can either be pre-formed or constructed in-situ. A range of pre-fabricated shockpads are available that use different materials such as rubber and closed-cell foam (Figure 2.4). The pre-formed rubber shock pads generally have a thickness of 8 – 15 mm. However, like the materials the thickness of the shock pad may vary across the surface as long as the playing characteristics meet the requirements dictated by the sport governing bodies (Figure 2.4). The in-situ shock pads can vary in thickness from 15 – 35 mm and generally consist of a polyurethane binder mixed with rubber crumb/shred. Thicker pads may also contain pea gravel or other smaller aggregates.

Figure 2.2. Example of different types of fibres used in the carpet of artificial turf surfaces, monofilament (left) consist of single fibres, whereas fibrillated (right) fibres are at first connected to each other and split during use.

Figure 2.3. Example of different types of rubber / polymers infills available for 3G artificial turf. Styrene-butadiene-rubber (upper left) is most commonly used, but specially developed infill (upper right and lower left and right) are also available.

Figure 2.4. Example of different types of pre fabricated shockpads available for 3G artificial turf made from rubber (middle), closed-cell foam (right) and a mixture of different foam products (left).

2.2.3 Surface Standards

As the behaviour of artificial turf can be modified in multiple ways, sports governing bodies have made certain criteria to which the turf has to comply. Before being approved the artificial turf is first tested in the lab, which also includes wear and aging tests with a lisport machine and UV lights. For a final approval a field test is performed in multiple locations after the installation of the pitch.

To approve the pitches FIFA uses two different rankings, FIFA one star pitches, for recreational use, and FIFA two star pitches, for professional soccer (Table 2.2). FIFA states that their standards are based on the readings of good natural turf pitches to ensure artificial turf pitches have similar playing characteristics as real grass (FIFA, 2004). However, the criteria for a good natural turf pitch are not given. The tests performed can be divided into two separate groups: player-surface interaction and ball-surface interaction. In the player-surface interaction tests linear friction, rotational traction, force reduction, and vertical deformation are considered. Whereas for the ball-surface interaction the vertical ball rebound, angled ball rebound and ball roll are tested. However, while sports governing bodies have set standards this does not mean that all artificial turf surfaces meet these standards. As of July 2012, 981 accredited pitches can be found globally, of which the majority (80%) is located in Europe. However, in July 2012 it was also estimated that there are approximately three to four thousand artificial turf pitches in the Netherlands alone, of which it can be assumed that many are also used for soccer since this is the most popular sport in the Netherlands with 20% of the sports participants being a member of the Dutch football association KNVB (Verzekerd, 2012; Breedveld & Tiessen-Raaphorst, 2006). This suggests that globally many soccer matches are played on surfaces that have not been tested, albeit mainly on an amateur level, and which possibly do not meet the FIFA standards.

Table 2.2. Tests and standards set by FIFA to ensure surface characteristics of artificial turf pitches in soccer (FIFA, 2012a).

Interaction	Test	Special conditions	FIFA One Star	FIFA Two Star
Ball – Surface	Vertical Ball Rebound		60 – 100 cm	60 – 85 cm
	Angled Ball Rebound	Dry	45 – 70 %	45 – 60 %
		Wet	45 – 80 %	45% - 80 %
	Ball Roll	Initial	4 – 10 m	4 – 8 m
		After 12 months		4 – 10 m
Player – Surface	Force Reduction		55 – 70 %	60 – 70 %
	Vertical Deformation		4 – 11 mm	4 – 10 mm
	Rotational Traction		25 – 50 Nm	30 – 45 Nm
	Linear Friction	Stud deceleration	3.0 – 6.0 g	3.0 – 5.5 g
		Stud slide	120 – 220	130 – 210

While FIFA has set the standards presented in Table 2.2 other sports governing bodies can use different values to which the surfaces have to comply. For example, for the force reduction the International Hockey Federation requires a value between 40 – 65%, whereas the International Rugby Board requires the same values as the FIFA 1 star qualification (55 – 70%), and in addition to the standards used by FIFA also uses energy restitution to quantify the surface behaviour (FIH, 2008; IRB, 2012). This shows that the surface standards are dependent on what properties and values the specific sports governing boards consider as appropriate for their sport.

Figure 2.5. FIFA approved pitches for per continent in July 2012 (www.fifa.com)

2.2.4 Surface Testing and Behaviour

As shown in §2.2.3 sports governing bodies have set different standards to ensure the quality and behaviour of artificial turf surfaces. Regarding player-surface interaction these include the surface hardness (force reduction), traction (linear translational and rotational), and deformation of the surface, and for some sports, such as the rugby, this also includes the energy restitution. In Chapter 4 the choice was made to modify the hardness and rotational traction of surfaces to be used in the player movement study. Therefore the following sub-sections will focus on what measurement methods are available to quantify the surface hardness and rotational traction and how these properties can be modified.

The surface hardness can, dependent on the mechanical measurement method, either be defined as the effect the surface has on impact forces, or as the effect an applied force has on the deformation of the surface (Twomey et al., 2012; McMahon & Greene, 1979). The way this is quantified is dependent on the test method used to measure the surface hardness. The rotational traction can be defined as the resistance of the rotation between the shoe outsole and the surface (Villwock et al., 2008). This is generally described using the moment of rotation with respect to the centre of pressure, referring to the rotation of the foot around a point of contact (Nigg & Yeadon, 1987; Wannop et al., 2010).

2.2.4.1 Surface Hardness

As mentioned, the surface hardness can be quantified in several ways, dependent on which method is used. The standard test used by FIFA to measure the surface hardness involves an (Advanced) Artificial Athlete. The (Advanced) Artificial Athlete is a portable device which works on the principle that a 20 ± 0.1 kg weight is dropped vertically from a height of 55.00 ± 0.25 mm above the surface (Figure 2.6). The force of the impact is then measured with either a load cell underneath a spring (2200 ± 100 N/mm) on which the weight drops (Artificial Athlete), or with a uni-axial accelerometer (9600 Hz) that is attached to the top of the weight that has the spring attached on the bottom (Advanced Artificial Athlete) (FIFA, 2009; FIFA, 2012b). After determining the impact force the hardness is then expressed as the reduction of force on the surface relative to a stable and rigid surface ("no significant deflexion under a 5 kg/cm^2 pressure") (FIFA, 2012b). The reference force for this is 6760 N, which is the theoretical value calculated for a concrete surface (FIFA, 2012b).

Another device used to measure the surface hardness is the Clegg Impact Hammer. The Clegg Impact Hammer, like the (Advanced) Artificial Athlete, is a portable impact test, with the main differences being that the weight of the falling mass is less (0.5, 2.25, or 4.5 kg), no spring is involved, and that the drop height is much higher (45 cm) (Figure 2.7). The falling mass of the Clegg Impact Hammer is dropped on the surface through a guide tube after which the surface hardness is expressed as the peak deceleration of the falling mass on impact with the surface in gravities.

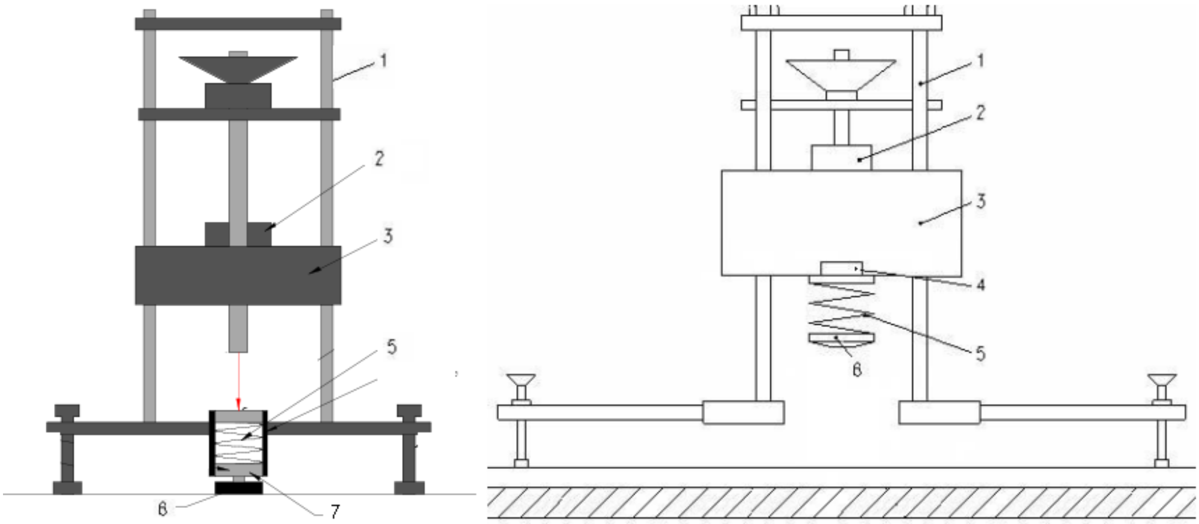

Figure 2.6. Schematic overview of the Artificial Athlete (left) and Advanced Artificial Athlete (right) including: 1:guide for the falling mass 2: electric magnet 3: falling mass 4: accelerometer 5: spring 6: test foot 7: load cell (FIFA, 2009; FIFA, 2012b). The Artificial Athlete uses the load cell to measure the impact force, whereas the Advanced Artificial Athlete uses the accelerometer data.

Finally specialist material testing machines, such as an Instron Electropulse (Figure 2.7), can be used to determine the surface hardness. With these devices a force-deflection curve can be created by increasing the load on the surface (Figure 2.8). After creating the curve the hardness can be determined at different force levels along the curve and is subsequently expressed as the amount of force that is needed to deflect the surface a certain distance, this is typically referred to as the surface stiffness and expressed in units of kilo Newton per metre (kN/m) (McMahon & Greene, 1979).

Figure 2.7. The Clegg Impact Hammer (left) (Severn, 2010) and an the Instron Electropulse (right).

From the methods described above it becomes clear that the way the surface hardness is expressed depends on the method used. The force reduction, measured with the (Advanced) Artificial Athlete, and the deceleration, measured with Clegg Impact Hammer, are the most similar as both are based on the principle of a weight dropping on the surface. Furthermore, a previous study has reported a good correlation between the Clegg Impact Hammer measurements and those of the (Advanced) Artificial Athlete (Fleming, 2011). In contrast with the force reduction and deceleration, the surface stiffness is based on the surface deforming under a compressive load instead of on an impact load. Previous studies have not tried to correlate the surface stiffness with the measurements of the (Advanced) Artificial Athlete or Clegg Impact Hammer, but a previous research using artificial turf surfaces did show that surfaces with a higher stiffness had lower force reduction values (Meijer et al., 2007).

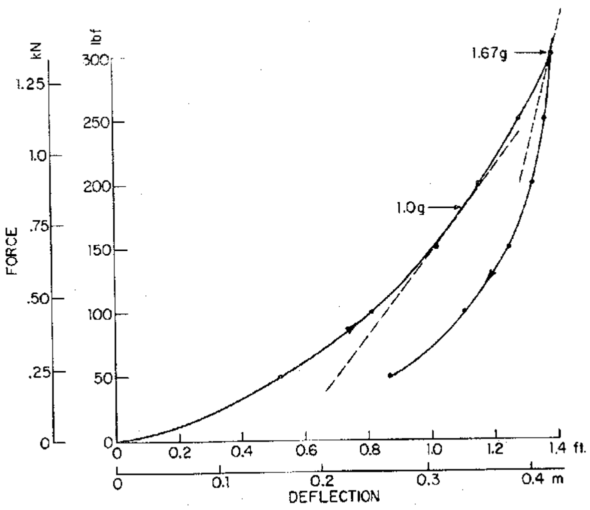

Figure 2.8. Force-deflection curve used to determine the surface stiffness (McMahon & Greene, 1979).

Apart from the differences in how the hardness is expressed the different measurement methods have a few other differences. First of all the (Advanced) Artificial Athlete and Clegg Impact Hammer are portable, whereas specialist material testing machines are less manoeuvrable. This means that to determine the surface stiffness the surfaces have to be placed inside the test device, which means that this method is less suitable to monitor surfaces and can put restrictions on the sample size that can be used. On the other hand, the force-deflection curve created to determine the surface stiffness allows for determining the surface hardness at different force levels, whereas the force reduction and deceleration are determined during a single impact condition. This is especially relevant as Figure 2.8 shows that the surface behaviour is non-linear when the loading is increased.

Previous studies on surface characteristics have shown that the surface materials used can affect the surface hardness. A study by Severn (2010) showed that both the infill and shockpad used can influence the outcomes. For the infill it was found that surfaces with a higher rubber infill thickness decreased the impact force leading to a higher force reduction and a lower deceleration value measured with the Clegg Impact Hammer (Figure 2.9). The rubber infill thickness was shown to be dependent on both the amount of infill used as well as the compaction of the infill (Figure 2.10). With regards to the shockpad, two shockpads were used with a different thickness and similar effects were found as for the infill thickness (Figure 2.9). However, the effect of the shockpad seems to be dependent on the rubber infill thickness.

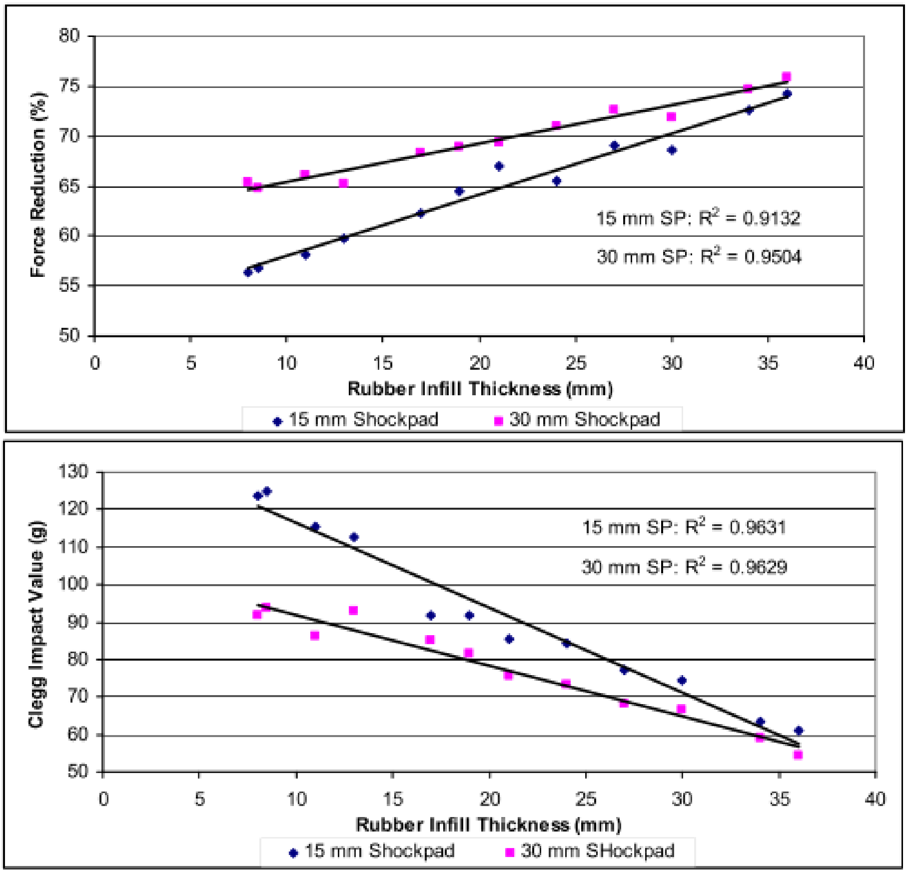

Figure 2.9. A study by Severn (2010) showed that both the rubber infill thickness and shockpad thickness have an effect on the force reduction and Clegg Impact value. The effect of the shockpad was largest for surfaces with a low rubber infill thickness.

Finally, a previous study that looked at the effects of the surface stiffness of 3G surfaces on running showed that the surface stiffness decreased and the force reduction increased when the shockpad thickness increased (Meijer et al., 2007). This was also found in a study by Ferris et al. (1998) on running on surfaces with a different stiffness.

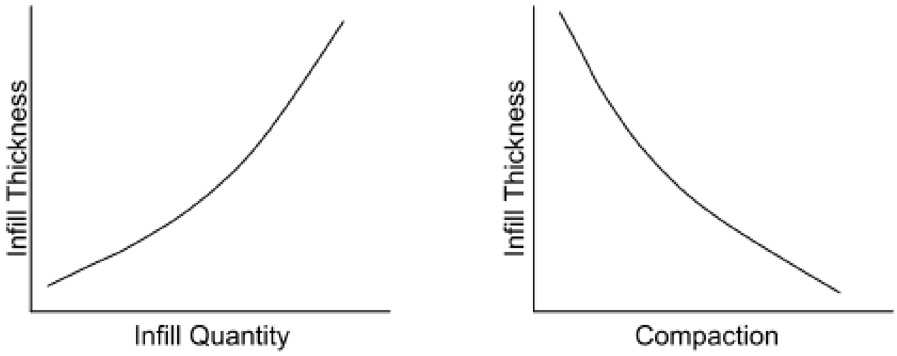

Figure 2.10. A study by Severn (2010) showed that the rubber infill thickness of a surface is dependent of both the infill quantity as well as the compaction of the surface.

2.2.4.2 Rotational Traction

To determine the rotational traction properties of a surface several methods are available. The standard FIFA test works on the principle that a studded test foot, which is loaded up to a weight of 46 ± 2 kg, is dropped from a height 6.0 ± 0.5 cm above the surface and rotated manually at a speed of 12 rev/min until the test foot moves and has reached a minimal rotation of 45° (Figure 2.11) (FIFA, 2012b). The test foot comprises of a metal disc with a diameter of 145 ± 10 mm with six rounded football studs (11 mm long) spaced equally at 46 ± 1 mm from the centre of the disc (Figure 2.11). After rotating the test foot the peak torque, expressed in Newton metre (Nm), is taken as a measure for the rotational traction.

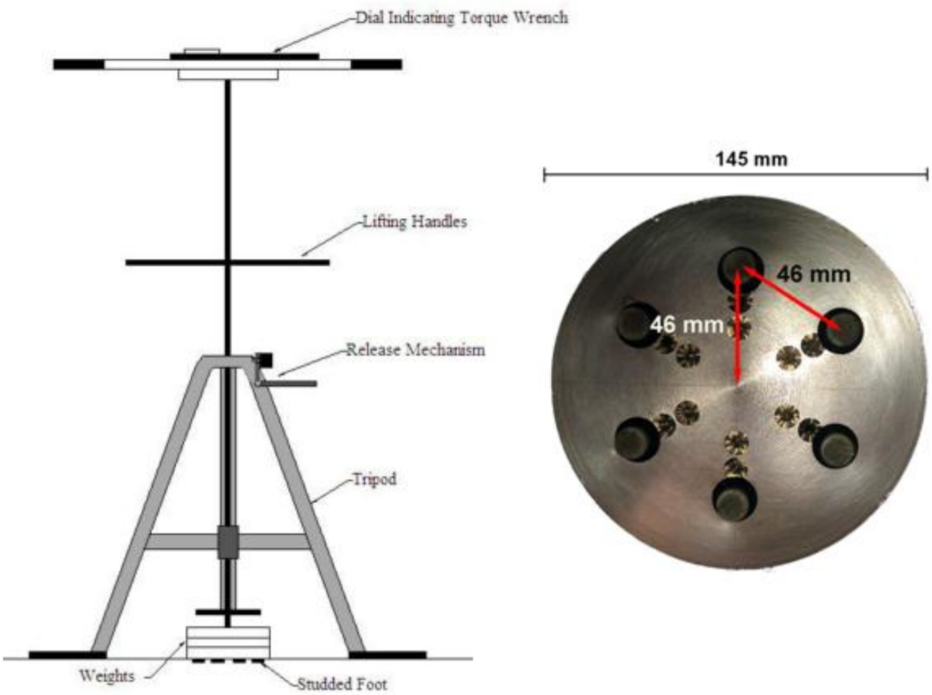

Figure 2.11. Schematic overview of a standard rotational traction device (left) to measure the rotational resistance of a surface and stud layout of the test foot (right) (FIFA, 2012b)

Previous studies on rotational traction have used different methods to measure the rotational traction properties of the shoe-surface interface. Studies by Wannop et al. (2010) and Stefanyshyn et al. (2010) used a similar principle as the standard FIFA test, but instead of using weights to load the studs they used a six degree of freedom Stewart platform (Figure 2.12). Furthermore, the platform was rotated rather than the test foot and the test foot comprised of a soccer boot that was placed at a 20° ankle plantar flexion angle to the surface to simulate the foot during a cutting movement (Wannop et al., 2010; Stefanyshyn et al., 2010). As for the standard test device the peak torque was used as a measure for the rotational traction.

In a study by Severn (2010) a traction device was used which was developed by Adidas, in addition to the standard rotational traction device (Figure 2.13). For the rotational traction the principle of the device was much the same as the device used in the studies by Wannop et al. (2010) and Stefanyshyn et al. (2010), with the main difference that the device rotated the test foot and not a platform, and the shoe was placed at an angle of 18°. However, while the platform was not rotated the surface sample still had to be placed in the test device. As for the previously discussed methods the peak torque was used as a measure for the rotational traction.

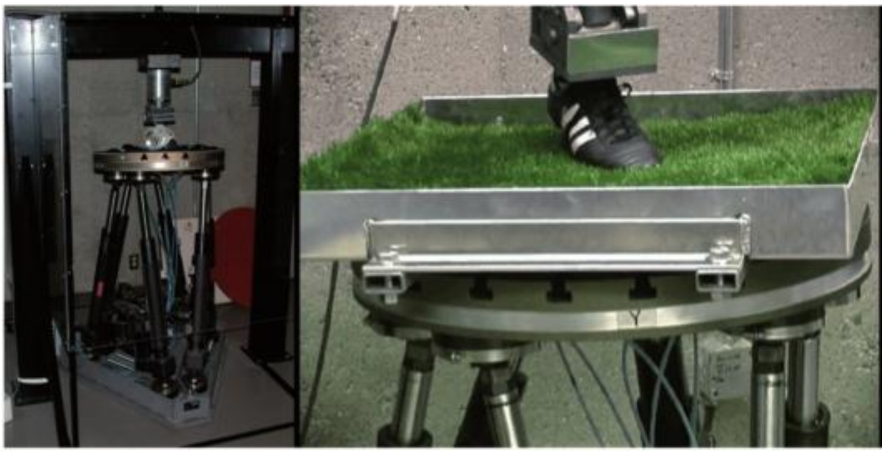

Figure 2.12. Test device used in studies by Wannop et al. (2010) and Stefanyshyn et al. (2010) to measure the rotational resistance of the shoe-surface interface

Other studies by Livesay et al. (2006) and Villwock et al. (2009) used more complex devices that were able to measure the rotational traction throughout the entire rotation (Figure 2.14). In essence both devices use the same principle as that of the standard FIFA test device, with the difference being that the test foot used by Livesay et al. (2006) used the forefoot part of the sole of a soccer boot and Villwock et al. (2009) used the entire soccer boot. As the devices used by Livesay et al. (2006) and Villwock et al. (2009) measured rotational traction throughout the rotation they were also able to determine the rotational stiffness of the surface in addition to the peak torque; Livesay et al (2006) measured the rotational stiffness at different rotation angles (0 – 2° and 2 – 10°), whereas Villwock et al. (2009) measured it at different torque values (3 Nm – 75% of peak torque).

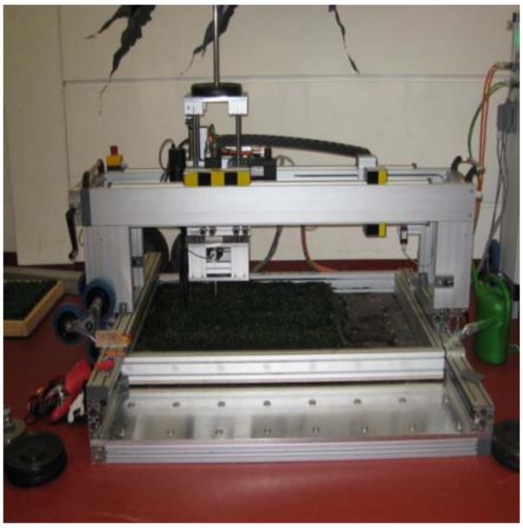

Figure 2.13. Test device developed by Adidas as used in a study by Severn (2010) to measure the rotational traction of the shoe-surface interface

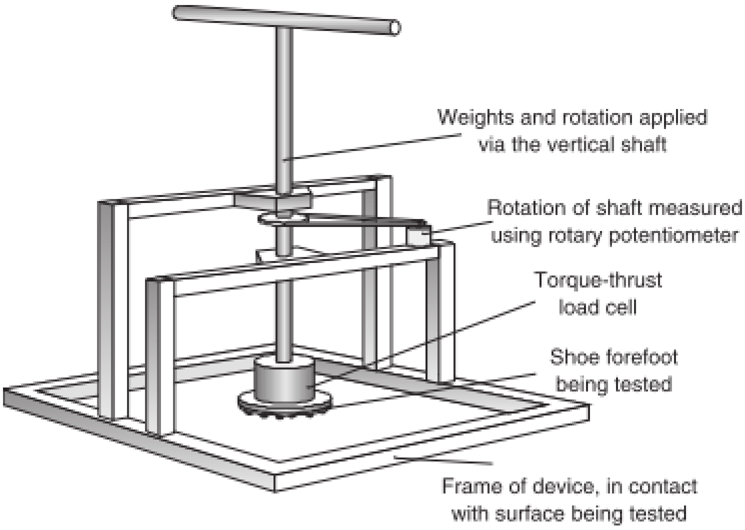

Figure 2.14. Custom-made test device used in study to measure the rotational resistance and rotational stiffness of the shoe surface interface (Livesay et al., 2006).

Comparing the different measurement methods shows that the custom made devices give more control regarding the rotation angle and speed than the standard test device. Furthermore, the devices use different test feet, with some using the forefoot part of the sole of soccer boots and others using complete boots. In addition to this, some devices that use soccer boots place the shoe in an angle to the surface. Finally, some studies use the rotational stiffness as an extra measure to quantify the rotational traction behaviour of the shoe-surface interface. However, irrespective of the measurement method all studies used the peak rotational traction as a key parameter.

The rotational traction of the shoe-surface interface can be affected in several ways. A study by Severn (2010) looked at how different surface components affected the rotational traction of a surface. With the standard FIFA test the study observed measurable differences, but did not find any clear relationship between varying designs including different carpets, bulk density values and infill thickness (Figure 2.14). With the custom made device (Figure 2.13) the study did find an increased rotational traction with an increased bulk density, which the study found to be dependent on the infill quantity, compaction of the infill and the type of carpet that was used. The study reported that the shockpad had no effects on the rotational traction properties.

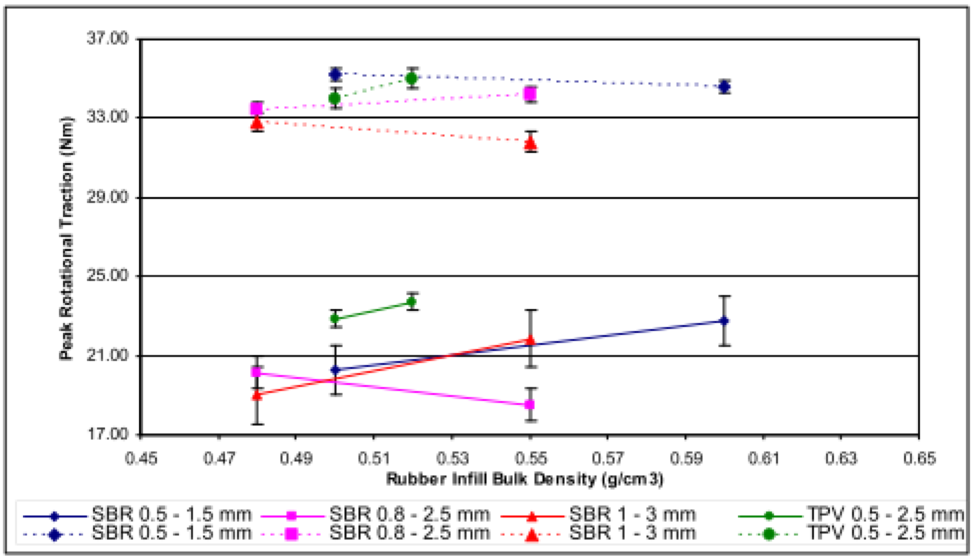

Figure 2.15. Effects of bulk density on rotational resistance properties measured with a FIFA standard device (dotted lines) and a custom measurement device (full lines) (Severn, 2010).

Apart from the surface components, the shoe may also have an effect on the rotational resistance. The study by Severn (2010) showed that the spacing of the studs can affect the rotational traction and small differences were found between different stud configurations, albeit non-significant. Regarding the shape of the used studs, rounded and blades, the study found no effects, which is in line with the results of other studies (Villwock et al., 2009; Stefanyshyn et al., 2010). For the length of the studs Severn (2010) found that this increased the penetration of the surface, but it was unknown what the effect of this was on the magnitude of the rotational traction due to restrictions of the test device used. Finally, studies by Livesay et al. (2006) and Villwock et al. (2009) showed that the development of the rotational traction during the rotation is dependent of the combination of the type of shoe and surface used, suggesting that depending on the rotation angle the peak rotational traction may not represent the rotational traction that is experienced by subjects performing a manoeuvre (Figure 2.16).

A final factor that may influence the rotational traction of the shoe-surface interface is the normal load that is placed on the shoe, with previous studies showing that the magnitude of rotational traction increased with the normal load. However, Livesay et al. (2006) found a linear relationship between the normal load and the peak rotational traction of different shoe condition, suggesting the difference in peak rotational traction found between conditions is independent of the normal load applied.

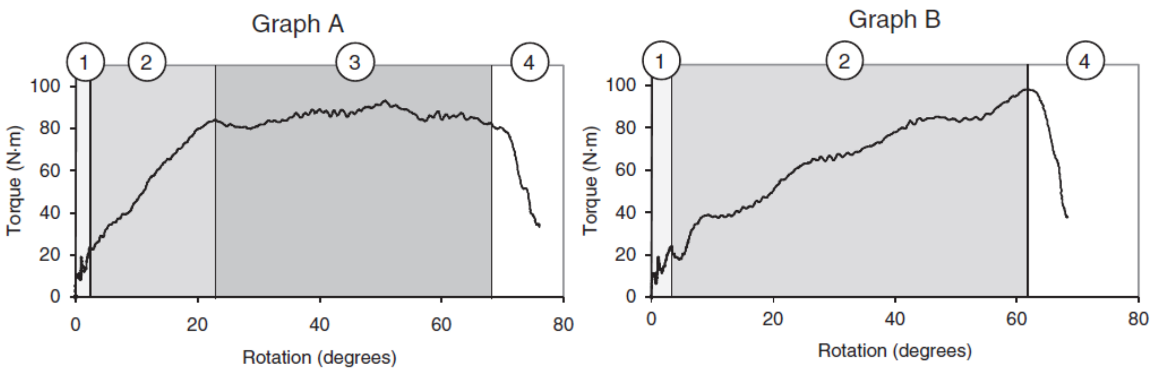

Figure 2.16. A study by Villwock et al. (2009) showed that the development of the rotational traction of the shoe-surface interface can be dependent of the combination of surface and shoes used. The graphs show the development of rotational traction for different shoe conditions, of which the shoe in graph B was typified by a leading edge that was twisted and appeared to plow into the surface omitting the slippage region (3) that was present in graph A.

2.3 Injuries in Soccer

2.3.1 Introduction

Injuries are inevitably related to sports and will always be a part of it as long as athletes push their bodies to the limit in order to increase their performance and to be the best at what they do. However, there are factors that can influence the loading of the musculoskeletal system and therefore the development of injuries. This section reviews the injury characteristics in soccer, namely: the locations and factors that have an influence on the injury risk, to gain insight into what the common injury locations are in soccer and how these can be affected.

2.3.2 Consensus in Injury Studies

Until recently, studies on the incidence of injuries (number of injuries sustained over a set time) all used their own definitions and methodologies to record injuries in soccer making comparisons between studies difficult. As a result, Fuller et al. (2006) created a consensus statement on injury definitions and data collection procedures for soccer injuries. This statement gave definitions for injuries, the severity of an injury, the injury location and types of injuries and was used as a guideline to compare the different studies on injuries in soccer with regards to the injury location, exposure and contact.

To compare injury studies the injury locations were divided into three categories (Table 2.3). Following this the lower limbs category was divided into six categories as the studies showed that most injuries occurred in the lower limbs (Table 2.5). In addition to this Fuller et al. (2006) identified the exposure and contact as important parameters regarding injuries. Exposure was divided between: match exposure, “Play between teams from different clubs“, and training exposure, “Team based and individual physical activities under the control or guidance of the team’s coaching or fitness staff that are aimed at maintaining or improving players’ football skills or physical condition“ (Fuller et al., 2006). The contact section indicated if the injury was a result of contact with another player or object, or if it was a non-contact injury (Fuller et al., 2006).

Table 2.3. Injury classification used to compare injury studies based on the consensus statement (Fuller et al., 2006)

Location	Lower limb	Exposure	Contact
Upper Limbs Trunk Lower Limbs	Hip / Groin Thigh Knee Lower Leg Ankle Foot	Match Training	Contact Non-contact

2.3.3 Injury Rates and Location

To get insight into the body locations of soccer injuries 14 studies were used of which the details on population and total number of included injuries were known (Table 2.4). These studies were selected as they all provided information on the body location of the injuries, and 11 of these included information on the injury location in the lower limbs. In addition to this these studies provided information on if the injuries were contact related and / or when the injury occurred (match versus training), which is discussed in the next subsection. While the details on the different locations vary between studies it is clear that the majority of all injuries (72.5 ± 9.9%) are located in the lower limbs, with the contribution to the total number of injuries varying from 56% to 88.6% (Table 2.5). Part of this variation may be caused by the way data was collected as studies that only recorded injuries that

Table 2.4. Details of injury studies used in this literature review

Study	Period	Skill	Population	Sex	Surface	Injuries	Injuries/1000h	Hours
1:(Woods et al., 2002)	1997 - 1999	4 English top leagues	91 English clubs	M	Natural	6030		
2: (Petridou et al., 2003)	1998	All	5 General hospitals Denmark	M/F		3752		
			7 Hospitals France			113		
			2 General, 1 trauma hospital Greece			659		
			17 General hospitals The Netherlands*			14000		
			18 Hospitals United Kingdom*			161513		
3: (A Junge, Cheung, et al., 2004)	2001	School	145 New Zealand youth players	M		261	27.9	9309
4: (A Junge, J Dvorak, et al., 2004)	2002	World Cup	32 National teams	M	Natural	171	80.96	2112
5: (Price et al., 2004)	1999 - 2001	English top youth	Youth academies from 38 English clubs	M		3805		
6: (Waldén, Hägglund & Ekstrand, 2005a)	2001	Swedish Super league	14 Swedish clubs	M		765	8.3	93353
7: (Waldén, Hägglund & Ekstrand, 2005b)	2001 - 2002	Champions League	11 European clubs	M	Natural	658	9.4	69707
8: (J Dvorak et al., 2007)	2006	World Cup	32 National teams	M	Natural	145	68.7	2112
9: (Angermann et al., 2007)	2003 - 2005	All	European Injury Database	M/F		2511000		
10: (Fuller, Dick, Corlette & Schmalz, 2007a)	2005 - 2006	College/University	52 Male, 64 female teams in 2005	M	Natural	665	23.92	
					Artificial	183	25.43	
			54 Male, 72 female teams in 2006	F	Natural	812	21.79	
					Artificial	134	19.15	
11: (Fuller, Dick, Corlette & Schmalz, 2007b)	2005 - 2006	College/University	52 Male, 64 female teams in 2005	M	Natural	629	3.01	
					Artificial	189	3.34	
			54 Male, 72 female teams in 2006	F	Natural	652	2.79	
					Artificial	122	2.60	
12: (Ekstrand, 2008)	2001 - 2006	Champions League, Swedish Super league	17 Clubs from 9 countries 14 Swedish clubs	M		6300	7.88	800000
13: (Rechel et al., 2008)	2005 - 2006	High school	100 High schools	M		372		
				F		334		
			National estimate	M		217616		
				F		182913		
14: (Stege et al., 2008)	2007	Dutch top leagues	15 Clubs from January-June 13 Clubs from July-December	M		632	6	107271

Table 2.5. Summary of results from injury studies on the number of injuries (% of total number of injuries) for different body locations sustained in soccer

Study*	Sex	Surface	Head/Neck	Upper Limbs	Trunk	Lower limbs	Undefined	Hip/Groin	Thigh	Knee	Lower leg	Ankle	Foot
1	M	Natural	7.0	3.0	2.0	87.0	1	12.8	26.7	19.8	14.0	19.7	7.0
2	M/F		7.8	21.1	3.4	67.7				31.8		35.5	
			14.6	18.4	7.8	59.2				25.5		53.2	
			11.4	25.3	6.5	56.8				28.9		48.4	
			9.0	23.0	5.0	63.0				23.8		42.9	
			11.0	24.5	6.8	57.7				22.2		43.0	
3	M		5.0	5.8	9.2	80.4		11.6	21.1	18.7	20.0	21.4	7.2
4	M	Natural	14.6	4.8	3.5	76.6		8.4	22.9	16.8	22.1	19.1	10.7
5	M		1.0	3.0	6.0	87.0	3	13.8	21.8	20.7	11.5	21.8	10.3
6	M		2.0		6.0	88.0	4	18.2	26.1	18.2	17.1	11.4	9.1
7	M	Natural	3.0		6.0	85.5	5.50	14.0	26.9	23.4	12.9	16.4	6.4
8	M	Natural	9.0	8.3	10.3	73.1		4.8	20.2	17.3	28.9	23.1	5.8
9	M/F		9.0	31.0	4.0	56.0							
10	M	Natural	9.9	6.3	16.2	67.4		12.7	21.3	16.8	11.7	24.8	12.9
		Artificial	17.0	6.6	9.3	67.2		6.1	26.0	20.6	9.2	25.2	13.0
	F	Natural	15.74	6.9	9.7	67.7		5.8	14.6	31.5	11.7	26.9	9.6
		Artificial	13.4	8.2	8.2	70.1		6.9	16.8	33.7	9.9	20.8	11.9
11	M	Natural	7.0	7.6	18.9	66.8		16.9	21.9	17.8	11.2	24.0	8.3
		Artificial	5.7	4.8	16.5	73.1		14.4	20.4	14.8	8.8	29.2	12.3
	F	Natural	6.5	5.0	16.9	72.0		13.00	24.2	23.4	10.8	19.5	9.1
		Artificial	12.3	5.0	11.5	71.2		9.3	22.1	19.6	17.7	22.1	9.2
12	M		3.0		7.0	85.0	5	14.1	27.1	23.5	12.9	15.3	7.1
13	M (Practice)		2.5	5.1	3.8	88.6							
	F (Practice)		10.2	4.9	4.0	80.9							
	M		19.7	8.4	6.8	65.1							
	F		21.1	6.3	3.4	69.2							
14	M		11.1	6.8	5.3	76.9							
			15.7	5.6	3.7	75.1		11.9	27.4	23.8	10.7	20.2	6.0
		Average	**9.0 (±4.6)**	**10.8 (±8.6)**	**8.3 (±4.6)**	**72.5 (±9.9)**		**11.5 (±3.9)**	**22.8 (±3.7)**	**22.4 (±5.2)**	**14.2 (±5.4)**	**26.5 (±11.1)**	**9.2 (±2.4)**

***** Numbers correspond with studies Table 2.4

needed hospital treatment show a relatively high contribution of the upper limbs (Petridou et al., 2003; Angermann et al., 2007). Petridou et al. (2003) suggested that this might be caused by the inclusion of unorganised competition and stated that in such situations the occurrence of arm injuries is relatively high.

Of the lower limb locations the ankle, thigh and knee are the most common injury locations, which combined are on average responsible for 77.7% of all injuries in the lower limbs (Table 2.5). The study by Petridou et al. (2003) only took the knee and ankle into account which had some effect on the overall results. When these results are left out the average percentage of the ankle changes to 21.2 ± 4.4% and the knee to 21.2 ± 5.1%. Still they are responsible for more injuries than lower leg (14.2 ± 5.4%), hip / groin (11.5 ± 3.9%), and foot (9.2 ± 2.4%).

2.3.4 Risk Factors

The information in §2.3.3 indicated that that the majority of injuries in soccer are located in the lower limbs. This sub-section discusses factors that can contribute to the injury risk. Surfaces properties, contact and match versus training are discussed first, followed by intrinsic factors that may contribute to the risk on injuries.

2.3.4.1 Surface Properties

Most previous studies on injuries focused on the difference between artificial turf and natural grass. With regards to this it is often claimed that artificial sport surfaces are associated with an increased incidence of injuries (Dixon et al., 2000; Orchard, 2002; Murphy, 2003; Ramirez et al., 2006), and it is also thought by elite professional teams and players that playing on artificial turf leads to more injuries (Fuller, Dick, Corlette & Schmalz, 2007a; Schalke04, 2011; Reuters, 2009). However, different studies that assessed the differences in injury risk between artificial turf and natural grass do not reach such a consensus. Some studies suggest there is no evidence that playing on artificial turf leads to an increased injury risk (Ekstrand et al., 2006; Fuller, Dick, Corlette & Schmalz, 2007a; Fuller, Dick, Corlette & Schmalz, 2007b; Bjørneboe et al., 2010). While a study by Meyers and Barnhill (2004) claimed that natural and artificial turf had similar risks on injuries, but found that artificial turf was related to a higher incidence of muscle-tendon overload injuries, while natural grass seemed to have a higher incidence of ligament tears. Finally a study by Ramirez et al. (2006) suggested there was an overall higher injury incidence on artificial turf.

While these studies made claims about the effects of artificial turf and natural grass they provide little information on the characteristics of the surfaces used in the study. Some state that the surfaces were 3G (Ekstrand et al., 2006; Fuller, Dick, Corlette & Schmalz, 2007a; Fuller, Dick, Corlette & Schmalz, 2007b), the manufacturer and type of infill (Meyers & Barnhill, 2004), or provide no information at all (Ramirez et al., 2006). Therefore, findings cannot be related to specific properties.

A few studies on surfaces and injuries in Australian Football have tried to relate injuries to the hardness and rotational traction properties of a field. The hardness was measured with a Clegg Impact Hammer, whereas the rotational traction was measured with a device similar to that of the standard FIFA test. These studies suggested that the surface properties can contribute to injuries. First of all a study that included rotational traction showed that 12 injuries, out of a total of 130, could be related to rotational traction, of which six were sustained on surfaces with a rotational traction value lower than 20 Nm and 5 on surfaces between 21 – 39 Nm (Twomey, 2010). This is in contrast with other studies that suggested that a high traction value leads to injuries (Nigg & Yeadon, 1987; Orchard, 2002). In addition to this, another study found a significant increase in injuries on surfaces with a low / normal Clegg Impact Hammer reading (30 – 69 g) and an unacceptably high reading (> 120 g) compared to surfaces with a preferable reading (70 – 89 g) (Twomey et al., 2012). The uniformity of the surface properties and location on the pitch did not affect the injury risk (Twomey & Fleming, 2011; Twomey, 2010).

2.3.4.2 Contact

Contact situations have also been identified as a risk factor for injuries in soccer. In previous studies contact situations were responsible for 40 – 76.5% of all injuries during a match or training (Table 2.6). The consensus statement by Fuller et al. (2006) divided contact situations into three groups: player-player, player-ball and player-any other object. Few studies distinguished between these groups, but the ones that did showed that the number of injuries per 1000 playing hours for player-player contact is more than three times as high during training and more than seven times as high during competition than for the other contact types (Fuller, Dick, Corlette & Schmalz, 2007a; Fuller, Dick, Corlette & Schmalz, 2007b). This also suggests that player-player contact is a higher risk factor during competition than during training.

While limited to ankle injuries, a study by Kofotolis et al. (2007) shows the same pattern that player-player contact is responsible for most injuries in soccer (58 out of 71).

Interestingly, it was reported that the majority of the injuries leading to a time loss of more than seven days were non-contact injuries (34 out of 51) (Kofotolis et al., 2007). Kofotolis et al. (2007) does not give an explanation for this finding, but it may have been related to the movements during which the injuries occurred. Above all, it shows that while more injuries occur during contact situations this does not mean that the injuries are more severe than the less frequent non-contact injuries.

Table 2.6. Details from injury studies on injury incidence during contact and match versus training situations in soccer

Study*	**Sex**	**Surface**	**Contact**	**Match**	**Training**
1	M	Natural	40.0		
3	M		48.3	66.3	18.8
4	M	Natural	73.0		
5	M			51.3	48.7
6	M			40.4	58.6
7	M	Natural		54.7	45.3
8	M	Natural	73.0		
10	M	Natural	68.7	*54.7***	
		Artificial	72.5	*49.2***	
	F	Natural	76.4	*55.5***	
		Artificial	74.6	*52.3***	
11	M	Natural	48.2		*45.3***
		Artificial	51.8		*50.8***
	F	Natural	44.1		*44.5***
		Artificial	51.5		*47.6***
13	M			55.9	44.1
	F			67.6	32.4
	M			55.0	45.0
	F			65.7	34.3
14	M			54.7	45.3
Average			**60.0 (±13.9)**	**57.0 (±7.8)**	**41 (±10.2)**

***** Numbers correspond with studies Table 2.4 ** Percentages relative to each study

2.3.4.3 Match versus Training

Studies that considered injuries in both match and training situations showed that on average 57% of all injuries occur in match situations (Table 2.6). However, studies that included the exposure showed that the injury incidence during matches (19.15 – 25.43 per 1000 h) can be more than seven times higher than during training situations (2.60 – 3.34 per 1000 h) (Fuller, Dick, Corlette & Schmalz, 2007a; Fuller, Dick, Corlette & Schmalz, 2007b).

The type of competition may also play a role in the injury incidence during matches. During the FIFA 2002 and 2006 world cups the injury incidence, over 64 matches, was respectively 80.96 and 68.7 per 1000h, which is relatively high compared to the other values reported in literature (Table 2.4) (A Junge, J Dvorak, et al., 2004; J Dvorak et al., 2007). It was suggested that the high injury incidence was caused by overloading of players by the demands of the match and inadequate recovery from previous competitions and / or injuries (A Junge, J Dvorak, et al., 2004).

2.3.4.4 Intrinsic Factors

Previous studies have identified several intrinsic factors that may affect the injury risk; these include the general fitness, age of the players, and injury history. Regarding the general fitness previous studies have shown that players with a reduced general fitness are fatigued more easily, which consequently can lead to changes in muscle activation pattern, reduced attention and decreased motor control abilities (Mizrahi et al., 2000; Johnston et al., 1998; Gribble & Hertel, 2004a; Gribble & Hertel, 2004b). The decrease in motor control of the lower limbs has previously been related to fatigue in the muscle groups around the hips and knees, which may increase the risk of injuries in those specific areas (Gribble & Hertel, 2004a; Gribble & Hertel, 2004b; Johnston et al., 1998). Finally, studies showed that fatigue can increase the loading of the musculoskeletal system (Chappell et al., 2005; Mizrahi et al., 2000; Oliver et al., 2008).

A study by Gabett et al. (2008) on injuries in rugby suggested that the fitness of a player may also be reflected in when an injury occurs during a match. In their study they found that in amateur competitions up to 70% of all injuries occurred in the second half of the game. It was suggested that this was related to the fitness since in semi-professional matches, for which they presumed the players were fitter and therefore got less fatigued, only 38% of all injuries occurred in the second half (Gabbett et al., 2008). Other studies in soccer found a relation between injuries and the match period. Hawkins et al. (2001) reported that most injuries occurred in the last 15 minutes of the first and last 30 minutes of the second half in a soccer match, whereas Kofotolis et al. (2007) found that 61.1% of all injuries occurred in the last 15 minutes of each half. This was related to fatigue, but also to more aggressive play at the end of each half as players wanted to score.

As mentioned, factors such as the age and injury history of a player may also be an injury risk factor. With regards to lower limb injuries previous studies in various sports have shown that the injury risk increases with age (Murphy, 2003; Arnason, 2004; Gabbe et al., 2006). Chomiak et al. (2000) supports this as age was an important factor for knee injuries in soccer. However, the overall injury incidence was equal across all age groups. At the same time, another study on injuries in soccer showed that a young age can also increase the risk on injuries (Peterson et al., 2000). Players in the age group of 14 – 16 years old had a higher injury risk than those in the age group of 16 – 18 years old. It was suggested by Peterson et al. (2000) that this difference is caused by the younger players being physically less well developed than the older ones.

Finally, studies have reported that a previous injury increases the risk on having a subsequent injury of the same type and in the same location (Arnason, 2004; Emery et al., 2005; Kofotolis et al., 2007; Maffey & Emery, 2007; Murphy, 2003; Hägglund et al., 2006), especially when the rehabilitation from the injury proved inadequate (Croisier, 2004). Murphy et al. (2003) stated that the increase in risk can mainly be attributed to a reduction in muscle strength and imbalance or impaired functionality of the joints. But also fear of re-injury may play a part due to altered muscle recruitment strategies and loss of focus causing reduced attention to appropriate visual cues (Murphy, 2003).

2.4 Movements

2.4.1 Introduction

Soccer consists of numerous movements and combinations of those, all which can load the musculoskeletal system differently. In addition to this, other factors, such as the surface properties or game situations, may affect the loading on the body. This section on movements has the goal to review the literature relevant to movements in soccer. The first section gives an overview of the different types of movements that are relevant in soccer, which helps with selecting movements for detailed biomechanical study. The second section gives an overview of the effects that surface properties have on player dynamics, followed by a third section on the effects of in-game scenarios. The final section discusses the player dynamics during specific manoeuvres, irrespective of surface properties or in-game scenarios, and helps identify possible confounding variables for any biomechanical study.

2.4.2 Types of Movements

Three types of studies considered movements in soccer; time-motion analysis, epidemiology of injuries in soccer, and biomechanics. Of these, time-motion analysis and injury studies give the most insight on the range of movements in soccer (Table 2.7). Biomechanical studies have tended to focus on a few movements such as running, jumps and landings, and cutting / turning manoeuvres (Kaila, 2007; Meijer et al., 2007; Oliver et al., 2008; Stefanyshyn et al., 2010).

Table 2.7. The range of movements mentioned in time-motion analysis and injury studies

Time - motion studies	**Movements discussed**
(Bloomfield et al., 2004; Bloomfield et al., 2007)	Sprint, run, shuffle, skip, jog, walk, stand still, slow down, jump, land, dive, slide, fall, get up, stop, swerve, impact, turns (sections of 90°) Ball: receive, pass, shoot, dribble, tackle, trick, other
(Carling et al., 2008)	Standing, walking, jogging, cruising, sprinting, alterations in pace, changing direction, execution of specific game skills, tracking opponents, backwards and sideways running
(Mohr et al., 2003)	Standing, walking, jogging, low-speed running, moderate-speed running, high-speed running, sprinting, backward running
Injury studies	**Movements discussed**
(Hawkins et al., 2001; Price et al., 2004)	Running, tackled, other(non-contact), tackling, twisting/turning, collision, stretching, kicked, shooting, landing, passing, jumping, other(contact), falling, diving, heading, dribbling, throwing
(Kofotolis et al., 2007)	Contact: another player, floor, ball, non specific Non contact: landing, twisting/turning, running, other, falling, jumping, shooting, heading, stretching, dribbling, passing, diving
(Rahnama, 2002)	Dribbling, goal catch, goal punch, goal kick, goal throw, heading, jumping, kicking, making a tackle, making a charge, passing the ball, receiving a tackle, receiving a charge, receiving a ball, shot on goal, throw in

Looking at the different movements discussed it becomes clear that running, sprinting and jumping are mentioned in most studies. Also, most studies fail to provide more detailed information about the movements, for example: it is obvious that the intensity of sprinting is higher than jogging, but for a jump it is not directly clear and typically not given. The same can be said for the twisting / turning, for example: a study by Kofotolis (2007) on ankle injuries in soccer failed to provide information on the twisting / turning angle. This issue is to some extent solved by a movement classification of Bloomfield et al. (2007) that in addition to the different movements included modifiers to describe the movements (Table 2.8).

While the Bloomfield classification gives the most extensive overview of the different movements in soccer, biomechanical studies reveal that it still lacks some detail. This is mainly the case when it comes to changing direction as many biomechanical studies focus on cutting manoeuvres such as the sidestep and cross-over cutting manoeuvre because of the high physical demands of these movements, a level of detail not included by Bloomfield et al. (2004, 2007) (Figure 2.17) (McLean et al., 2004; Kaila, 2007; Nyland et al., 1999). These studies also suggest that the turning angles used by Bloomfield et al. (2004, 2007) may not be sufficient to describe a movement as most of them used angles smaller than 90°. Finally, a literature review on the biomechanics of soccer also identified a throw in as a soccer relevant manoeuvre that was not mentioned in any of the time-motion analysis or injury studies (Lees & Nolan, 1998).

Table 2.8. The 'Bloomfield movement classification' (Bloomfield et al., 2007)

BEHAVIORS (Modifiers in parenthesis)	**MODIFIERS**
1. TIMED **Motion** Sprint (A+B), Run (A+B), Shuffle (A+B), Skip (A+B), Jog (A+B), Walk (A), Stand Still, Slow Down (A+B), Jump (C), Land, Dive (D), Slide (D), Fall, Get Up (B) **Initial Channel** Start of Observation	**(A) Direction** Forwards, Forwards Diagonally Right/Left, Sideways Right/Left, Backwards, Backwards Diagonally Right/Left, Arc Forwards Left to Right/Right to Left, Arc Backwards Left to Right/Right to Left, Arc Sideways Right/Left **(B) Intensity** Low, Medium, High, Very High **(C) Jump** Vertical, Forwards, Backwards, Sideways (E)
2. INSTANTANEOUS (NON-TIMED) **Other Movement** Stop (B), Swerve (E), Impact(F+B) **Turns** 0^0-90^0 (E) 90^0-180^0 (E) 180^0-270^0 (E) 270^0-360^0 (E) $>360^0$ (E) **On the Ball Activity** Receive (G), Pass (H+I), Shoot (H+I), Dribble (J+K), Tackle, Trick, Other	**(D) Dive** Feet first, Head first **(E) Turn** Right/Left **(F) Type** Push, Pull, Pushed, Pulled, Other **(G) Control** Right/Left foot, Head, Chest, Thigh, Other **(H) Pass/Shoot** Long Air, Short Air, Long Ground, Short Ground, Other **(I) How** Right/Left Foot, Header, Backheel, Overhead, Other **(J) Dribble** Start, End **(K) Touches** Start,1-3, 4-6, 7-10, >10

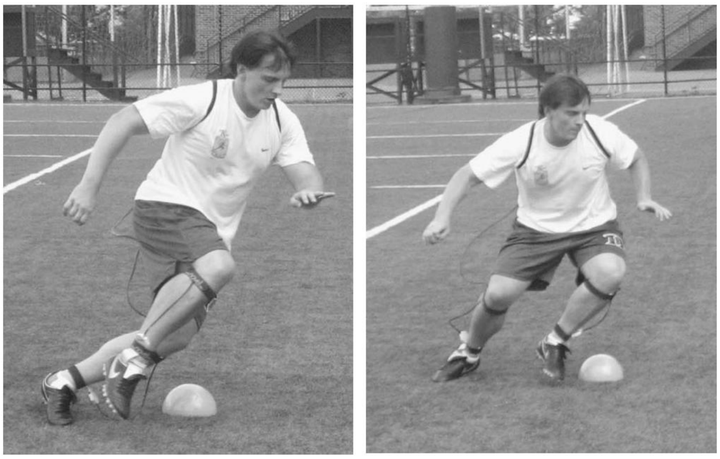

Figure 2.17. Example of a sidestep (left) and cross-over (right) cutting manoeuvre (Queen et al., 2007). For the sidestep cut one foot is planted and the cutting manoeuvre is performed in the opposite direction. For the cross-over cut one foot is planted while the other foot crosses it to change direction.

With the information gathered from the literature a new and more comprehensive table on the different movements in soccer was constructed (Table 2.9). The first column of the table consists of movements that are used in soccer. The second column lists modifiers that influence the movements and are lined up with the different categories of movements. Finally, the third column is an additional column that consists of an overall ball modifier as all actions, next to the ball activity ones, can involve a ball and a sport specific movements / actions category, as the throw in requires the use of hands which is in contrast with all other ball activities in soccer.

Table 2.9. Overview of relevant movements for soccer created with the help of current literature. For each movement there are modifiers that can affect the movement, with an additional overall ball modifier as all movements can be performed with and without a ball and the throw-in in a separate category as the ball is normally handled with the feet.

Movements/actions	**Modifiers**	**Additional**
Linear movements		
Stand still	**Direction**	**Overall ball modifier**
Walk	Forwards / Backwards	Ball involved: Yes/No
Jog	Forwards / Backwards diagonally right / left	
Skip	Arc forwards left to right / right to left	
Shuffle	Arc backwards left to right / right to left	
Run	Arc sideways left to right / right to left	
Sprint		
Accelerate	**Intensity**	
Decelerate	Low, medium, high, very high	
Jump		
Change of direction		
Swerve	**Direction**	
Turn- /twist	Left / Right	
Crossover cut	**Angle**	
Side-step cut	30°, 60°, 90°, etc.	
	Intensity	
	Low, medium, high, very high	
Contact		**Specific movements/actions**
Impact	**Type of impact**	Throw in
Slide	Deliver / Receive: push, pull, tackle	
Dive	**Intensity**	
Land	Low, medium, high, very high	
Fall / Stumble		
Ball activity		
Pass	**Pass/Shoot**	
Receive	Long / short air, long/short ground	
Shoot	**Method**	
Trick / Fake	Right / left foot, head, chest, thigh, heel	

2.4.3 Effect of Surface Properties on Movements

Section 2.2.4 showed that the surface properties of artificial turf surfaces can be affected by their construction. The shockpad as well as the rubber infill thickness can affect the force reduction, deceleration, and surface stiffness values, whereas the bulk density of the infill can affect the rotational traction values. In Chapter 4 the choice was made to modify the hardness and rotational traction of surfaces to be used in the player movement study. Therefore the following sub-sections will focus on these properties, which are also the properties most studied in biomechanical studies.

2.4.3.1 Surface Hardness

The surface hardness is one of the most extensively studied properties, mainly in combination with running and hopping. As explained in §2.2.4.1 the surface hardness can be quantified in several ways. Most studies only use one of the available measurement methods making it difficult to relate the findings to other measurement methods. Therefore this section discusses the hardness of the surface regardless of the measurement methods used.

Previous studies have shown that the surface hardness can affect different parameters such as the vertical ground reaction force (vGRF) (the force exerted by the ground on the body in contact, which is equal and opposite to the force exerted by the body to the ground, derived from Newton's third law), joint moments and angles during different movements. With regards to the magnitude of the vGRF not all studies agree on the effects of the surface hardness. This is related to the type of movement and other characteristics that can influence the GRF curve and magnitude of the vGRF. Different movements and techniques can produce a different GRF curve. For example, during toe running / sprinting and hopping only a single active peak is present, whereas during heel-toe running a passive / impact and active peak are present (Figure 2.18).

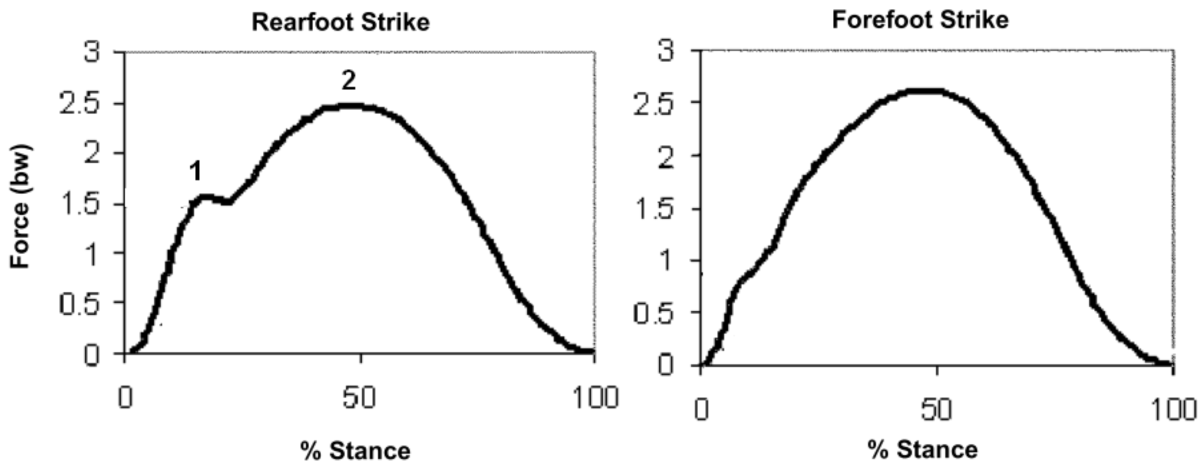

Figure 2.18. Typical ground reaction curves during running with a heel strike and with a forefoot strike (Laughton et al. 2003). During a heel strike the curve shows a passive/impact peak (1) and an active peak (2), whereas during a forefoot strike only an active peak is present.

Regarding the hardness, studies on hopping, which shows a single peak, found an increase for the vGRF with an increase in hardness. (Ferris & Farley 1997; Farley et al. 1998; Moritz & Farley 2005). In heel-toe running, which has both an impact peak (peak force within 50 ms after contact with surface) and an active peak (peak after 50 ms after contact with surface) several studies found that the impact peak increases with an increase in hardness whereas the active peak remains the same (Ferris et al. 1998; Ferris et al. 1999; Meijer et al. 2007). The change in impact force was related in these studies to the deceleration of the lower leg. In toe running / sprinting, which has a single peak, studies found no effect for the vGRF (Stafilidis & Arampatzis 2007; Stiles et al. 2011), which was also the case in a previous study on drop jumps (Arampatzis et al. 2004). In studies on turning manoeuvres an effect for surface hardness was found in a study by Low (2010), whereas another study by Stiles et al. (2011) found no effect. Finally a study on a tennis specific manoeuvre, a running forehand foot plant, reported that the highest impact force was found on the softest surface, which is in contrast with the findings in heel-toe running studies (Stiles & Dixon 2007). The shape of the vGRF curve however does not only determine the effect the surface hardness has on the vGRF as studies on hopping did find an effect, but studies on drop jumps, which also have a single peak did not. This may be explained by the different intensities of the movements, which can be influenced in example by the running speed or jumping height, with a higher intensity increasing the vGRF (Keller et al. 1996; Yeow et al. 2009). Arampatzis et al. (2004) suggested that the adjustment of a subject on a surface also depends on the demand of the activities. This is also shown in studies on maximal sprinting and sub-maximal running. A study by Stafilidis and Arampatzis (2007) in which the subjects had to perform a maximal sprint did not show an effect for the surface hardness, whereas a study by Meijer et al. (2007) using two sub-maximal running speeds did find an increase of the vGRF with an increase in surface hardness.

With regards to the movement dynamics, previous studies on running and hopping have shown that humans adjust their lower limbs in response to the hardness of a surface to maintain similar centre of mass dynamics (Ferris & Farley, 1997; Ferris et al., 1998). As a result subjects landed with straighter legs on less stiff surfaces (Farley et al., 1998; Kerdok et al., 2002) and increased their leg stiffness to maintain a similar overall stiffness (Ferris & Farley, 1997; Farley et al., 1998; Ferris et al., 1998; Ferris et al., 1999; Moritz & Farley, 2005). The straightening of the leg mainly occurs in the knee joint (Farley et al., 1998; Kerdok et al., 2002), whereas the leg stiffness is mainly regulated by changes in the ankle stiffness (Farley et al., 1998; Farley & Morgenroth, 1999). A study by Ferris et al. (1999)

showed that people can adjust their leg stiffness for their first step on a new surface to make a smooth transition between surfaces.

In contrast, studies by Arampatzis et al. (2004) and Stafilidis and Arampatzis (2007) on drop jumps and sprinting, did not find any effects for the joint angles or leg stiffness with a change in hardness. Other studies on running and turning and a tennis specific manoeuvre also did not find any significant effects on the joint kinematics (Stiles & Dixon, 2007; Stiles et al., 2011), whereas a study by Dixon et al. (2000) on running did not find any group effects but noted some individual differences for the initial knee and ankle angle.

A few studies also looked at the effects that surface hardness has on joint moments. Studies on hopping (Farley et al., 1998; Moritz & Farley, 2005) and running (Meijer et al., 2007) found an increase in ankle plantar flexion moments during respectively hopping and running with an increased surface hardness. The study by Farley et al. (1998) also found an increase for the knee moment. Other studies on drop jumps, sprinting, and turning did not find any effects of surface hardness on the joint moments of the lower limbs (Arampatzis et al., 2004; Stafilidis & Arampatzis, 2007; Low, 2010).

2.4.3.2 Rotational Traction

Section 2.2.4.2 discussed that the rotational traction properties of a surface can be influenced by the infill as well as the stud spacing and configuration. Previous biomechanical studies investigating the rotational traction effects have used cutting and turning manoeuvres and manipulated the rotational traction properties by using different shoes. Studies by Wannop et al. (2010) and Stefanyshyn et al (2010) are the only ones that report the traction properties studied. For this Wannop et al. (2010) used shoes with a different sole design (tread and smooth) in combination with a cutting manoeuvre at maximal speed, whereas Stefanyshyn et al. (2010) used two soccer boots with a traditional soccer cleat design, a soccer boot with bladed cleats, and a running shoe in combination with a cutting and turning manoeuvre at 4.0 m/s.

The results for the cutting manoeuvre by Wannop et al. (2010) and Stefanyshyn et al. (2010) contrast each other. Wannop et al. (2010) found a significant increase for the peak knee and ankle rotation moment, and knee adduction moment for the high traction condition, whereas Stefanyshyn et al. (2010) did not find any significant effects for knee and ankle loading. The different intensities of the cutting manoeuvre in both studies may explain the different findings. Other studies on sub-maximal cutting manoeuvres that used different soccer boots also did not find any significant effects between shoe conditions (Kaila, 2007; Queen et al., 2008). However, these studies failed to provide any details on the traction properties of the shoes-surface interface. Considering that Stefanhyshyn et al. (2010) did not find any significant differences in traction between the studded and bladed soccer boots it may be that the difference in traction between shoe conditions used by Kaila (2007) and Queen et al. (2008) was simply not large enough.

With regards to the turning manoeuvre, the study by Stefanyshyn et al (2010) found a significant increase in knee and ankle rotational joint moments with an increased traction, as well as a trend to increased ankle eversion and knee abduction moments. As no effect was present for the cutting manoeuvre, Stefanyshyn et al. (2010) suggested that the traction properties of the shoe-surface interface only affect movements with a large rotational component. Another study on a turning manoeuvre using studded and bladed soccer boots did not find any significant effects for knee loading (Gehring et al., 2007). While Gehring et al. (2007) failed to provide information on the rotational traction properties this concurs with the findings of Stefanyshyn et al. (2010) which also did not find any effects between studded and bladed cleats.

2.4.4 Effect of In-game Scenarios on Movements

An important aspect of the research is the inclusion of in-game scenarios. Previous studies that have tried to recreate an in-game scenario in some form in a lab environment have made use of: a simulated opponent, anticipation of a manoeuvre, ball control, and fatigue protocols to resemble match fatigue. The inclusion of a simulated opponent has been used in a study by McLean et al. (2004) on a sidestep cutting manoeuvre. For this they used a skeleton which they placed 20 cm behind the prescribed sidestep location (a force platform) (Figure 2.19). The subjects were to approach the force platform at a speed between 4.5 – 5.5 m/s, after which they were required to land on the force platform with their right leg and perform a 30 - 40° sidestep cutting manoeuvre. After the sidestep cut they were required to continue running for another five steps.

McLean et al. (2004) found that the simulated opponent led to an increased medial ground reaction force, increased hip abduction and knee valgus angles, as well as knee and hip flexion angles. Based on these findings McLean et al. (2004) suggested that with the presence of a simulated opponent subjects perceive a need to change direction more rapidly during the plant and cut phase of the movement. The increased knee and hip flexion angles were related to a more rapid deceleration at initial contact. Overall McLean et al. (2004) concluded that a simulated opponent increased the loading of the knee and could bring the cutting movement closer to a knee injury scenario.

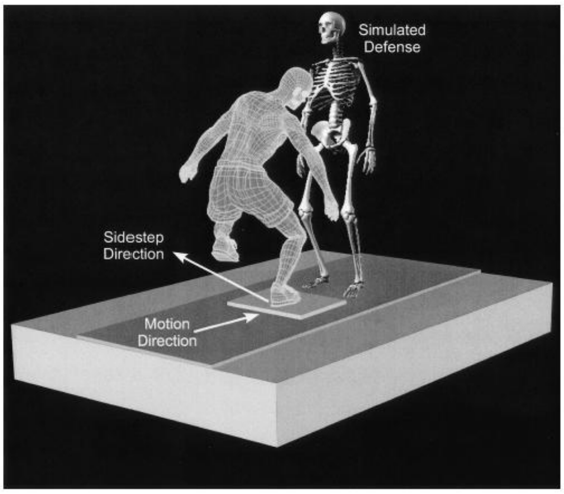

Figure 2.19. Illustration of the simulated defender situation used in the study by McLean et al. (2004). A skeleton was placed right behind the force platform to represent a defender. Kinematic data of the right leg of the subjects was collected with the use of a force platform and a 3D motion analysis system.

Another factor that can affect the musculoskeletal loading during cutting manoeuvres is whether a subject anticipates on the manoeuvre or not. Studies that investigated this made use of different situations (e.g. run, sidestep cut, crossover cut, stop) for which they got cues, for example, by a LED board indicating which manoeuvre to perform either at the start of the run or just before reaching the force platform area in which to perform the manoeuvre (Figure 2.20). Between the anticipated and unanticipated trials previous studies found an increase in knee loading with increases in varus / valgus moments, as well as internal / external rotation moments applied to the knee (Besier, Lloyd, Ackland, et al., 2001; Collins et al., 2009). The anticipation on the manoeuvre did not affect the knee flexion / extension moments. The study by Besier, Lloyd, Ackland et al. (2001) suggested that these effects were caused by inadequate time to make appropriate postural adjustments. The exact nature of the postural adjustment strategies was unknown, but it was suggested that these were related to the foot placement and the amount of lean in the new direction of travel.

With regards to ball control previous studies have shown that dribbling a ball during running and cutting manoeuvres can affect the energy expenditure of a subject and the loading of the knee (Chan et al., 2009; Reilly, 1997). The increase in energy expenditure during the dribbling of a ball in soccer was irrespective of running speed and was attributed to the extra muscle activity needed to both control the ball and propel the ball forward

(Reilly, 1997). The changes in knee loading were found in female basketball players, therefore it is not directly related to soccer, however, the increased knee flexion angle and moment, as well as the increased knee abduction angle and moment, were related to additional neuromuscular control (Chan et al., 2009). This additional neuromuscular control is also likely needed when dribbling a ball in soccer as this requires an extra task to normal running.

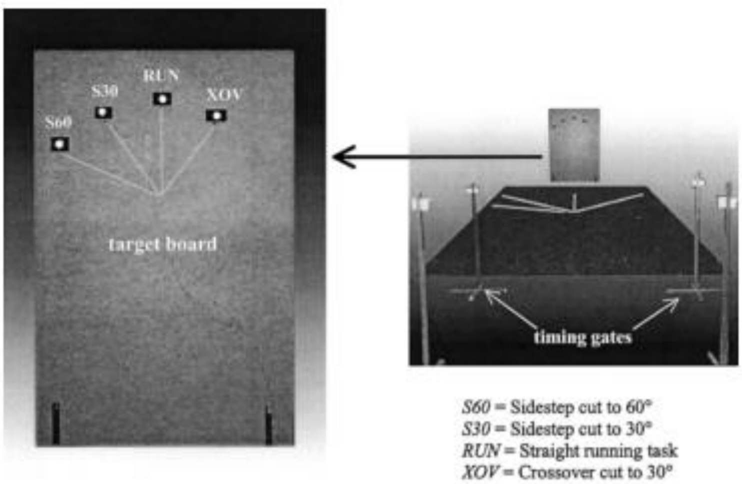

Figure 2.20. Overview of a set-up used for a study on the effects of anticipation on a cutting manoeuvre. The LED board on the left indicated what manoeuvre had to be performed, either at the start of the run or just before reaching the designated area in which the manoeuvre had to be performed (Besier, Lloyd, Ackland, et al., 2001).

In addition to dribbling a ball, a study by Ford et al. (2005) showed that a ball as an overhead target can increase the jumping height and knee flexion moment during a drop jump. The direct relevance of the study to soccer was limited as the subjects had to grab the ball, which was suspended from the ceiling at maximal jump height, with both hands (Ford et al., 2005). This is a manoeuvre that normally is only performed by goal keepers. However, it may be that a ball as an overhead target has similar effects during other jumping manoeuvres in soccer, such as heading.

Finally studies have tried to replicate an in-game scenario by using fatigue protocols. Most of these just involved straight-line running protocols during which different speed conditions were used: walking, jogging, cruising, and sprinting (Rahnama et al., 2006; Greig et al., 2007; Greig & Siegler, 2009; Oliver et al., 2008). The duration of the different protocols varied from 45 minutes, with a total of 9 minutes rest, to 90 minutes plus 15 minutes rest. Some studies incorporated changes of direction into the protocol. A few studies did this by using a shuttle-run protocol during which the subjects had to run 20 m at a certain speed, turn around run etcetera (Sanna & O’Connor, 2008; Collins et al., 2009). A study by

Small et al. (2010) used a parcours in which changes in direction were incorporated, leading to a total of 1350 changes in direction over 90 minutes.

The majority of these studies looked at the muscle activity pre and post fatigue and found it to be decreased after the fatigue protocol (Rahnama et al., 2006; Greig & Siegler, 2009; Small et al., 2010). Furthermore studies found that fatigue can impair the jump performance and increase the experienced vGRF (Oliver et al., 2008; Sanna & O'Connor, 2008). Though Oliver et al. (2008) suggested that the effect of fatigue was dependent on the type of jump used. During cutting manoeuvres previous studies reported increases in transverse plane angles of the lower limb joints, as well as an increased range of motion in the transverse plane for the knee joint (Sanna & O'Connor, 2008; Collins et al., 2009). In addition to this, Collins et al. (2009) also found a trend for the sagittal range of motion and peak moment. Finally, soccer specific fatigue can also affect the alertness of an athlete shown through increased inaccuracy of a vigilance test (Greig et al., 2007). It was suggested that this may be a risk factor for injuries.

2.4.5 Player Dynamics During Cutting / Turning and Jumps / Landing

Section 2.4.2 showed that a broad range of movements are part of soccer, some showing some resemblance to each other as jogging and sprinting, and others being completely different such as cutting manoeuvres or jumps. The focus of this thesis is on a stop and turn (i.e. a full 180° turn) and a jump / landing manoeuvre (see Chapter 4); therefore, the following sections will focus on the player dynamics during these movements. As few studies have looked into a full 180° turn, the choice was made to also look into cutting manoeuvres as these also involve a change in direction.

2.4.5.1 Cutting / Turning Manoeuvres

Previous studies on cutting and turning manoeuvres looked at sidestep and cross-over cuts, at angles varying from 30 – 90°, and full 180° turns. The studies used different data collection methods including: kinematic data with 2D / 3D video analysis and force platforms, and plantar pressure data with pressure insoles. The studies that collected kinematic data all used a runway approach after which the subject had to land on the force platform with a designated leg before making the cutting or turning manoeuvre. Studies that looked at the effects of cutting manoeuvres at different angles compared to running in a straight line showed that during cutting manoeuvres the knee loading was significantly greater than during running (Besier, Lloyd, Cochrane, et al., 2001; Kaila, 2007). These changes involved both the internal / external rotation as well as valgus / varus moments that act on the knee, with the sidestep cut leading to greater internal rotation and valgus moments, and the crossover cut leading to greater external rotation and varus moments (Besier, Lloyd, Cochrane, et al., 2001; Kaila, 2007). The knee flexion / extension moments and angles were not affected by the different manoeuvres. Differences between running and cutting were also found in studies on plantar pressure as it was found that during cutting manoeuvres peak plantar pressure shifted to the medial side of the foot compared to running and sprinting (Eils et al., 2004; Wong et al., 2007).

With regards to turning, no study has made a direct comparison with running or cutting. A study by Stefanyshyn et al. (2010) that looked at both a cutting and turning manoeuvre did not specifically compare the different movements, but it did find that changes in traction had an effect during the turning manoeuvre and not during the cutting manoeuvre, which suggests that the traction of the shoe-surface interface has a greater effect on a turning manoeuvre than on a cutting manoeuvre. Finally, a study by Stiles et al. (2011) that looked at both running and turning showed that the knee flexion angle during a turn was larger than during running, whereas the ankle flexion angles were similar during both movements.

During cutting and turning manoeuvres several factors, such as the surface properties, in-game scenarios, technique, experience, and foot preference, may affect the kinematics and kinetics of the movement. Sections 2.4.3 and 2.4.4 already showed that the surface properties and in-game scenarios can affect cutting and turning manoeuvres. A study by Dempsey et al. (2007) showed that instructing subjects to modify their technique during a sidestep cutting manoeuvre can affect the loading of the knee joint. To examine this they compared the movement dynamics of a normal cutting technique of male team sport athletes to alternated techniques. Compared to the normal technique of the subjects, the study found that placing the foot as far away as possible, an inward rotation of the foot, and rotating the torso in the opposite direction of the cut led to significant changes in the knee loading (Dempsey et al., 2007). In addition to this, the study also found significant effects for the knee loading between interventions regarding the placement and rotation of the foot, and leaning of the torso. All these findings suggested that the knee loading can be increased or decreased by a change in technique.

Of the remaining factors, a study on plantar pressure in soccer related movements found that the foot preference can affect the overall plantar pressure underneath the foot (Wong et al., 2007). In the preferred foot the overall pressure was highest during the take off phase, whereas the non-preferred foot had higher pressure values during the landing phase. As a result of this it was suggested that the preferred foot might be used to generate a higher force during a movement, while the non-preferred foot might play a greater role in body stabilisation.

Finally, experience may also affect the loading during a movement as a study by Sigward and Powers (2006) found that less experienced female soccer players exhibited significantly smaller knee flexor, adductor and internal rotator peak moments. As an explanation for this they suggested that players change to a more efficient movement strategy when gaining experience and confidence with the manoeuvre to reduce muscle activity (Sigward & Powers, 2006).

2.4.5.2 Jumps / Landings

Studies on jumps and landings consider a variation of manoeuvres, such as drop landings, drop jumps, maximal height stop-jumps, squat jumps and counter movement jumps (Oliver et al., 2008; Chappell et al., 2005). Of these the stop-jump is the only one that requires a run-up, typically three to four steps followed by a two footed landing and jump (Chappell et al., 2005).

Previous studies have shown that several factors can affect the lower limb biomechanics during a jump and landing. The effects of the surface properties and in-game scenarios have already been discussed in §2.4.3, other factors include the drop height during a drop jump / landing, instruction, and fatigue (which already has been discussed to some extent in §2.4.4). Studies on the effects of the drop height during a drop jump showed that the vGRF increases with an increase in drop jump height (Bobbert et al., 1987; Bisseling et al., 2007; Yeow et al., 2009). With regards to the joint flexion, studies showed that the effect of the drop jump height is dependent on the landing. Bisseling et al. (2007) showed that during a single leg drop jump the knee and hip flexion increased, whereas studies on double legged drop jumps did not find any significant effects for the joint flexion angles (Bobbert et al., 1987; Yeow et al., 2009). Despite the difference in joint flexion, all studies related the increase in drop height to increased joint loading in the lower limbs.

Instructions to modify the landing strategy can also affect the musculoskeletal loading, these strategies involve changes in both the upper and lower body. In the lower limbs studies tried to modify the landing strategy by instructing subjects to change their foot position as well as the amount of knee and hip flexion. Considering the foot position it was found that a forefoot landing led to a straighter posture during the initial landing phase, which was caused by a lower hip flexion, whereas for the rear foot landing the knee flexion was increased during the initial phase, but increased during peak vGRF, which was suggested to be a risk factor for injuries (Cortes et al., 2007). Regarding the knee and hip flexion a previous study found that a reduced flexion impaired the ability of the respective joints to absorb the energy of the landing, increasing the knee valgus angle and varus moment (Pollard et al., 2010). Finally, an increased trunk flexion was shown to increase the flexion of the hip joint while decreasing the vGRF (Blackburn & Padua, 2008; Blackburn & Padua, 2009).

The effect of fatigue on a jump / landing manoeuvre has already been discussed to some extent in §2.4.4. However, this was limited to fatigue protocols that resembled conditions during a soccer match. Other, non soccer specific, studies have shown that fatigue can impair the jump performance (Oliver et al., 2008; Sanna & O'Connor, 2008). However, with regards to the GRF and joint moments and angles it appears that the effect of fatigue is dependent on the landing performed. Previous studies on jumps that use two legged landings found that fatigue increased the GRF and knee flexion moment, while the knee flexion decreased (Chappell et al., 2005; Oliver et al., 2008). Another study on single legged landings found a decrease in GRF, while the peak knee flexion and ankle dorsi flexion angle increased (Madigan & Pidcoe, 2003). Finally, a study by Gehring et al. (2009) found no effects for the movement kinematics during a two legged landing. This may be caused by the fatigue protocol used as Gehring et al. (2009) did not use a functional exercise protocol as used in the other studies, which may have fatigued different muscles.

That the fatigue pattern can affect the results is shown in a study by Kellis and Kouvelioti (2009) that studied the fatigue effect during a single leg drop landing after fatiguing the knee flexor and knee extensor muscles. This study found that fatiguing the knee flexor muscles mainly led to an increased muscle activity of several muscles in the leg, and did not affect the vGRF. Fatiguing the knee extensor muscles led to a decreased vGRF and higher knee flexion angle, and did not increase the muscle activity. Based on this, it was concluded that the fatigue response during landing is highly dependent on which muscle is fatigued (Kellis & Kouvelioti, 2009).

2.5 Discussion

Several studies have characterised the effects different surface properties, such as the hardness and traction, have on human dynamics. In these studies the hardness was mainly modified by adjusting the surface, whereas the traction was modified by changing the footwear. While these studies have shown that both the hardness and rotational traction of a surface can affect the human dynamics still some gaps in knowledge exist. With regards to quantifying the effect of surface properties the gaps in knowledge are partly caused by the fact that some biomechanical studies failed to characterise the surface properties, whereas other studies that did quantify the surface properties failed to provide any biomechanical data. Another gap in knowledge concerning the surface properties is caused by the fact that studies use different mechanical measurement methods, such as the (Advanced) Artificial Athlete, Clegg Impact Hammer, and specialist material tests for the hardness, and different traction devices for the rotational traction, as identified in §2.2. As few biomechanical studies used the same mechanical measurement methods as the standard tests used by FIFA it is difficult to relate the results to the ranges set by FIFA for the hardness (FIFA one star: 55 – 70%, FIFA two star: 60 – 70%) and rotational traction (FIFA one star: 25 – 50 Nm, FIFA two star: 30 – 45 Nm). This is caused by the fact that the measurement methods for the hardness express the surface hardness differently, whereas for the rotational traction the different set-ups of the test devices, such as the test foot angle, may cause differences in the resistance between the test foot and the surface compared to the standard device. In addition to this, to the author's knowledge, only one previous biomechanical study included surfaces with force reduction values close to the ranges set by FIFA (Meijer et al., 2007).

In addition to the limited knowledge on the effects of the FIFA standards on musculoskeletal loading, previous biomechanical studies only investigated the hardness and traction properties separate from each other. This has the advantage that only one factor has to be considered when drawing conclusions. However, previous studies have shown that both the hardness and traction properties of the shoe-surface interface can affect the human dynamics. It may therefore be that these properties influence each other regarding the effects they have on human dynamics, causing the effects of a change in surface hardness to increase or decrease by a change in surface traction and vice versa.

A further gap in knowledge can be identified in the current literature with regards to the movements used. Biomechanical studies have mainly considered running, different types of jumps, cutting manoeuvres, and a few turning manoeuvres; generally characterised with the help of video analysis, force platforms, and pressure insoles. The movement classification in §2.4.2 however shows that there are many other soccer relevant movements. A study by Bloomfield (2007) included most of the movements of the classification and showed that during a soccer match players often change direction (average 727 times per match).

Furthermore, it found that 18% of the time players perform purposeful movements during a match they perform movements such as jumping, landing, diving, sliding, slowing down, falling and getting up. Of these different manoeuvres injury studies have identified turning manoeuvres, landing, and jumping, as the non-contact movements during which injuries are most likely to occur (Hawkins et al., 2001; Price et al., 2004; Kofotolis et al., 2007). This suggests that the movements used in biomechanical studies are relevant from a point of frequency of use and musculoskeletal loading. However, in addition to this the choice was made to consult soccer players to gain insight into what movements are most relevant for them and how they perceive the loading on the body during the different movements. With this information the most relevant high demanding movements could be selected for the player movement study.

Section 2.4.2 also identified other factors, such as the intensity or the inclusion of a ball, which may influence the dynamics of a movement. The inclusion of the ball brings us to the aspects of in-game scenarios as §2.4.4 showed that the inclusion of a ball or a simulated opponent can significantly affect the human dynamics during running, cutting and jumping manoeuvres. Few studies have used in-game scenarios, but the studies that did suggest they can provide insight in the musculoskeletal loading during actual match situations. The in-game scenarios that have been used still leave room to increase the realism; for example, the study by McLean et al. (2004) used a static skeleton to resemble an opponent. It is expected that interacting with a human will have a greater effect on the movement dynamics than moving past a skeleton, as a skeleton is static and running into it will not have any major consequences.

Combining the different movements, verified with the input of soccer players, with different surface properties and in-game scenarios increases the current knowledge in how surface properties affect the musculoskeletal loading during different movements. Using different movements increases the knowledge because of the variation in loading conditions, whereas the in-game scenarios provide insight into how movements are affected during match situations. Finally modifying multiple surface properties within the FIFA guidelines increases the knowledge both on how the surface properties and FIFA standards affect the human dynamics, but also increases the knowledge on how the combination of the different properties affect the musculoskeletal loading.

Apart from different movements, surface properties and in-game scenarios, there are a few other factors that have to be taken into consideration for the research design such as: fatigue, footwear, experience, and instruction. As all of these factors can affect the human dynamics their effects have to be kept to a minimum or incorporated in the design. Fatigue can be dealt with by ensuring each subject has enough rest between trials, whereas footwear and experience can be dealt with by making sure the subjects have similar footwear and amount of experience. Carefully instructing the subjects on how to perform a manoeuvre is necessary to avoid unnecessary variance in techniques. However, this could affect the results when the movements are not performed in a natural manner. Therefore careful consideration on the instructions is required together with the data collection methods. Gender has also been identified in previous studies to affect the human response during cutting and jumping / landing manoeuvres (McLean et al., 2004; Gehring et al., 2009). With regards to this FIFA showed that women only make up ~10% of all soccer players (FIFA, 2007). This means that many more experienced male players are available to participate in the player movement study. Therefore the choice was made to only use male players, eliminating the gender factor.

With the information and the gaps of knowledge identified in this literature review a research philosophy (Chapter 3) can be formulated which forms the approach for the rest of the thesis to meet the objectives set in Chapter 1. For this approach several aspects have to be considered carefully regarding the surfaces and biomechanics. Regarding the surfaces this involves: what surface properties to use and how to quantify these properties, what range for each of the surface properties, how to design surfaces to meet different values, and how to control the different surface properties during the player movement study. Regarding the biomechanics this involves: what movements and in-game scenarios to use during the player movement study, what subjects, what test parameters and data collection methods, what test set-up, and how to control confounding variables.

2.5.1 Limitations

Regarding this literature review several limitations can be identified with respect to the sections on surfaces, injuries in soccer and movements. The main limitation in the surfaces section can be found regarding the different test methods available to quantify the surface characteristics. This only contained a selection of the available methods, which are developed constantly. However, it is believed that the selection presented gives a good representation of what options there are to quantify the surface characteristics.

Regarding the section on injuries in soccer the main limitation involves the selection of the studies used to identify the injury rates and locations. This could have been more systematic, for example by only selecting studies that complied with the consensus statement by Fuller et al. (2006), or by only selecting studies that collected data on the different parts of the lower limbs. Nonetheless, it is believed that a more systematic approach would also have provided the same outcomes as in all studies the majority of injuries were located in the lower limbs, and in the studies that included the different parts of the lower limbs the thigh, knee and ankle were the biggest contributors.

The section on movements is mainly limited by the number of movements and in-game scenarios used, while many more movements and in-game scenarios are possible in soccer. This was necessary to maintain the focus on the rest of the thesis.

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3. RESEARCH PHILOSOPHY

3.1 Introduction

The literature review in Chapter 2 identified several gaps in knowledge with regards to the effects surface properties have on human movement dynamics. It was found that studies used different methods to quantify the surface properties, identified in §2.2.4, which makes it difficult to relate findings of some biomechanical studies to the standards set by sports governing bodies such as FIFA. Other limitations involve the fact that some studies on surface properties failed to provide any biomechanical information and vice versa, some biomechanical studies that suggested changes in the shoe-surface interface failed to quantify the properties of the interface. Finally, previous studies that have looked into the surface properties only focused on a single property. However, it may be that different properties, such as the hardness and traction, show an interaction effect as studies have shown that both properties can affect the human dynamics during movement.

With regards to the movements used, in previous biomechanical studies the literature review showed that mainly running, jumping / landing, and cutting manoeuvres have been used, and to some extent turning manoeuvres. However, §2.4.2 showed that there are many more manoeuvres in soccer that may also be relevant. While injury studies have shown that these movements may be relevant from an injury point of view it may be from a soccer player point of view other movements are of equal importance. Furthermore, the literature review showed that in-game scenarios may be a useful addition to biomechanical studies to gain insight into the human dynamics in actual game situations.

This chapter explains the approach to the rest of the thesis to meet the objectives set in Chapter 1. This approach was chosen as various chapters in this thesis are interlinked with each other (Figure 3.1) and this chapter therefore shows this relation and the choices made in a comprehensive way. To achieve this the approach to the selection of surface properties, design and measurement methods, and selection of movements, in-game scenarios, biomechanical aspects and study design are discussed with the help of relevant questions presented in §3.2. Following this hypotheses are presented regarding the player movement study in §3.5 and the contribution to knowledge of this research is discussed in §3.6.

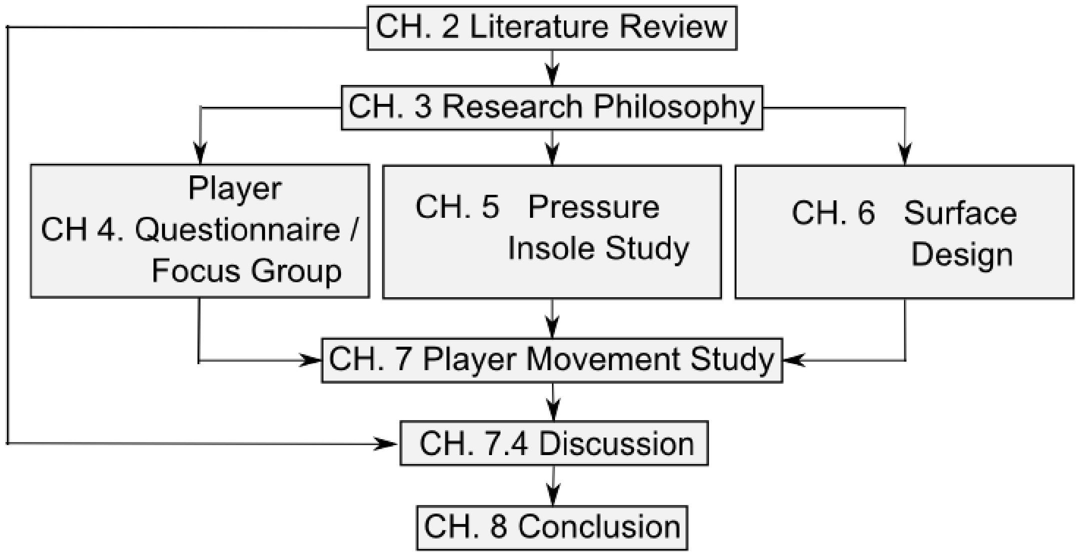

Figure 3.1. Flowchart presenting how the chapters of this thesis are interlinked with each other.

3.2 Objectives

To achieve the aim of this PhD and answer the research questions the following six objectives were set in Chapter 1, which form the basis for the approach of the rest of this thesis.

1: Review current knowledge on: surface design, standards and test methods; player movements in soccer; and the effects of surface properties and in-game scenarios on player kinematics and loading during soccer-specific movements.

2: Select relevant surface properties and range of properties, movements and develop suitable in-game scenarios to form the basis of an experimental investigation into the effects of surface properties on player kinematics and loading

3: Design artificial turf systems that represent the range of surface properties identified in Objective 2

4: Design an experimental study to measure the player kinematics and kinetics on the different surfaces and in-game scenarios

5: Measure the effects of controlled surface properties and in-game scenarios on player kinematics and loading during selected soccer movements (as identified in Objective 2)

6: Evaluate the results from Objective 5 with respect to the effects of surface properties on player movement and loading, and the relevance of in-game scenarios under lab testing conditions

The first objective has been achieved by reviewing the current literature in Chapter 2. For the remaining objectives the following questions can be asked with regards to the surfaces and biomechanics, which will be discussed in the following sections:

Surfaces:	**Biomechanics:**
Which surface properties?	*What movements?*
What surface measurement methods?	*What in-game scenarios?*
What range for each of the properties?	*What subjects?*
What surface design?	*What test parameters?*
How to control surface properties?	*What biomechanical data collection methods?*
	What test set-up?
	How to control confounding variables?

3.3 Surfaces

As mentioned in §3.2 there are several questions that can be asked with regards to the surfaces to use for the player movement study. This section discusses each of the questions presented in §3.2, including the different options that are available and the choices that were made to meet the objectives of this thesis. At the end of this section an overview is presented regarding the approach and choices made.

3.3.1 Which Surface Properties?

The literature review showed that previous biomechanical studies mainly focussed on the surface hardness and to a lesser extent on the traction properties of the shoe-surface interface. Studies showed that both properties can affect the human movement dynamics, and there were also some suggestions that the hardness and rotational traction can contribute to the injury risk. Apart from the surface hardness and rotational traction, there are other surface properties that can be modified such as the surface damping and the translational traction. The effects of the surface properties can be dependent of the movements performed as a study by Stefanyshyn et al. (2010) suggested that the rotational traction of the shoe-surface interface mainly affects movements with a rotational component, whereas for the hardness a study by Arampatzis et al. (2004) suggested that the effects of the surface hardness depends on the demands of an activity. Therefore, the choice of surface properties has to be in conjunction with the choice of movements.

For the selection of movements, the choice was made in §3.4.1 to consult soccer players, through the use of a focus group and player questionnaire (Chapter 4). This also provided insight into what surface properties soccer players preferred, for example a hard or soft surface, how they rated the surface properties of different pitches they play on, and their attitude when playing on these pitches regarding the loading on their body and injury risk. Based on the outcomes of the literature review and the results in Chapter 4, the choice was made to investigate the effects surface hardness and rotational traction, as presented in Table 7.31, on the selected movements.

Table 3.1. The surface properties selected to be used in combination with the player movements.

Surfaces		**Rotational traction**	
		High	**Low**
Hardness	**Hard**	Hard – High	Hard – Low
	Soft	Soft – High	Soft – Low

3.3.2 What Surface Measurement Methods?

Section 2.2.4 of the literature review showed that different measurement methods are available to quantify the surface properties. For surface hardness these involve the (Advanced) Artificial Athlete, the Clegg Impact Hammer, and specialist material testing machines to create a force – deformation curve. For rotational traction these involve the standard rotational traction device as defined by FIFA and range of custom made devices. Each of the different measuring methods has its advantages and disadvantages which are discussed in the following sub-sections, plus for the surface hardness the measuring method also dictates how the hardness is expressed.

Regarding the selection of the mechanical test method it was considered important that the surface properties could be quantified across the surface samples and that the test surfaces used in the player movement study (Chapter 7) could be monitored throughout the test period. Furthermore it was important that the findings of the player movement study could be related to the FIFA standards as the research questions set in Chapter 1 are aimed at soccer. In addition to this, currently little is known on how surfaces meeting these standards affect the movement dynamics as the literature study showed that few previous biomechanical studies used these to describe the surface characteristics.

3.3.2.1 Surface Hardness

The (Advanced) Artificial Athlete is the measurement device that is used as a standard by sports governing bodies such as FIFA and is the only standard test available (FIFA, 2012b). The advantages of this device are that it is easy to transport, which allows it to be used to monitor the surfaces during the player movement study, and it is used by FIFA, which makes it possible to relate the biomechanical findings directly to the standards set in soccer (Table 3.2). In addition to this the FIFA protocols are aimed to perform multiple tests in the field, which ensures the repeatability of the test in the lab. The main disadvantage of the (Advanced) Artificial Athlete is that it is questionable to what extent the single vertical impact condition of the device represents the human impact during various movements.

Table 3.2. Standards set by FIFA for rotational traction and shock absorption: One Star for recreational use and Two Star for professional use (FIFA, 2012a).

FIFA Qualification	**One Star**	**Two Star**
Rotational traction	25 – 50 Nm	30 – 45 Nm
Shock Absorption	55 – 70 %	60 – 70 %

While the Clegg Impact Hammer is not a standard measuring device it has been used in previous studies to quantify the hardness of the surface (Severn, 2010; Johnson & Forrester, 2011; Stiles et al., 2011; Twomey et al., 2012). As with the (Advanced) Artificial Athlete the device is easy to transport, making it a suitable device to monitor the surfaces during the player movement study. Furthermore, different weights are available for the Clegg Impact Hammer (0.5, 2.25, or 4.5 kg) and different drop heights can be used, which allows for measuring the surfaces during different impact conditions. The disadvantages of the device are that, as with the (Advanced) Artificial Athlete, it is questionable to what extent the single vertical impact of the device represents a human impact. Furthermore, §2.2.4.1 of the literature review showed that the hardness measure (peak deceleration in gravities) is different to that of the FIFA standard (force reduction). With regards to this, a study by Fleming (2011) did report a good correlation between the Clegg Impact Hammer measurements and those of the (Advanced) Artificial Athlete. However, it also stated that it is inadvisable to estimate the force reduction values measured with the (Advanced) Artificial Athlete by a conversion from the Clegg Impact Hammer measurements. As a result, measurement with the (Advanced) Artificial Athlete would still be necessary when using the Clegg Impact Hammer.

The surfaces stiffness is also commonly used in previous studies to quantify the surface hardness (McMahon & Greene, 1979; Kerdok et al., 2002; D. Ferris et al., 1999; Arampatzis et al., 2004). The advantage of the way that the surface stiffness is measured is that different loading conditions can be used to create a force-deformation curve, which also allows determination of the surface stiffness or hardness at a similar force level to which the surface is exposed during different movements. As a result, this method may give a better representation of the surface response during human movements. The main disadvantage of using this method is that, as shown in §2.2.4.1, to measure the surface stiffness a specialist material testing device, as such as an Instron Electropulse, is necessary that can load the surface gradually to create a force-deformation curve and ideally can do this at a similar loading rate as during human movements. This has the limitation that the surface sample has to be placed in the device and means that it would not be possible to monitor the surface hardness during the player movement test. Furthermore, in case of the Instron Electropulse the maximum width of the test samples is restricted to 45.5 cm, which restricts determining the hardness in multiple locations, which normally is done within the FIFA protocols. In addition to this, the surface stiffness (N/m) is a different measure of surface hardness to that used in the FIFA standards (force reduction), making it difficult to relate any biomechanical findings directly to the standards in soccer.

Comparing the different measurement options it is clear that none of the available methods would allow the creation of different human impact conditions, monitoring the test surfaces and relating biomechanical findings directly to the FIFA standards. As the latter two of these criteria were deemed important the choice was made to use the use the (Advanced) Artificial Athlete to quantify the surface hardness in the surface design phase (Chapter 6) and player movement study (Chapter 7).

3.3.2.2 Rotational Traction

To measure the rotational traction FIFA uses a standard device which consists of a loaded studded test foot that is rotated for a minimum of 45° to determine the peak rotational traction, which also is the only standard test device available (FIFA, 2012b). The main advantage of this device is that it is easy to transport making it suitable to monitor the surfaces during the player movement study. The main disadvantage is that it is only possible to record the peak traction over a certain rotation angle. Therefore, it is questionable to what extent the traction value represents the amount of traction players experience during movements with a smaller rotation angle. This is especially relevant since previous studies showed that rotational traction of the shoe-surface interface is dependent on the rotation angle of the test device, as discussed in §2.2.4.2 (Livesay et al., 2006; Villwock et al., 2009).

In addition to the rotation of the test device, it is questionable to what extent the orientation of the test foot represents the foot during a rotation, as previous research showed that during cutting manoeuvres the foot does not always move flat on the surface as occurs for the test device (Stacoff et al., 1996). For this reason, previous studies measured the rotational traction with the foot being at an 20 degree plantar flexion angle to the surface to simulate the orientation of the foot to the surface during a cutting manoeuvre (Wannop et al., 2010; Stefanyshyn et al., 2010). Finally, previous studies have shown that the shoe design can affect the rotational traction, which would require a test foot with a similar design to the shoes that will be used during the biomechanical tests.

The main advantage of the custom devices used in previous studies is that they overcome the main disadvantages of the standard test device. Some of the devices allow the use of actual soccer boots, which in some cases can be placed at an angle to the surface. Other devices allow the continuous measurement of traction, giving insight in how the traction develops over different rotation angles in addition to the peak value. The main disadvantage of these devices is that commonly they are substantially larger than the standard test device, making them more difficult to use to monitor the surfaces during the player movement studies. For some, like the device used in studies by Wannop et al. (2010) and Stefanyshyn et al. (2010), an added difficulty is that they require the surface to be placed in the test device. This means that larger surface samples cannot be monitored, and surfaces may be disturbed when placing them in the test device, which could affect the surface properties. A final disadvantage for the custom devices is that, in contrast with the standard test device, they cannot be bought off the shelf and detailed designs are unavailable. Therefore, to use one of these devices, the device itself or the design needs to be located, or a new custom made device has to be developed.

After comparing the different options the choice was made to use the standard test device to measure the rotational traction properties of the surfaces in the surface design phase (Chapter 6) and player movement study (Chapter 7). This choice was made as the device is available at Loughborough University and its transportability meant that it is suitable to monitor the surfaces during the player movement study. While it does not provide information on the rotational traction properties at different rotation angles it does provide the value used in the FIFA standards. Furthermore, the studs of the test device were similar to those on the soccer boots used in the player movement study (Chapter 7).

3.3.3 What Range for Each of the Surface Properties?

Several factors have to be considered for the range of the surface properties. First of all, from an ethical point of view it is undesirable if the surface properties lead to an increased risk of injuries. For example, a surface with very low traction could prove slippery and cause the players to fall and / or be injured during a movement, the same may happen on surfaces with a too high traction causing a high load on joints which could potentially cause injuries. When designing different surfaces the standards set by sports governing bodies can be used as a guideline as it can be assumed that the players are used to playing on surfaces with similar hardness and rotational traction conditions. Therefore using surface conditions similar or close to the ranges set by the sports governing bodies would not lead to an increased risk of injuries compared to that experienced when they play.

As mentioned in §2.2.3, the standards of different sports governing bodies can vary. Since this thesis focuses on artificial turf in soccer the choice was made to use the FIFA standards as a guideline as this is the expected range to which soccer players are exposed on artificial turf (Table 3.2). To gain insight into how the FIFA standards affect the human dynamics the choice was made to create surfaces close to the limits of the standards. The surface design phase (Chapter 6) has to provide surfaces with largest range that can be realised and considered safe for the players.

3.3.4 What Surface Design?

Before designing different surfaces to meet different properties several aspects have to be considered with regards to the materials used. The literature review showed that the hardness of the surface can be regulated by the infill depth and by the use of shockpads. On the other hand, the infill used may also affect the rotational traction properties of the surface as a study by Severn (2010) indicated that the bulk density (mass of infill per volume of the surface system typically expressed as g/cm^3) can be affected by the carpet used (fibre type) and the infill material (type, size, shape, and infill depth), in example a greater volume of fibres or increased size of the infill particles reduces the bulk density. Therefore, for the main approach to modify the surface hardness it was decided to make changes to the shockpad, whereas for modifying the traction the main approach involved making changes to the carpet and infill.

The different materials for the carpet and infill also affect the appearance of the surface, for example the different infill materials identified in §2.2.2. As the appearance may affect the perception players have of the surface the choice was made to use as similar as possible products to keep the appearance as equal as possible. With regards to the rubber infill, the choice was made to use styrene-butadiene-rubber (recycled tyres) as this is commonly used in artificial turf surfaces and freely available in different grades that may affect the traction properties. With regards to the carpet, the choice was made to use the same carpet across all surfaces.

3.3.5 How to Maintain Surface Properties?

One of the objectives set for the research involves measuring the effects of controlled surface properties on player kinematics and loading during selected soccer movements. This means that the surfaces need to be monitored and maintained to ensure that the surface conditions are similar for all subjects. While previous biomechanical studies using artificial turf surface did not report doing this, this was deemed important as §2.4 of the literature review showed that compaction of the infill, for example through player loading, can affect the surface properties.

To control the surfaces there are several options available. First of all the surface measurement methods could be used to quantify the surface properties regularly during the player movement study. However, it may be that the disturbance caused by the measurement devices causes the surface properties to change. Furthermore, measuring the surfaces in multiple locations could prove to be a time consuming activity. The literature review showed that rubber infill thickness affects the hardness and the bulk density of the surface. Considering this, measuring the infill depth may be a valid method to monitor the surface hardness without disturbing the surface. The bulk density is more complicated to monitor. However, a study by Severn (2010) reported that the bulk density of the infill increases when the infill is being compressed, therefore the infill depth may also be suitable to monitor the traction properties. The surface design phase in Chapter 6 has to show to what extent measuring the infill depth is a suitable method for monitoring the surface properties.

Maintaining the surface mainly involves keeping the state of the infill similar as this will be disturbed by player and surface movements and can affect the hardness and rotational traction. To do this the bulk density has to be kept the same and the infill may need to be topped up to compensate for any infill coming out of the surface during the player movement study (Chapter 7). To keep the bulk density the same the infill can be brushed or raked as the lowest bulk density in a study by Severn (2010) was reached when the surface samples were raked. The surface design phase in Chapter 6 has to show what maintenance is most suitable and how frequently this has to be performed.

3.3.6 Overview of Surface Approach and Choices

Table 3.3. The different considerations that were made for the surfaces and the objective(s) they address, including the different options available and selected.

Consideration	Objective	Options	Selected option(s)
Which surface properties?	2	Literature review Player feedback	Hardness Rotational traction Preliminary study (Chapter 4)
What surface measurement methods?	3	Standard Equipment: Hardness / Traction Clegg Impact Hammer: Hardness Fanuc Robot: Hardness Instron Electropulse: Hardness Custom traction devices: Traction	Standard Equipment: (Advanced) Artificial Athlete: Hardness Standard traction device: Traction
What range for each of the properties?	2, 3	Literature review FIFA standards Expected range on pitches	Values close to limits of FIFA standards Preliminary tests (Chapter 6)
What surface design?	3	Carpet (fibre types, spacing) Infill (type, grade, shape) Shockpad	Same carpet Same type of infill Shockpad to modify hardness Different infill grades to modify traction Preliminary tests (Chapter 6)
How to control surface properties?	5	Surface measurement methods Infill depth Brushing Raking	Surface measurement methods Infill depth Light brushing Preliminary tests (Chapter 6)

3.4 Biomechanics

As mentioned in §3.2 there are several questions that can be asked with regards to the biomechanical aspect of the player movement study. This involves both the movements and in-game scenarios to be used in conjunction with the different surfaces, as well as the experimental design including the subjects, test parameters and data collection methods. This section discusses each of the questions presented in §3.2 regarding the biomechanics, including the different options that are available and the choices that were made to meet the objectives of this thesis. At the end of this section an overview is presented regarding the approach and choices made.

3.4.1 What Movements?

The literature review formed the initial guide for selecting the movements for the player movement study. Most biomechanical studies focussed on running, jumping / landing, and cutting / turning manoeuvres. However, while previous studies showed that these movements can put a high loading on the body and are important from an injury point of view, §2.4.2 of the literature review showed that there are many more soccer relevant movements. To aid the decision making process on which movements to use for the player movement study the choice was made to consult soccer players on how they perceive the importance of movements to perform well, how frequently they perform movements during a match, and how much loading they perceive the movements put on their bodies.

To consult the players several methods were available such as individual interviews, focus groups (discussion amongst a small group of players) and questionnaires (list of questions to reach a large group of players). Of these different methods individual interviews have the advantage that they can provide detailed information and participants can express their opinion without them being affected by the opinions of others (Greenbaum, 2000; Grudens-Schuck et al., 2004; Morgan, 1997). The main disadvantage of the individual interviews is that the process is time consuming and therefore fewer players can be reached than with the other methods.

The main advantage of the focus group is that more players can be reached at the same time and that a discussion could take place between players for which feedback by one player might stimulate another player to express his ideas (Greenbaum, 2000). In addition to this, during discussions in the focus group the terminology the players used could be identified, which later could help to clarify aspects of the research to the players (Greenbaum, 2000). However, still a limited number of players could be reached with the focus group.

Finally the main advantage of the questionnaire is that a large cohort of players could be reached in a limited amount of time. At the same time the main disadvantage is that the answers in questionnaires are less detailed than in interviews and focus groups. Considering these options the choice was made to use a focus group and a questionnaire to both gain detailed feedback from the players in the focus group as well as reach a large number of players with the questionnaire.

Regarding the construction of the questionnaire the choice was made to use open questions for general questions such as age and experience, whereas for the other aspects the choice was made to use closed questions as it was expected that open question would lead to a large variation in answers and terminology. Regarding the closed questions several options were available such as a continuous scale, rank ordering, or Likert scale (Oppenheim 1992). Of these options the rank ordering, which requires to rank the different options (e.g. most frequent movement a rating of 1 and least frequent a rating of 10), was considered to be unsuitable for a large number of movements. This would make ranking complicated, especially if the players want to make changes going through the list of movements.

The remaining options meant that each aspect (e.g. frequency of movement) would have to be rated separately. The main difference between the continuous scale and Likert scale is that the continuous scale has limitless options (e.g. players can be asked to rate a movement on a scale from 1 – 100) whereas the Likert scale has a limited number, typically 5 – 7, of visually represented options (Oppenheim 1992). Comparing these scales the continuous scale has the advantage that it is easier to differentiate between the different options, such as the movements, but has the disadvantage that it may be more difficult for participants to directly compare the ratings of the various options and this method generally is considered as more difficult to code during data analysis. The Likert scale has the advantage that it is easy to code and understand by the participants, and while filling in the questionnaire the participants can easily see how they rated the different options and compare them to each other. The disadvantage of this method is that the options given to the participants are limited and the risk exists that people avoid choosing the "extreme" options. This risk could to some extent be resolved by using a larger 7 point scale and the Likert scale. Considering the different advantages and disadvantages the choice was made to use a Likert scale as this would allow easy comparison of the options by the participants as well as meant that the questionnaire would be easy to understand.

In addition to the literature and the player feedback, the movements also had to complement the different surface properties as discussed in §3.4.1. With the information of the literature review and results of the player focus group and questionnaire, the choice was made in Chapter 4 to investigate the effects the surface hardness and rotational traction, and in-game scenarios on a stop and turn, which was expected to be mainly affected by the rotational traction, and on a jumping / heading manoeuvre, which was expected to be mainly affected by the surface hardness.

3.4.2 What In-game Scenarios?

Section 2.2.4 of the literature review showed that previous studies tried to incorporate in-game scenarios in different ways including a simulated opponent, anticipation of a manoeuvre, ball control, and fatigue protocols to resemble match fatigue. These gave some guidance in deciding what in-game scenarios to use, but obviously there are many more scenarios that occur during game situations. Therefore the choice was made to use the focus group and player questionnaire (Chapter 4), which was also used for the decision making on movements, to consult players on what other in-game scenarios they could think of, how frequently they encountered these, how important they considered them to be in order to perform well, and how they affected the perceived loading on their bodies.

In addition to this, the selection of the in-game scenarios also had to complement the selected movements as well as be viable for use within the restrictions of the lab environment, including space restrictions and data collection methods. To examine if the in-game scenarios discussed in Chapter 4 were viable with regards to lab space and data collection methods the choice was made to perform a pilot test with a few soccer players. After this the choice was made to not make use of dynamic scenarios involving players chasing each other due to the limited lab space, the added timing factor of players having to react to each other and possible effects on the consistency of the movement. Furthermore, using dynamic players in in-game scenarios such as heading duels, or avoiding a tackle, which were identified in Chapter 4, increased the chance on player-player contact, which was identified as an important injury risk factor in soccer in the literature review.

Looking at the remaining options for in-game scenarios a simulated opponent, as used in the study by McLean et al. (2004), was considered most appropriate for the stop and turn manoeuvre. For the jumping manoeuvre, heading a ball was considered to be most appropriate as in soccer, except for the goal keeper, a jumping manoeuvre is generally accompanied with a heading manoeuvre.

3.4.3 What Subjects?

Several aspects had to be taken into consideration in order to make the decision on what subjects to use. These include experience, technique and gender, which were identified in the literature review as factors that could affect the outcomes of the player movement study. As this thesis focuses on soccer the choice was directly made to make use of soccer players, which to some extent resolved factors like experience and technique as soccer players are used to performing the selected movements. However, some aspects with regards to experience and technique remained. The first aspect involved how long the players have been playing soccer as this is directly related to the experience of the players, plus it was assumed that more experienced players are more able to perform the selected movements in a natural manner. To deal with this, the choice was made to use soccer players from the Loughborough University teams, with at least five years experience playing soccer to ensure they had plenty of experience and were able to perform the movements in a natural way. The five years was based on previous research that classified subjects with less than five years experience playing soccer as inexperienced (Sigward & Powers, 2006).

Another concern was the experience the players have on artificial turf. If players had no experience at all playing on artificial turf it may be that the movements of the players was affected by the assumptions they have about playing on artificial turf. As reports in the media tend to be negative, as shown in Chapter 1, it may be that the players would move more cautiously on the artificial turf, affecting the human movement dynamics. Therefore the choice was made to only use players with significant experience in playing on artificial turf. This experience was set on two years as it was believed that, with typically multiple trainings per week, this would provide sufficient exposure to artificial turf.

As far as gender is concerned, the choice was made to only use male players. The main argument for this choice was the fact that the vast majority, approximately 90%, of soccer players are male (Matthias Kunz, 2007).

3.4.4 What Biomechanical Test Parameters?

The biomechanical test parameters for the player movement study had to cover the aspects of technique and human loading. Changes in movement technique can be identified by measuring the joint angles of the bodies. Previous studies on cutting / turning and jumping / landing manoeuvres quantified the joint angles of the entire body, the lower body, or just a single joint. It is expected that mainly the lower limbs will be affected by the changes to the surface properties. However, previous studies showed that the upper body can affect the human dynamics during cutting and landing manoeuvres (Dempsey et al., 2007; Blackburn & Padua, 2008). Therefore the choice was made to not only look at the lower limbs but also at the upper body to identify if the surface conditions and / or in-game scenarios led to any changes in upper body movement that may have affected the lower limb dynamics.

The joint moments have been used in previous studies as a measure for the loading on the individual joints. This estimation is done with the help of inverse dynamics that uses segment kinematics and inertial parameters together with the external forces to calculate the internal joint moments. This approach is necessary as it is not possible to directly measure the loading on the joints inside the body. The main disadvantage of this is that it is not possible to determine the forces and moments acting on the individual tissues in and around the joints. The closest available option to do this is with the use of computer simulation models that use kinematic and other available biomechanical data to calculate the in-vivo loading.

As mentioned above, data has to be available on the external forces acting on the human body in order to calculate the joint moments. With the selected movements and in-game scenarios the main external force acting on the body will be the ground reaction force. Therefore the ground reaction force also has to be a test parameter included in the player movement study.

Other methods used in previous biomechanical studies are the plantar pressure data and muscle activity. The plantar pressure data is mainly used in previous studies to investigate changes in pressure underneath the foot which may indicate changes in technique and loading of the foot (Wong et al., 2007; Queen et al., 2008; Queen et al., 2007). Previous studies that looked at changes in the shoe-surface interface only found changes in the cushioning of the shoe (Queen et al., 2008). While the pressure insole data may provide more detail on the centre of pressure in relation to the foot and the force distribution underneath the foot it is expected that the key changes in technique can be identified with the data on the joint angles and joint moments of the lower limbs, for which the ground reaction forces are needed. Therefore the choice was made to not include plantar pressure data.

The muscle activity is a useful way to quantify how and when different muscles are activated during a movement. The main concern that existed involves the fact that the use of EMG would increase the number of sensors placed on the body, in addition to the Vicon markers used to track the movements. As this may affect how the players perform their movements the choice was made not to collect any muscle activity data.

3.4.5 What Biomechanical Data Collection Methods?

The biomechanical data collection methods had to be able to capture the test parameters discussed in §3.4.4. To track the movements and determine the joint angles, previous studies made use of 2D / 3D motion capture systems. These motion capture systems use markers placed on the subject's body to track the movement. Looking at the literature previous studies used different marker sets, some used marker sets that allow tracking of the entire body, whereas other marker sets used only tracked the lower limbs or only one leg (McLean et al., 2004; Dempsey et al., 2007; Sell et al., 2007; Meijer et al., 2007). As in §3.4.4 the choice was made to also investigate the joint angles of the upper body, a full body marker set was necessary to track the entire body.

Several motion capture systems are available on the market of which the Vicon and Codamotion 3D motion capture system were available at Loughborough University. The most important difference between the systems involves the sampling rate on which the markers placed on the body can be tracked. For the Vicon system the camera resolution dictates the maximal recording frequency, with the highest available resolution (MX T40) having a maximal frequency of 512 frames per second. The maximal recording frequency for the Coda system is 800 frames per second. However, the maximal frequency of the Coda system is dependent of the number of markers used. This would mean that with a full body marker set to track the entire body that contains 39 markers the maximal sampling rate would lay between 100 and 200 frames per second. Therefore the choice was made to use the Vicon system as the higher recording frequency means that the movements can be tracked more accurately. In addition to the Vicon system, the choice was made to use a high speed video camera for additional feedback on the movement of the foot as the impact of the foot with the surface was hard to identify with the Vicon system, as well as any twisting of the foot.

Several options are available to collect the ground reaction force data, namely a force platform and pressure insoles. In general force platforms are considered to be a gold standard in biomechanical research in collecting ground reaction force data and are used in many studies. While it is a gold standard there are some concerns with the use of a force platform. A force platform puts some restriction on movements as the maximal sizes available are: 60 x 90 cm (Kistler), 90 x 90 cm (Bertec) and 120 x 120 cm (AMTI), and therefore the movements can only be performed in a restricted area. In addition to this, in combination with artificial turf surfaces the force platform measures the ground reaction force underneath the artificial turf and not directly underneath the foot, which may not completely reflect the forces that act on the body.

Pressure insoles may be a solution to quantify the ground reaction forces without being restricted to a limited area as the pressure insoles are placed directly underneath the foot. Furthermore, the force is measured directly underneath the foot instead of underneath a few centimetres of surface as with a force platform which may give a better representation of the forces that act on the body. There are different types of pressure insoles available on the market, such as Pedar, Tekscan, Footscan, of which the Tekscan F-scan (# 3000) pressure insoles were available at Loughborough University. Regarding these, some concerns existed as previous studies reported issues (e.g. in durability and temperature sensitivity) that might affect the reliability of the pressure insoles (Luo et al., 1998; Woodburn & Helliwell, 1997; Morin et al., 2001; Sih, 2001). Therefore the choice was made to evaluate the reliability, durability and repeatability of Tekscan F-scan (#3000) pressure, and to assess the accuracy of reproducing the ground reaction force compared to a force platform in Chapter 5, before making a final decision on what method to use. Based on the results in Chapter 5 the choice was made to only use force platforms to quantify the ground reaction forces.

3.4.6 What Test Set-up?

The test set-up of the player-movement study had to accommodate for the different movements, in-game scenarios and surface conditions, as well as the data collection methods. Considering the previous studies that looked into different movements and in-game scenarios and used similar data collection methods it becomes apparent that a runway of some sort leading to the force platform(s), on which the movements had to be performed, is the most common set-up used (McLean et al., 2004; Kaila, 2007; Wannop et al., 2010). Dependent on the movement, studies also incorporated a run-off area after the force platform. While this run-off area was not directly necessary for the stop and turn or jumping / heading manoeuvre as they did not have to continue their movement behind the force platform the choice was made to include this in case the players would not be able to perform the movements in the designated area. This would also provide an area for the simulated opponent for the stop and turn manoeuvre.

In Chapter 5 it was decided to use force platforms to quantify the ground reaction forces. This means that the test set-up was partly dependent on the force platform locations in the lab as these are incorporated in the floor. The main factor affecting the set-up is the fact that a unit of cabinets runs through the lab which cannot be moved. Therefore if the small force platforms (60 x 40 cm) were used for the stop and turn the runway would have to be cut short (from approximately 9.5 m to 7.0 m) compared to using the large force platform (90 x 60 cm) (Figure 3.2). Consequently players would have less space to reach the desired speed and decelerate to a complete stop on top of the force platform. Therefore, the choice was made to use the large force platform for the stop and turn due to the added runway length. Furthermore, the large force platform would reduce the risk of the players focussing their landings on the force platform (Abendroth-Smith, 1996).

The location of the force platforms was also important for the jumping / heading manoeuvre as the players were required to land with each foot on a separate force platform in order to calculate joint moments. The options for this were to either use the large force platform and one of the small platforms, or to use two small force platforms. The main difference between these options is that the use of the large and small force platform created the largest landing area length wise, but a slight offset would exist between the two force platforms, which would not be the case with the small force platforms. Considering the differences it was not expected that this would affect the results of the test and it was deemed preferable to have as large as possible a landing area to increase the chance of players landing on the force platforms. Therefore, the large and one of the small force platforms were chosen to be used for the jumping / heading manoeuvre.

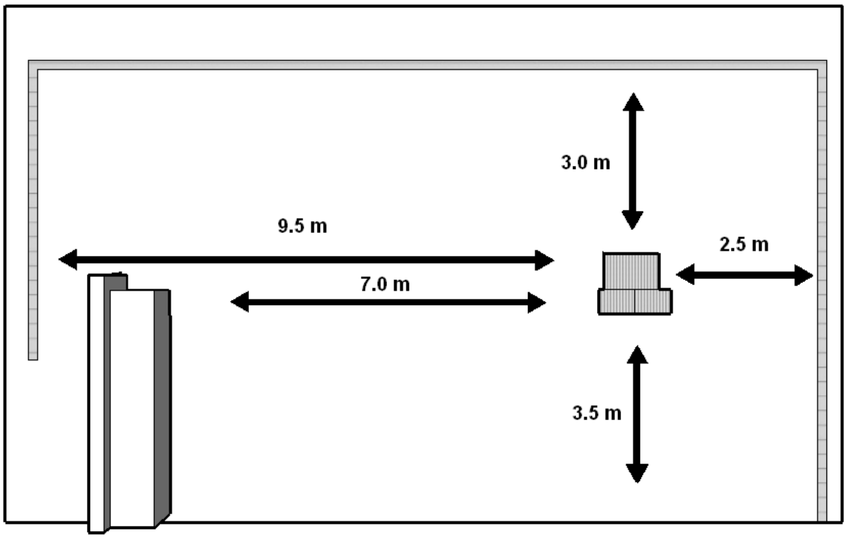

Figure 3.2. Dimensions of the lab around the force platforms that could be used for the test set-up. For the stop and turn the choice was made to use the large force platform as this increased the run-up with approximately 2.5 m due to the location of cabinets in front of the small force platforms. For the jumping / heading manoeuvre the choice was made to use the large force platform and one of the small force platforms as this increased the landing area after the jump.

A final consideration for the test set-up involves the four different surfaces that were used to create different surface conditions. This was especially a concern with regards to the stop and turn as this required a longer runway than the jumping / heading manoeuvre. Due to restrictions in lab size it was not possible to have four runways with dimensions of 9.5 x 1.5 m in the lab (Figure 3.2). It would also be difficult to move a runway of this size as typically 1 m^2 of artificial turf consists of approximately 10 kg of sand and 10 kg of rubber infill, leading to a mass of approximately 285 kg for one runway, without considering the weight of a shockpad. To cope with this, the choice was made to only adjust the properties of the final few metres of artificial turf before the force platform. This is possible as a previous study on running showed that humans are able to adjust their body dynamics for the first step on a new surface during running (D. Ferris et al., 1999). The only consistent difference that was found was a substantial reduction in peak impact force on the soft surface, while the peak active force remained the same. However, as the peak impact force is related to the deceleration of the shank it is believed that this difference would also be present if the entire runway had a similar hardness. Therefore, only changing the final few metres of artificial turf before the force platform would allow the players sufficient time to adjust their dynamics to the new surface and would make it much easier to modify the surface properties.

3.4.7 How to Control Movements and Confounding Variables?

Several factors were identified in the literature review that can affect the movements and as a result affect the outcomes of the player movement study. Some of these factors such as experience and upper body movement have already been discussed in previous sections on what subjects, and the test parameters and set-up. Other factors that can affect the results include movement related factors such as the running speed, jump height, and technique, and external factors like fatigue and footwear.

Regarding controlling the selected movements, previous studies have used different methods. With regards to the stop and turn previous studies on cutting and turning manoeuvres have controlled the cutting / turning angle, the cutting / turning foot, and the approach / exit speed. The turning angle during the stop and turn did require little control as the players were required to turn and run back to the starting point, leaving little other option than to make a 180° turn.

For the cutting / turning foot, previous studies controlled this factor either by requiring all subjects to use the same foot, or by having the subjects use their preferred foot. Comparing these options, it was decided to have the subjects use their preferred foot as a previous study showed that the foot preference can affect the plantar pressure underneath the foot (Wong et al., 2007). This also ensured a natural movement as players would turn on the foot they were most comfortable with.

With regards to controlling the approach / exit speed, most previous studies only controlled the approach speed before a cutting / turning manoeuvre. A few studies also controlled the exit speed, whereas some studies did not control the speed at all due to limitations in speed measurement. Considering the different options for controlling the speed, the choice was made to only control the approach speed. This choice was made as the exit speed after the stop and turn would be dependent on the acceleration qualities of each individual player, as during the stop and turn the players would come to a complete stop.

Several options were available to measure the approach speed. Most previous studies made use of timing gates, whereas a study by Dempsey et al. (2007) determined the approach speed with the help of one of the markers placed on the hip. While the approach speed could potentially be determined more accurately when using one of the hip markers, the choice was made to use timing gates. This choice was made as the timing gates allowed immediate feedback to the players on their approach speed.

Regarding the jumping / heading manoeuvre the main movement factors to be controlled are the take-off and jumping height. The main reason that the take-off of the jump had to be controlled is that otherwise variations in take-off may occur, one footed or two footed take-off, which may affect the jumping and landing technique. Looking at the literature previous studies on stop-jump manoeuvres used a two footed jump (Chappell et al., 2005; Chappell et al., 2007; Sell et al., 2007; Yu et al., 2005). Because of this and because of concerns on the ability to line up with the two force platforms during landing with a one footed take-off the choice was made to use a two footed jump to ensure this was the same for all players during the jumping / heading manoeuvre.

Controlling the jump height was of importance as a variation in jump height may affect the outcomes of the study. During the heading condition controlling the jump height was no issue as a suspended ball, placed on the maximal jump height of each player, would ensure they jumped to the same height in each trial. During the jumping condition without heading a ball the jump height could not be controlled as placing an object to reach for or jump over could nullify the in-game scenario aspect of the research. Therefore the choice was made to instruct the players to perform a maximal vertical jump as this was the best option to create a similar jump height as during the heading condition. Moreover, since the ball for the heading condition was placed on the maximal jump height without a ball.

Fatigue and footwear have been identified in the literature review as factors that can affect the human movement dynamics and should therefore be controlled during the player movement study. The obvious way to deal with fatigue is by giving players sufficient rest between trials as has been done in previous studies (Chappell et al., 2007; Nigg et al., 2009; Queen et al., 2008). Furthermore, fatigue can be dealt with by randomising the surface and in-game conditions. This limits the effects any possible fatigue has on the results as the order of conditions is different for each subject.

With regards to the footwear, the main effect it can have involves the properties of the shoe-surface interface. Therefore, if players were allowed to wear their own shoes the properties of the shoe-surface interface could be slightly different for each player and may affect the outcomes of the player movement study. Therefore the choice was made to provide all players with the same type of shoes. As different types of studs are available, the choice was made to use shoes with normal rounded studs as similar studs are used on the rotational traction device, and this type of studs are also often used by players.

3.4.8 Overview Biomechanics Approach and Choices

Table 3.4. The different considerations that were made for the biomechanics and the objective(s) they address, including the different options available and selected.

Consideration	Objective	Options	Selected option(s)
What movements?	2	Literature review Preliminary study (Player perspective)	Preliminary study (Chapter 4) Stop and turn Jumping / Heading
What in-game scenarios?	2	Literature review Preliminary study (Player perspective) Pilot test (Lab restrictions)	Stop and turn: simulated opponent Jump: Heading a ball
What subjects?	4	Experience playing soccer Experience playing on artificial turf Gender	Male soccer players with sufficient experience playing soccer and experience in playing on artificial turf
What biomechanical test parameters?	4, 5	Joint angles Joint moments Ground reaction forces Foot pressure Muscle activity	Joint angles: lower and upper body Joint moments: lower limbs Ground reaction forces
What biomechanical data collection methods?	4, 5	Marker sets: full body, lower body Motion analysis system: Vicon, Coda High speed video Ground reaction forces: force platforms, pressure insoles	Full body Vicon system High speed video Preliminary study (Chapter 5)
What test set-up?	4, 5	Literature review Runway: approach, run-off, length, change surface conditions Force platforms	Initial runway followed by interchangeable section to modify change surface conditions Large force platform for stop and turn for sufficient runway length Large and small force platform for jumping / heading for sufficient landing space
How to control movements and confounding factors?	4, 5	Literature review Stop and turn: approach / exit speed, turning foot, turning angle Jumping / heading: take off, jump height Other: fatigue, footwear	Stop and turn: control approach speed, use preferred foot, 180° turn Jumping / heading: two footed take off, maximal jump height Fatigue: sufficient rest, randomised trials Footwear: same footwear for all participants

3.5 Hypotheses

During the player movement study (Chapter 7) the effects of different surface and in-game conditions on the human dynamics were investigated to answer the following research questions set in Chapter 1:

A: How do varying surface properties of artificial turf in soccer affect the movement dynamics of players during soccer relevant movements?

B: How do in-game scenarios affect the movement dynamics of players during soccer relevant movements?

Due to the different nature of the research questions and interventions the hypotheses were divided into two groups: surfaces and in-game scenarios. The development of the hypotheses is discussed in the following sections, with an overview at the end of each section. The literature review (Chapter 2) formed the basis for the development of these hypotheses.

3.5.1 Surface Hypotheses

Section 3.3.1 of this chapter showed that the surface hardness and surface traction were the chosen surface properties to investigate during a stop and turn and jumping / heading manoeuvre. The literature review showed that previous studies on the surface hardness mainly considered running and hopping manoeuvres, with a few studies also including landings after a jump. Previous studies on the rotational traction properties mainly considered cutting / turning manoeuvres.

Section 2.4.3.1 of the literature review showed that during different manoeuvres the surface hardness can affect the ground reaction forces, movement dynamics and joint moments. However, there were also studies that did not find any effects on these parameters, which was suggested to also be dependent of the demands of the activities. The studies that did find effects for the surface hardness generally found that the ground reaction forces, and ankle and knee joint moments increased on the harder surfaces. Furthermore, studies found that on harder surfaces subjects landed with a more flexed leg and decreased their leg stiffness to maintain similar centre of mass movement dynamics.

Based on these studies, it was expected that the ground reaction forces (mainly the peak vertical impact force and loading rate), joint moments and flexion of the lower limbs will increase on the hard surfaces. The effects were mainly expected for the jumping / heading manoeuvre due to the vertical aspect of the movement leading to higher ground reaction forces and larger flexion angles compared to the stop and turn. As a previous study by Blackburn et al. (2008) showed that an increased upper body flexion can reduce the load of the lower limbs during a landing it is also expected that the players will increase the upper body flexion during the jumping / heading manoeuvre.

Considering the rotational traction, few studies have looked into the effects of the rotational traction on human dynamics. Section 2.4.3.2 of the literature review showed that the studies that did, found increases in knee and ankle rotation moments during cutting and turning manoeuvres for the higher traction condition, as well as an increased knee adduction moment during a cutting manoeuvre and a trend towards an increased ankle eversion and knee abduction moment during turning. Based on this, it was expected that an increased surface traction would have similar effects during the stop and turn.

Besides the previous findings in literature on the effects of the rotational traction on the joint moments, it was expected that the increased traction of the surface would allow the players to decelerate faster. Therefore it was expected that the high surface traction condition would lead to increased ground reaction forces, especially in the anterior / posterior direction. This increase in deceleration / acceleration may also affect the performance, but as a study by Wannop et al. (2010) on cutting manoeuvres did not find any differences in performance it was expected that the change in traction would not affect the ground contact times.

3.5.1.1 Hypotheses

Harder surfaces will lead to:	**High traction surfaces will lead to:**
Increased ground reaction forces *Increased flexion angles lower limbs* *Increased flexion / extension moments lower limbs*	*Increased ground reaction forces, mainly horizontally* *Increased joint moments, both medial / lateral and rotational moments* *Similar ground contact times as on low traction surfaces.*

3.5.2 In-game Scenario Hypotheses

Section 3.4.2 showed that for the stop and turn manoeuvre a simulated opponent was used to create an in-game scenario, whereas for the jumping a heading manoeuvre was used to create an in-game scenario. The simulated opponent used to create an in-game scenario for the stop and turn manoeuvre is similar to the in-game scenario used in a study by McLean et al. (2004) on cutting manoeuvres, with the main difference being that in this case human being was used instead of a skeleton. In the study by McLean et al. (2004) the simulated opponent led to increased hip flexion and adduction, knee flexion and valgus angles, as well as medial ground reaction forces. The study by McLean suggested that these effects were caused by a perception to change direction more rapidly. It is expected that the simulated opponent during the stop and turn will lead to similar effects as those found in the study by Mclean et al. (2004) and will also increase the sagittal and frontal plane joint moment of the lower limbs.

With regards to the heading scenario for the jumping / heading trials little information is available on the possible effects as no previous studies have compared the landing after a jump with landing after a jump that included a heading manoeuvre. However, previous studies on injuries have indicated that during a soccer match heading a ball can result in non-contact injuries and a study by Nelson et al. (2007) reported a high proportion of ankle injuries in soccer when landing from heading a ball (Rahnama, 2002; Andersen et al., 2004). It is therefore thought that landing after a jump with a heading manoeuvre will result in a higher musculoskeletal loading than landing after a vertical stop jump.

A study by Ford et al. (2005) comes closest to the heading scenario for the stop-jump. They found that a ball as an overhead goal can increase the jumping height and knee flexion moment during a drop jump. The main difference to this study, however, is that they had to use their hands to grasp the ball at the top of their jump. Furthermore, as the ball for the heading manoeuvre in this study was placed on the maximal stop-jump height without a ball, it was expected that the jumping height would not be affected by the addition of the ball.

It was expected that heading a ball would shift the focus of the players from primarily being on landing after the jump to heading the ball. As a result, it was expected that the players will land in a more erect position and absorb the impact of the landing with an increase in flexion after the impact. It was also expected that this more erect posture would increase the vertical ground reaction forces, whereas the anterior / posterior ground reaction forces were expected to be increased due to an added forward motion related to the heading manoeuvre as identified in previous research. Due to this added forward motion it was also expected that the upper body flexion would increase during the heading condition

3.5.2.1 Hypotheses

Simulated opponent will lead to:
Increased ground reaction forces
Increased flexion and medial / lateral joint angles in lower limbs
Increased flexion / extension and medial / lateral joint moments in lower limbs

Heading a ball will lead to:
Increased anterior / posterior ground reaction forces
Decreased flexion lower limbs during initial impact, increased flexion after impact
Increased upper body flexion
Increased flexion / extension joint moments in lower limbs

3.6 Contribution to Knowledge

This PhD contributes to the current knowledge in several ways regarding the surfaces, movements and in-game scenarios. First of all this research combined the rotational traction and hardness properties of artificial turf surfaces, whereas previous studies have either looked at the hardness or the rotational traction. In relation to the surfaces, this research provides detailed information on both the surface properties and design, while many previous studies have failed to provide this information. This helps to give insight into how the surface properties are affected by the design of the surface, as well as how the surface properties affect the human movement dynamics during the selected movements. With regards to the surface properties, this research also contributes to the current knowledge as few previous studies looked at how the FIFA standards affect the human movement dynamics.

Regarding the movements used in this research few previous studies have used a stop and turn, and to the author's knowledge no previous studies have used a stop and turn or maximal stop-jump manoeuvre in combination with surfaces that have been designed around the limits of the FIFA standards. This will provide insight into how the FIFA standards, and other similar standards, affect the human movement dynamics during these movements. In addition to this, the included in-game scenarios provide insight into how the human movement dynamics are affected during match situations, compared to a lab situation. For the stop and turn this is done with a simulated opponent as used in a previous study by McLean et al. (2004), with the difference that a real person is used to add to the realism. For the stop-jump the in-game scenario involves a ball suspended in mid-air which the players have to head, which to the author's knowledge has not been done in previous research.

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4. PLAYER PERSPECTIVE ON: MOVEMENTS, IN-GAME SCENARIOS AND SURFACE CHARACTERISTICS IN SOCCER

4.1 Introduction

The literature review (Chapter 2) helped identifying a large number of soccer relevant movements. Furthermore, it showed that previous biomechanical studies only considered a few of these movements, typically running, cutting / turning manoeuvres, and jumps / landings. Therefore to aid the decision making process on what movements and in-game scenarios to use for the player movement study the choice was made to consult soccer players to get insight into what movements and in-game scenarios are most relevant to them. This option was chosen over analysing match data to extract relevant movements and in-game scenarios as motion analysis studies that use manual analysis, which would be required for this, typically include video data of multiple players and multiple matches (Burgess et al., 2006; Bloomfield et al., 2007; Rahnama, 2002). Analysing match data would however only provide information on how frequently the movements are performed during a match, while consulting players would also allow to gain information on the physical demands and performance as shown in previous player perception studies (Andersson et al., 2008; Muller et al., 2010). Furthermore, this also allowed to gather information on the player perception regarding the playing surfaces (Fleming et al., 2005; Hopper et al., 2010; Muller et al., 2010).

To consult the players the choice was made in §3.4.1 to use both a focus group and questionnaire. The focus group allowed to get more detailed information, whereas the questionnaire was chosen to reach a larger cohort. Both address objective 2 (Chapter 1) of this thesis, which involves selecting relevant surface properties and range of properties, movements and develop suitable in-game scenarios to form the basis of an experimental investigation into the effects of surface properties on player kinematics and loading.

The first aim of this study was to select relevant soccer related movements for the player movement study. For the relevance of movements different aspects were considered, such as how frequently they perform a movement, the perceived loading on the body, and the overall importance of the movement. The second aim was to gain insight into what in-game scenarios players encounter during soccer matches, how often they encounter these and how they perceive the loading on the body during these scenarios. This assisted in the selection and creation of in-game scenarios for the player movement study. The third aim was to gain insight into what surface properties soccer players prefer and if their perception of the surface properties affect their attitude when playing on different pitches.

This chapter first discusses the methodology of the focus group and questionnaire. Following this the results of the focus group and questionnaire are presented, followed by a discussion on the main findings. Finally a conclusion is formulated in which the choices regarding the movements, in-game scenarios and surface properties for the player movement study are presented.

4.2 Methodology

4.2.1 Focus Group

The focus group had two aims. The first aim was to gain an initial insight into what types of movements, 'in-game' scenarios and surface characteristics are considered relevant and important for soccer players. The second aim was to use the information gathered to make a comprehensive list of movements, in-game scenarios and surface characteristics for the development of the questionnaire to address the aims of this study, while also making sure that the terminology used in the questionnaire was appropriate for soccer players.

The focus group was organised with six players from the first team of Loughborough University. Three of these players were defensive minded, defenders and defending midfielders, and the other three were offensive minded, forwards and attacking midfielders. This allowed for gaining insight into whether the role of the player on the field affected the perception players have on movements, in-game scenarios and surface properties. Furthermore, the number of players meant that the players could have discussions amongst themselves. This avoided bias by the interviewer giving his opinion as open questions could be asked which the players then could discuss (Morgan, 1997; Greenbaum, 2000). In addition to this, the discussion could also stimulate players to express their opinions (Greenbaum, 2000).

To avoid interference between the different topics the focus group was divided into two main sections, both adding up to a total session time of approximately one hour. The first section involved identifying what movements the players considered important and what in-game scenarios they encountered during a soccer match. The second section focussed on the surface properties the players considered to be important, as well as their preferences. The following definitions were used for the importance of the movements:

The importance of a movement in order to perform successfully in a game of soccer.

and surface properties:

The importance of a surface characteristic of a soccer pitch in order to perform successfully in a game of soccer.

To prevent any bias by the input of the interviewer the set-up of the focus group was such that the interviewer gave as little guidance as possible and allowed as much as possible discussion between the players on each topic. Possible bias by players misunderstanding the questions was avoided by keeping the questions clear and simple as well as keeping an eye on how the answers were interpreted by the players to ensure the questions were understood correctly (Appendix A**)** (Morgan, 1997; Greenbaum, 2000). Furthermore, examples of movements, in-game scenarios, and surface properties were available in case the players did not understand what was meant and for several questions a follow up question was available to aid the discussion between players. The whole session was recorded, both audio and video, and all participants signed an informed consent form before participating in the focus group. Ethical clearance was gained from Loughborough University Ethical Advisory Committee.

The focus group session was transcribed using the audio and video data. This data provided movements, in-game scenarios, and surface properties for the construction of the player questionnaire, as well as the correct terminology. Finally, an overall top five of movements, considered to be the most important for the players, was compiled for later comparison with the results of the player questionnaire.

4.2.2 Questionnaire

The aim of the questionnaire was to gain insight into what movements, in-game scenarios, and surface properties / characteristics are relevant to soccer players. The questionnaire was constructed with the use of the focus group results, in combination with movements, in-game scenarios and surface properties identified in Chapter 2 and consisted of six main sections: general questions, movements, one-on-one situations, surface preferences, surface perception, and player attitude (Appendix B).

Section one involved general questions about age, position, playing level, amount of experience of playing on artificial turf and the training, match and recreational exposure both on natural grass and artificial turf. In section two the players were asked to rate 17 movements selected from the literature review and focus group on: how *important* they consider a movement to be in order to perform well during a match; how *frequently* they perform a movement during a match; and how much *loading* a single movement puts on the body. To make sure the players understood the 'loading on the body' the following definition was placed in the questionnaire:

> *Loading on the body can be defined as the amount of stress and strain that is put on the body (joints, muscles etc.) during a certain movement.*

The choice for the different categories was made to get a clear picture on how relevant movements are in a game of soccer. Regarding this it was expected that the movements that players perform most often and find most demanding are most relevant to soccer. However, it was also thought that some movements may not be rated the highest for either the frequency or loading, but the combination of these factors may still cause them to be perceived relevant by the players. Therefore to cover these movements the choice was made to include the importance as a parameter that was not directly connected to the frequency and loading on the body.

Section three asked the players to rate six in-game scenarios. Based on the focus group in-game scenarios were named 'one-on-one situations' to improve the clarity for the players. The players were asked to rate the one-on-one situations on: how *frequently* they encountered a one-on-one situation during a match; and how much *loading a* one-on-one situation puts on the body.

Section four consisted of the player preferences for surface properties and characteristics. Following this, section five asked the players to rate how they perceived the surface properties and characteristics of the two artificial turf pitches (PEC and EHB) on the campus of Loughborough University (Table 4.1). This section was included as previous studies showed a good correlation between the player perception and surface measurements (Young, 2006; Hopper et al., 2010). Finally section six involved questions on the player attitude when playing on different surfaces to get insight into how they perceived the injury risk of the three pitches and if they approached the pitches in a different manner (Appendix B).

The sections on movements and in-game scenarios helped selecting relevant movements and in-game scenarios for the player movement study, whereas the sections on surfaces helped with selecting what properties to include.

Apart from the first section, for which open questions were used, a seven point Likert scale was used by which the players could rate the movements, one-on-one situations and surfaces. The Likert scale was chosen in Chapter 3 as this scale would be easy to understand by the players and it would allow them to easily compare the ratings of the different movements, one-on-one scenarios and surfaces. Furthermore it was believed that the seven point scale would provide enough options to the players to differentiate between the different movements, one-on-one situations and surfaces. For all the scales a value of one was considered as a low rating, e.g. a movement was executed rarely, and a value of seven was considered as a high rating, for example, e.g. a movement was executed very often.

Table 4.1. Design characteristics of the two Loughborough University artificial turf pitches

Pitch	Pile	Infill depth	Sand	Rubber	Shockpad	Base
PEC	61mm	40-50mm	10mm	30-40mm	None	Bound Asphalt
EHB	35mm	25mm	10mm	15mm	25mm	Bound Asphalt

The results of the questionnaires were analysed with the help of non-parametric tests in SPSS 17 (SPSS inc., Chicago, IL, USA). A Mann-Whitney U test was used to compare the results of the different playing levels and a Kruskas-Wallis H and Mann-Whitney U test to analyse the results of the different playing positions. The results between movements as well between the two artificial turf pitches were compared using a Wilcoxon test. For all statistical tests significance was set at a p –value of 0.05. A Bonferroni correction was used to correct for multiple comparisons.

The questionnaire was completed by 58 players from four different Loughborough University teams with an average age of 20 ± 1.3 years. All participants signed an informed consent form before filling out the questionnaire and ethical clearance was gained from Loughborough University Ethical Advisory Committee. For analysis on the effect of playing position on the results of the questionnaire, the players were divided into four different positions: defenders, defending midfielders, attacking midfielders, and forwards. Goal keepers were not included in this comparison due to the different role they have in soccer compared to the field players. Furthermore, the players were also categorised in two groups to investigate the effect of the playing level on the results of the questionnaire; upper for the players in the 1st and 2nd teams, and lower for the players in the 4th and 5th teams (Table 4.2).

Table 4.2. Overview of playing positions and level of the players who completed the questionnaire

Playing level	Goal keepers	Defenders	Defending Midfielders	Attacking Midfielders	Forwards	Not Specified	Total
Upper	4	8	5	9	3	0	29
Lower	3	8	7	7	3	1	29
Total	7	16	12	16	6	1	58

Note: Upper = Level 1st/2nd team; Lower = Level 4th/5th team

4.3 Results

4.3.1 Focus Group

4.3.1.1 Movements and In-game Scenarios

All players placed "change of direction" first place in their individual top 5, whereas straight line running / sprinting was placed second place by four out of six players (Table 4.3). Movements that were named in the individual top 5's, but did not make the group top 5, were "planting non-kicking foot" and "tackle" which suggests that these are also amongst the more important movements for some players. Notably not all movements were considered equally important for all positions, e.g. arc run was considered more important by the offensive players, whereas stop and turn or shuffle were considered more important by the defensive players.

Table 4.3. Top 5 of movements identified in the focus group as being important to perform successfully in a game in soccer

1	Change of direction
2	Straight line running/sprinting
3	Sidesteps/Shuffle
4	Jump/Land
5	Stopping

Situations the players considered to be in-game scenarios were: one-on-one situations, unit work, set pieces, formations and counter attacks. All of these, apart from one-on-one situations, are scenarios in which a large part of the team is involved. Therefore one-on-one situations are more practical and most suitable to recreate in a lab environment and resemble in-game scenarios used in previous studies. To benefit the understanding the player questionnaire the choice was made to change the term 'in-game scenarios' to 'one-on-one situations'. Examples of one-on-one situations given were: "taking someone on" and "trying to get past a player".

Concerning the player questionnaire the movements and one-on-one situations mentioned in the focus group were included as it was thought the focus group gave a good overview of the movements relevant to soccer.

4.3.1.2 Surface Perception

Of the surface characteristics a flat surface with smooth ball roll was considered to be very important. In general none of the players were very satisfied with the artificial turf playing characteristics. Some of the comments they made with respect to this were: "the surface is too hard"; "the shock absorption is too low"; they experience "bad stud penetration": "boots get caught in the fibres and rubber"; "the ball roll is not smooth"; and "the ball bounce is different compared to normal grass".

In relation to performance and injuries the players preferred to have a reduced physical performance, e.g. lower running speed, if that would result in fewer injuries. Their main argument for this was: "It comes down to the player, at the end of the day it is you versus someone else. If the pitch is quicker you both will be quicker. So if it is a boggy pitch you both are going to be a bit slower."

Regarding the questionnaire the mentioned surface characteristics, such as the evenness and stud penetration, were taken forward. For the surface hardness it was decided to both use the term hardness (hard / soft) and 'shock absorption' (high / low) as both were used by the players in the focus group. Therefore it was believed that using both terms would increase the clarity of the questionnaire. In addition to this, the choice was made to include questions on the loading / injury perception (e.g. if they worry about injuries) and playing attitude (e.g. if they move more cautiously) on different artificial surfaces on the campus of Loughborough University and their match pitch (natural grass). These questions were included to gain insight into if the players perceive that a pitch causes a higher loading / more injuries and if they adjusted their behaviour when playing on these pitches. This choice was made as during the focus group it appeared that the players were more wary of playing on artificial turf than on natural grass. Therefore these questions would provide insight into whether the attitude when playing on different surfaces was different amongst a larger group of players, and if this attitude could be related to any differences in perception of the surface properties.

4.3.2 Questionnaire

4.3.2.1 Section One - General Questions

The experience of playing soccer ranged from 5 – 18 years over the 58 players, which had an average age of 20 ± 1.3 years. The experience on artificial turf ranged from 0.5 – 16 years (average 7.8 ± 4.0 years). On average the players train 0.9 ± 1.9 hours per week on natural grass and 4.3 ± 1.7 hours on artificial turf (Table 4.4**)**. All players trained at least 2 hours per week on artificial turf, the majority (39 players) never train on natural grass. All players play matches on natural grass ranging from 10 – 60 per season (average 32 ± 16). Twenty-two players reported that they also play matches on artificial turf (1 – 10 per season). Thirty-three players reported to play recreationally on artificial turf (1 – 6 hours per week) and 23 players reported to play recreationally on natural grass (1 – 5 hours per week).

Between playing levels the players in the upper playing level group train significantly more on artificial turf and play significantly more matches on natural grass (Table 4.4). Players in the lower playing level group play significantly more recreationally on artificial turf.

Table 4.4. Comparison training, match and recreational exposure of both playing levels and all playing positions per week and per season (mean + SD)

		Training (h / week)		Matches / season		Recreational (h / week)	
		natural grass	**artificial turf**	**natural grass**	**artificial turf**	**natural grass**	**artificial turf**
Overall		0.9 ± 1.9	4.3 ± 1.7	32 ± 16	1.5 ± 2.7	0.8 ± 1.2	1.2 ± 1.5
Playing Level	**Lower**	0.5 ± 1.0	3.9* ± 0.9	25* ± 9	2 ± 3	1.1± 1.2	1.7* ± 1.6
	Upper	1.3 ± 2.5	4.8* ± 2.2	37* ± 18	1 ± 3	0.5 ± 1.2	0.8* ± 1.3

*= Significant difference between playing levels 2= Significant difference with Defenders
3= Significant difference with Defending Midfielders 4= Significant difference with Offensive Midfielders

4.3.2.2 Section Two - Movements Rating

The movements that were rated by the players as being the most important in order to perform successfully during a game of soccer were sprinting, a general change of direction and stop and turn with averages rating of 6 or higher (Figure 4.1a). The movements considered to be the least important were walking and diving. Running, planting non-kicking foot, and a general change of direction were rated to be performed the most frequently, whereas diving was scored to be the least performed movement (Figure 4.1b).

Regarding the experienced loading on the body the players rated sprinting, stopping, jump / land and ‘stop and turn’ to have the highest loading with an average rating of higher than 5 (Figure 4.1c). Walking, jogging and diving were rated as the movements with the lowest loading on the body during a complete match. The movements rated highest on importance, frequency and loading were rated significantly higher than the majority of the other movements (Table 4.5).

Between the playing levels a few significant differences were present (Table 4.6). The importance and frequency of a general change of direction, and frequency of planting non-kicking foot were all rated significantly higher by the players of the lower playing level group. No significant differences were found between playing levels for the ratings of the perceived loading on the body of the different movements.

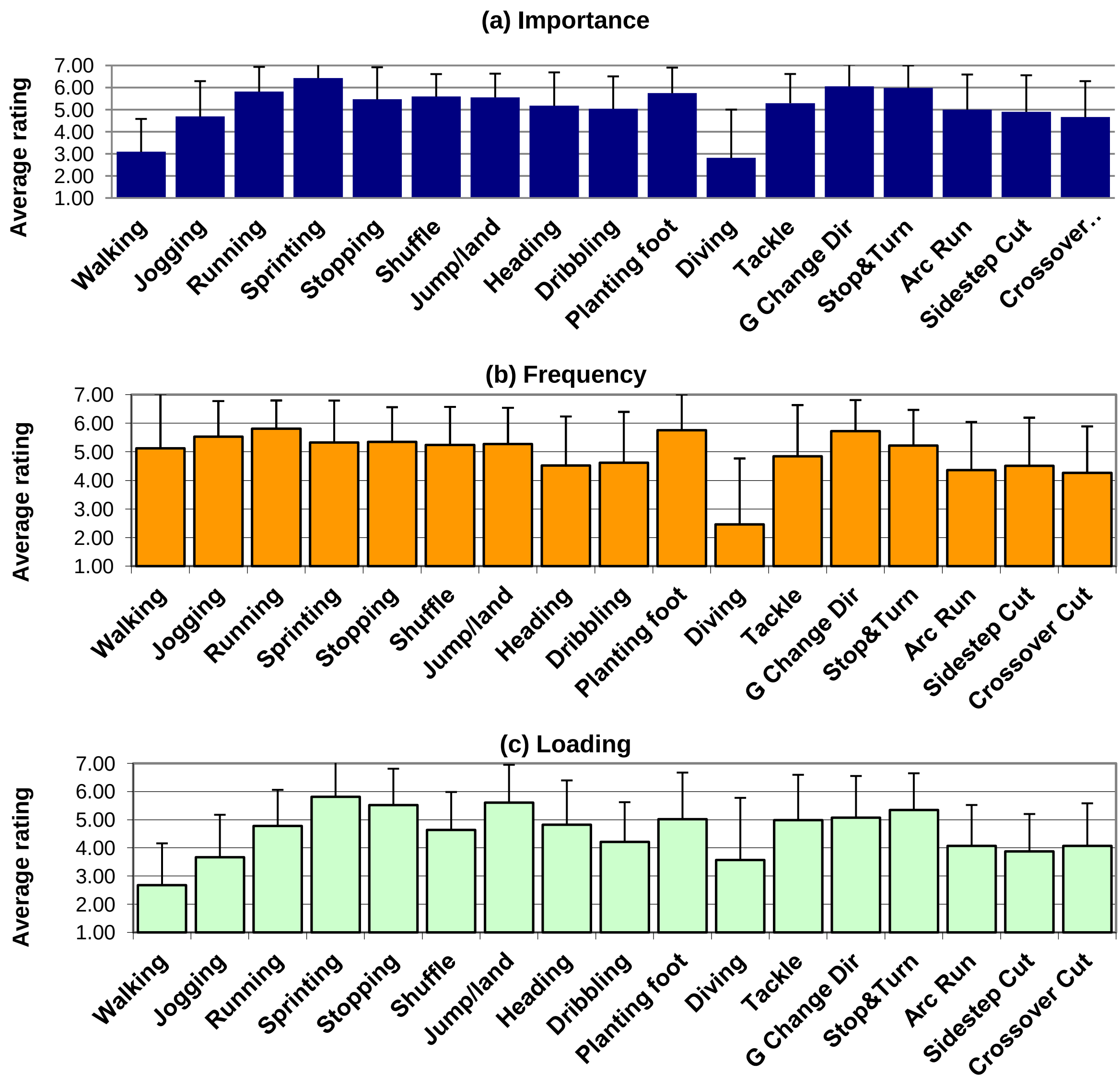

Figure 4.1. Average ratings (± SD) for the 17 movements included in the questionnaire

Significant differences were present between playing positions for the scores on the importance of heading, arc run and crossover cut, and the frequency of heading, dribbling, diving, tackle, arc run and crossover cut (Table 4.7). For all these movements a significant difference was present between the defenders and one or more of the other positions. For the frequency of heading a significant difference was also present between the attacking midfielders and forwards. The ratings on the perceived loading on the body showed no significant differences between playing positions.

Table 4.5. Significant differences between highest rated movements and all other movements

Movement		Walking	Jogging	Running	Sprinting	Stopping	Shuffle	Jump/Land	Heading	Dribbling	Planting foot	Diving	Tackle	G Change Dir	Stop & Turn	Arc run	Sidestep cut	Crossover cut
Importance	**Sprinting**	+	+	+		+	+	+	+	+	+	+	+	0	0	+	+	+
	G Change Dir	+	+	0	0	+	+	+	+	+	0	+	+		0	+	+	+
	Stop & Turn	+	+	0	0	0	0	+	+	+	0	+	+	0		+	+	+
Frequency	**Running**	0	0		+	0	0	0	+	+	0	+	+	0	+	+	+	+
	Planting foot	0	0	0	0	0	0	0	+	+		+	+	0	+	+	+	+
	G Change Dir	0	0	0	0	0	0	0	+	+	0	+	+		+	+	+	+
Loading	**Sprinting**	+	+	+		0	+	0	+	+	+	+	+	+	0	+	+	+
	Stopping	+	+	+	0		+	0	+	+	+	+	0	0	0	+	+	+
	Jump/Land	+	+	+	0	0	+		+	+	+	+	+	+	0	+	+	+
	Stop &Turn	+	+	+	0	0	+	0	0	+	0	+	0	0		+	+	+

+ = Significant difference between movements 0= No significant difference between movements

Table 4.6. Movement ratings that demonstrated a significant difference between playing levels (mean ± SD)

Movement		Playing Level	
		Lower	**Upper**
Planting non-kicking foot	Frequency	6.1 ± 1.0	5.4 ± 1.4
General change of direction	Importance	6.2 ± 1.1	5.9 ± 0.7
	Frequency	6.0 ± 1.0	5.6 ± 1.0

Table 4.7. Significant differences in average movement ratings between playing positions (mean ± SD)

Movement		Playing Position			
		Defender	**Defending Midfielder**	**Attacking Midfielder**	**Forward**
Heading	Importance	6.3^{23} ± 0.9	5.2^{1} ± 1.3	4.9^{1} ± 1.2	6.0 ± 1.9
	Frequency	5.1^{3} ± 1.7	4.8 ± 1.5	4.2^{14} ± 1.4	6.0^{3} ± 0.6
Dribbling	Frequency	3.8^{234} ± 1.4	5.3^{1} ± 1.5	5.5^{1} ± 1.4	6.0^{1} ± 0.6
Diving	Frequency	1.7^{4} ± 1.7	1.6 ± 1.4	1.8 ± 1.5	3.5^{1} ± 2.5
Tackle	Frequency	5.7^{3} ± 1.0	5.6 ± 1.1	4.4^{1} ± 1.8	5.0 ± 1.4
Arc Run	Importance	4.6^{34} ± 1.1	4.7 ± 1.8	5.7^{1} ± 1.0	6.0^{1} ± 0.9
	Frequency	3.9^{3} ± 1.6	4.4 ± 1.7	5.3^{1} ± 0.9	5.2 ± 1.5
Crossover Cut	Importance	4.3^{34} ± 1.1	4.7 ± 1.8	5.3^{1} ± 1.4	5.5^{1} ± 1.8
	Frequency	3.8^{3} ± 1.7	4.5 ± 1.6	4.9^{1} ± 1.2	4.8 ± 1.6

Significant difference with 1: Defenders Midfielders 3: Attacking Midfielders
2: Defending Midfielders 4: Forwards

4.3.2.3 Section Three - One-on-One Situations Rating

The differences for the ratings between the different one-on-one situations were small (Figure 4.2). Marking an opponent and a heading duel were rated to be the most frequently encountered one-on-one situations during a complete match, whereas avoiding a tackle was rated to be the least frequent. No significant differences were present for the frequency ratings. A heading duel was rated as the one-on-one situation with the highest loading, while marking an opponent and avoiding a tackle were rated significantly lower than the four other one-on-one situations.

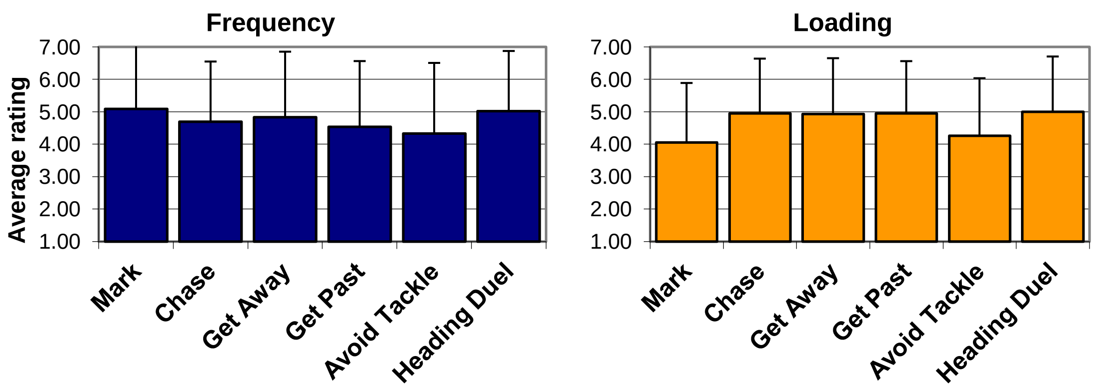

Figure 4.2. Average ratings (± SD) on frequency and perceived loading of six one-on-one situations

No significant differences were present between playing levels in how the players rated both the frequency and the perceived loading of the one-on-one situations. Between playing positions significant differences were present for all one-on-one situations regarding the frequency and for marking and chasing the opponent a significant difference was present for the perceived loading (Table 4.8). However, significant differences were only present between offensive and defensive players and not between defenders and defending midfielders or forwards and attacking midfielders.

Table 4.8. One-on-one situation ratings for the different playing positions (mean ± SD)

One-on-One situation		Playing position			
		Defender	Defending Midfielder	Attacking Midfielder	Forward
Mark	Frequency	$6.6^{34} \pm 0.7$	$6.3^{4} \pm 0.9$	$5.0^{1} \pm 1.9$	$4.7^{12} \pm 1.4$
	Loading	4.6 ± 1.5	$5.5^{34} \pm 1.7$	$3.6^{2} \pm 1.5$	$5.7^{2} \pm 1.5$
Chase	Frequency	5.6 ± 1.3	$5.8^{3} \pm 1.1$	$4.7^{2} \pm 1.3$	5.0 ± 1.4
	Loading	5.5 ± 1.1	$6.0^{3} \pm 1.0$	$4.9^{2} \pm 1.3$	5.2 ± 1.6
Get Away	Frequency	$4.2^{34} \pm 1.7$	$4.9^{34} \pm 1.4$	$6.3^{12} \pm 0.7$	$6.3^{12} \pm 0.8$
	Loading	5.2 ± 1.5	5.5 ± 1.2	5.4 ± 1.1	5.5 ± 1.4
Get Past	Frequency	$3.6^{34} \pm 1.5$	5.0 ± 1.4	$5.9^{1} \pm 1.2$	$5.8^{1} \pm 1.2$
	Loading	5.1 ± 1.3	5.4 ± 0.8	5.5 ± 1.0	6.0 ± 1.3
Avoid Tackle	Frequency	$3.6^{34} \pm 1.7$	4.2 ± 2.0	$5.6^{1} \pm 1.8$	$5.8^{1} \pm 1.0$
	Loading	4.4 ± 1.5	3.9 ± 2.0	4.8 ± 1.3	5.7 ± 1.5
Heading Duel	Frequency	$6.3^{3} \pm 0.9$	5.2 ± 1.9	$4.9^{1} \pm 1.6$	6.2 ± 0.4
	Loading	5.9 ± 1.1	5.1 ± 1.3	4.7 ± 1.5	5.8 ± 0.8

Significant difference with 1: Defenders Midfielders 3: Attacking Midfielders
2: Defending Midfielders 4: Forwards

4.3.2.4 Section Four - Surface Preferences

Overall a flat/even surface, a smooth ball roll, and a predictable ball bounce were rated to be the most important surface characteristics for the players (Figure 4.3). A good stud penetration and uniformity of the pitch were still rated to be important, though scored significantly less than the other characteristics. Of the other characteristics, the respondents preferred an intermediate height of the ball bounce, amount of giving in by the pitch and hardness (Figure 4.3). A slightly higher than intermediate traction and shock absorption by the surface were preferred and the grass/fibre length of the pitch was preferred short.

No significant effects were present between playing levels and playing positions.

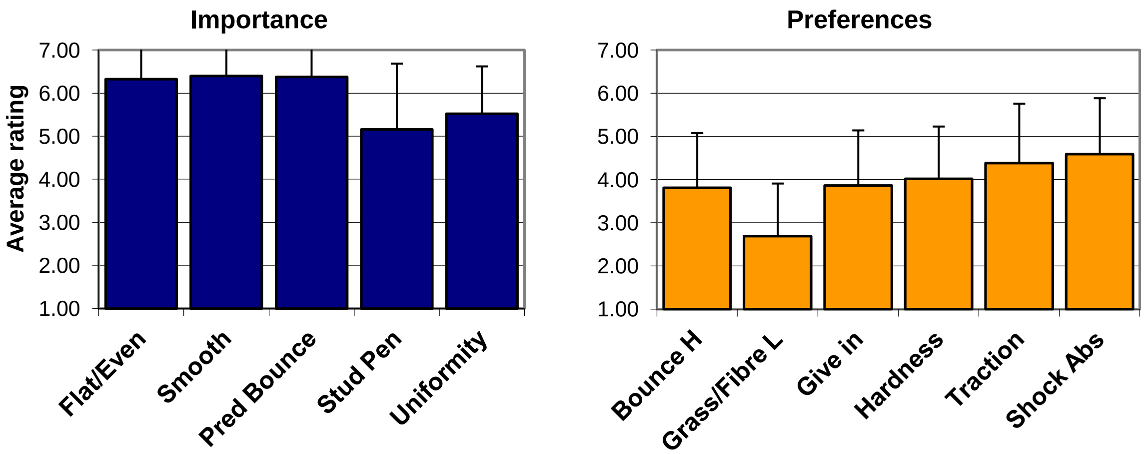

Figure 4.3. Average ratings (± SD) on importance (left) and preference (right) of different surface characteristics

4.3.2.5 Section Five - Player Rating of Two Loughborough University Artificial Turf Pitches

The ratings of the Loughborough University artificial turf pitches were similar for most properties. Between the pitches the traction was rated to be significantly higher on the PEC pitch (Figure 4.4). The uniformity and stud penetration of the pitch was rated to be slightly better on the PEC pitch. In addition to this, the differences in rated hardness approached significance (p: 0.080) for which the hardness of the PEC pitch was rated lower than that of the EHB pitch.

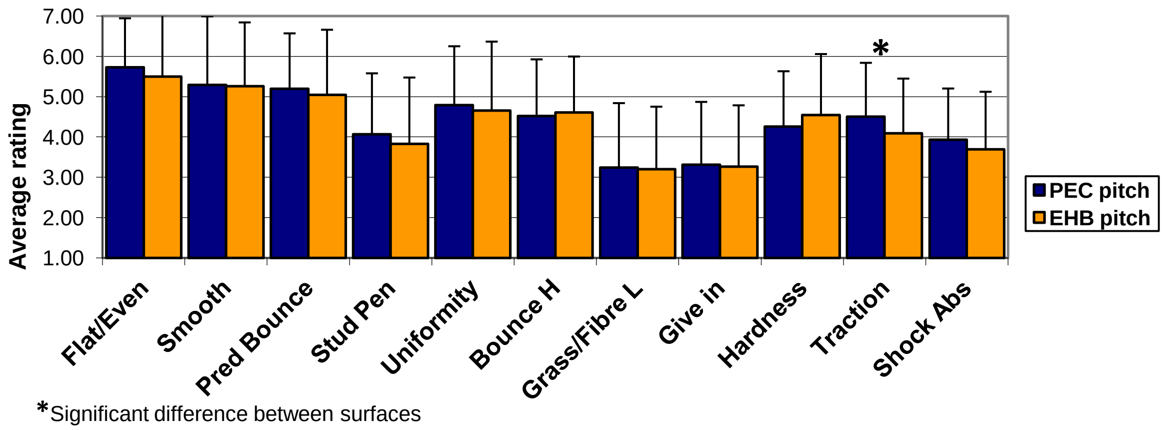

Figure 4.4. Comparison of the average ratings (± SD) on surface characteristics of both Loughborough University artificial turf pitches

Regarding the playing levels, the players in the lower playing level group rated the smoothness and stud penetration of the PEC pitch significantly higher than the players in the upper playing level group (Table 4.9). No significant differences were found between playing levels for the EHB pitch.

Table 4.9. Significant differences in rating of the PEC pitch between both playing levels (mean ± SD)

Surface characteristic		**Playing level**	
		Lower	**Upper**
PEC	**Smooth**	5.7 ± 1.6	4.9 ± 1.5
	Stud Penetration	4.7 ± 1.3	3.5 ± 1.6

4.3.2.6 Section Six - Player Rating of Attitude on Playing Pitches

The questions about the attitude of the players on different pitches showed that the players rated the EHB pitch as the worst and their match pitch (natural grass) as the best of the three pitches (Figure 4.5). According to the ratings the players experienced a significantly higher loading on the EHB pitch than on the two other pitches and the players worried relatively more about getting injuries when playing on this pitch. Furthermore, they rated that they are more likely to get injured when playing on the EHB pitch compared to both other pitches, with a significant difference with their match pitch. They also indicated that they move significantly more cautiously on this pitch compared to the other pitches and judged that they cannot move as freely on the EHB pitch as they can on the other pitches, with a significant difference compared to their match pitch. On all aspects their match pitch was rated significantly better than the artificial turf pitches.

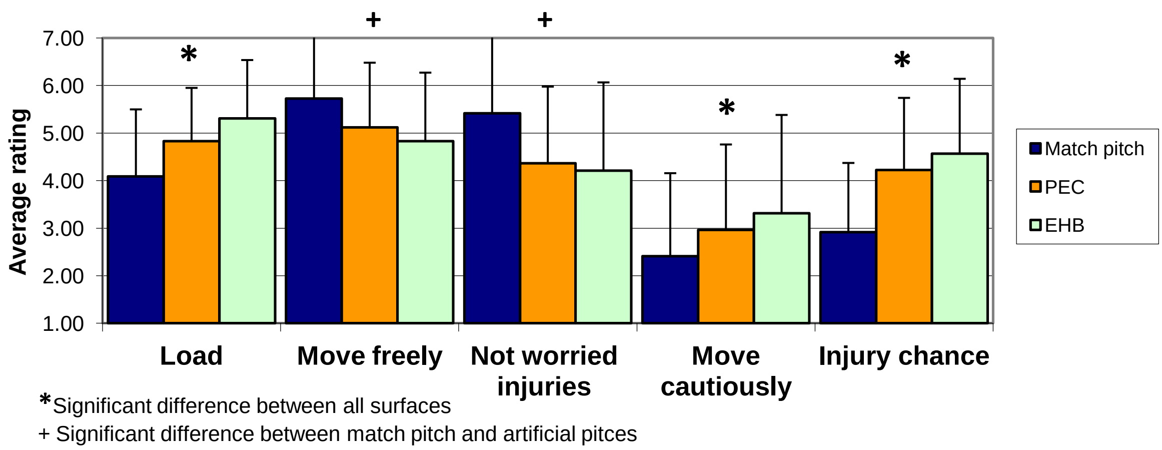

Figure 4.5. Comparison of the average rating (± SD) on the attitude of players on their match pitch and both artificial turf pitches

Comparing the two playing levels showed the players in the upper playing level group rated the loading and the injury chance on their match pitch significantly lower than the players in the lower playing level group (Table 4.10).

Table 4.10. Significant differences in rating of the attitude between playing levels (mean ± SD)

Player Attitude	Playing Level	
	Lower	Upper
Load Match Pitch	4.6 ± 1.3	3.6 ± 1.3
Injury Chance Match pitch	3.3 ± 1.4	2.6 ± 1.4

4.4 Discussion

The aim of this study was to understand from the player’s perspective, which movements and in-game scenarios are relevant during a game of soccer, as well as to gain insight into their perception and attitude when playing on different pitches and what surface characteristics they prefer. The aims were met with the help of a focus group and questionnaires involving questions on movements, in-game scenarios and surfaces.

The insight gained in this study aided the selection of relevant movements, in-game scenarios and surface properties for use in the player movement study.

4.4.1 Movements

Of the listed movements, ‘sprinting’, ‘a general change of direction’ and ‘stop & turn’ were rated as the most important by players in order for them to perform successfully during a game of soccer and were rated significantly higher than most other movements. ‘Walking’ and ‘diving’ where rated as the least important movements. On the aspect of how frequently the movements were performed during a complete match ‘running’, ‘planting non-kicking foot’ and ‘a general change of direction’ were rated the highest. The importance and frequency of sprinting and running supports the results of previous studies that have reported players cover a total distance of 10 – 12 km during a match, of which up to 11% constitutes sprinting (Stølen et al., 2005; Carling et al., 2008; Mohr et al., 2003; Bloomfield et al., 2007). Also, the importance and frequency of changing direction is reflected in previous research which reported that on average 727 turns and swerves were made during a match (Bloomfield et al., 2007).

‘Sprinting’, ‘stopping’, ‘jump/land’ and ‘stop & turn’ were the rated the highest for loading on the player, with significant differences to most other movements. Comparing the ratings on the importance, frequency and loading showed that ‘sprinting’, ‘a general change of direction’ and ‘stop & turn’ were rated high in two of the three categories. Of these different movements the importance of the change in direction was also reflected in the results of the focus group in which it was rated highest by all players.

Some of the movements leave room for some variation. A ‘stop and turn’, ‘arc run’, ‘sidestep cut’ and ‘crossover cut’ could all be defined as a ‘general change in direction’, and also within these movements variation in turning and cutting angles are possible. Of the four movements that were specific changes in direction, the ‘stop and turn’ was rated the highest for importance, frequency and loading. During the focus group the players mentioned that they mostly use a ‘stop and turn’ to “turn towards the goal” and that “defenders are more likely to do a 180”, meaning they turn towards the opposite direction. Both the turning towards the goal and the 180 degree turn indicated a large turning angle during the ‘stop and turn’.

Few significant differences were found between the two different playing levels of which two out of three involved ‘a general change of direction’. Both the importance and frequency of the ‘general change of direction’ was rated higher by the players in the lower playing level group. However, for the specific changes of direction like the ‘stop and turn’ and ‘arc run’, and for the perceived loading no significant differences were present between playing levels. It may therefore be that the players in the low playing level group interpreted ‘a general change of direction’ differently than those in the high playing level group, though it also has to be noted that the differences in rating between playing levels were small. Since no significant differences were found in rating for the specific changes of directions or any of the other movements it seems that the playing level does not have an effect on how players experience the movements during a match. Therefore it is expected that recruiting players from different playing levels will not affect the results of the player movement study.

Regarding the playing positions, effects were present for the rated importance and frequency of movements. The offensive players (attacking midfielders and forwards) rated both the frequency and importance of the ‘arc run’ higher than the defensive players (defenders and defending midfielders). Even though this was not always significant it indicates that the role of a player can have an effect on how important a movement is to perform successfully during a game of soccer and how frequently it is used. This is also in agreement with the findings of the focus group, which indicated that some movements are considered to be more important for some positions, like the arc run for an offensive player. Differences between playing positions were also found for ‘crossover cut’, ‘dribbling’, ‘tackle’ and ‘heading’. However, the playing position did not affect the ratings on the experienced loading. This indicates that depending on the playing position, some players may have more experience when performing a movement, but that this does not affect how demanding they perceive the movement to be.

4.4.2 One-on-One Situations

The one-on-one situations ‘marking an opponent’ and ‘heading duel’ were rated to be encountered most frequently by the players. ‘Heading duel’ was also rated to have the highest loading, followed by ‘chasing an opponent’, ‘getting away from an opponent’ and ‘getting past an opponent’. Some differences were visible between playing positions regarding the ratings on frequency and experienced loading.

A ‘heading duel’ was rated higher by the defenders and forwards than both midfield positions in terms of frequency and perceived loading, with a significant difference between the defenders and attacking midfielders regarding the frequency rating. While the differences were not significant between all positions it seems that heading duels are more relevant for defenders and forwards than midfield players. ‘Marking an opponent’ was rated as being performed more often by the defensive positions than the offensive positions. Whereas the frequency rating for ‘getting away from an opponent’, ‘getting past an opponent’ and ‘avoiding a tackle’ increased from defenders through to forwards as the role of the players became more offensive. For ‘marking an opponent’ and ‘chasing an opponent’ a significant difference was also present for the loading between some positions. However, no pattern was present between positions that could be related to the role of the players on the field.

Similar to the movements, the one-on-one situation results show that some players encounter some situations more often than others, depending on their field position. The playing positions that rated the frequency of ‘heading’ high in the movements section also rated the frequency of ‘a heading duel’ high. The results indicate that depending on the playing position some players may have more experience in certain one-on-one situations, but for most situations and playing positions this does not affect how demanding players perceive the situation to be. The playing level showed no significant effects on the rating of the one-on-one situations. Therefore it is expected that recruiting players from different playing levels will not affect the results of the player movement study.

4.4.3 Surface Preferences, Ratings and Attitude

The players rated all surface characteristics to be important for a good soccer pitch. Especially a ‘smooth ball roll’, ‘predictable ball bounce’, and a ‘flat/even surface’ were considered to be important characteristics for a soccer pitch. The surface preferences were mostly given a neutral rating of 4 (scale 1 – 7). For the surface hardness this means that they preferred a surface that is not very hard or very soft. The preferred fibre / grass length was the exception to this as this was preferred short by the players. These findings were in line with the focus group in which the players stated that the behaviour of the ball, speed and predictability, were mainly important to them and stated they wanted a surface to be not too hard or too soft.

The differences in rating between the Loughborough University pitches were small. A significant difference was only present for the traction, which was higher on the PEC pitch. The PEC pitch was also rated to be softer, though this difference only approached significance. These differences between the EHB and PEC pitch may be related to the attitude of the players as they perceived to experience a higher loading on the EHB pitch and thought they are more likely to get injured. In addition to this, they indicated to move more cautiously on the EHB pitch. The attitude of the players when playing on their match pitch (natural grass) was substantially better compared to both artificial turf pitches as they perceived the lowest loading on this pitch as well as the lowest injury risk.

The difference in perceived traction was also present in previous mechanical measurements on the EHB and PEC pitch, with the PEC (34 – 41 Nm) pitch having a higher rotational traction value than the EHB (29 – 35 Nm) pitch. However, the difference in perceived hardness was not present in previous mechanical measurements. Tests with a Clegg Impact Hammer showed that the PEC pitch was of similar hardness as the EHB pitch or harder. Regarding this, it may be that the perception of the players was based on other factors, such as the surface response in multiple directions, and not only the vertical impact with the surface on which the Clegg Impact Hammer is based.

The results of the questionnaire suggest that the traction and hardness of the surface are the main surface properties related to the perceived loading and injury risk of the players. The lower traction and shock absorption, as well as the higher hardness of the EHB pitch was related to an increased loading and injury risk perceived by the players. The relation between the lower traction and perceived loading and injury risk of the surface is in contrast with the finding in the focus group, in which it was stated that a high traction surface puts a higher load on the body, and previous studies which found a higher human loading on surfaces with an increase in traction (Wannop et al., 2010; Stefanyshyn et al., 2010).

4.4.4 Limitations

Regarding this study several limitations can be identified. First, all participating soccer players were members of Loughborough University teams. While everyone could express their own opinions regarding the movements, in-game scenarios and surfaces it is possible that their opinions on these aspects are influenced by each other and external factors like their coaches. Therefore it may be that using other teams would have led to different outcomes. However, as there was a good variation in the answers/ratings given by the participating players and clear differences were present between movements, in-game scenario and surface ratings it is believed that the present study gives a good representation of the perception of soccer players regarding these aspects.

Other limitations as a result of only using players from Loughborough University teams include the age and experience, and sample size. That all players were from

Loughborough University teams meant that the average age (20 ± 1.3 years) was quite young considering the average age in studies using professional players was 6 – 9 years older (Andersson et al., 2008; Ronkainen et al., 2012). This also meant that the overall experience of the participants could have been higher if older players were included. However, the participants in the questionnaire had a minimally five years experience in playing soccer which was believed to be sufficient taking their playing level into account. Furthermore, the players had sufficient experience in playing on artificial turf, on average 7.8 ± 4.0 years, which was an important aspect of this study. Considering this it was believed that the age and experience was not a major limitation in this study.

That only players from the Loughborough University teams were used also meant that the sample size of the study was smaller compared to some other player perception studies (Andersson et al., 2008; Zanetti, 2009; Ronkainen et al., 2012). Using more players may have given a greater statistical distinction between the movements and surface characteristics. However, it is believed that the sample size was sufficient to meet the goals of this study, namely getting insight into and selecting relevant soccer related movements, in-game scenarios and surface properties for the player movement study.

A final limitation of the present study regards the fact that the different teams may use one or the other artificial pitches of Loughborough University more or less than the other. This may have influences how they rated the pitches. However, the questionnaire did not include questions regarding the exposure to these different pitches, which means that no analysis could be performed to investigate if this was the case or not.

4.5 Conclusions

While the data collected in this study was subjective, the findings of the focus group and questionnaire give some guidance for the selection of movements, in-game scenarios and surface properties for the player movement study. The results of this study showed that multiple movements and in-game scenarios can be considered relevant for soccer due to high ratings in multiple categories. Regarding the selection of movements for the player movement study, the choice was made to select movements that scored high in each category. The first movement selected was the stop and turn. This movement was selected as it was rated high on the perceived loading and importance. Furthermore, changes in direction scored high frequency, of which the stop and turn was rated as being the most important and having the highest loading on the body. In addition to this, previous studies on changes in direction mainly focused on cutting manoeuvres. Therefore selecting the stop and turn for the player movement study will contribute to the current knowledge on how surface properties affect the movement dynamics and human loading.

The second movement selected for the player movement study was jump / land. This movement was selected as it got high ratings on importance and how frequently it is performed in soccer, but above all it got the second highest rating on perceived loading. While this movement has often been used in previous biomechanical studies, few have used this in combination with different surface conditions. Therefore selecting jump / land for the player movement study will contribute to the current knowledge on how different surface conditions affect the movement dynamics and human loading.

The selection of in-game scenarios for the player movement study had to be in conjunction with the selected movement. Several options were available for the stop and turn, such as ‘chase an opponent’ or ‘get away from an opponent’. However, as highlighted in §3.4.2 these in-game scenarios encountered several issues regarding the lab space and timing of the interaction between players. Therefore the choice was made to use a simulated opponent as used in a previous study on cutting manoeuvres (McLean et al., 2004). This still provided some interaction between the player and an opponent, but provided more control over the in-game scenario to minimize the variability between trials.

Regarding the jump / land manoeuvre the choice was made not to include an opponent. This choice was made as in-game scenarios such as a ‘heading duel’ would require close proximity of an opponent increasing the chance of player-player contact, which has been identified as an important injury risk factor in soccer in the literature review. As heading also scored high on importance and perceived loading in the questionnaire, the choice was made to include this as an in-game scenario for the jump / land manoeuvre. This choice was also made as, to the author’s knowledge, no previous study has compared a normal jump to a jump during which a player has to perform a heading manoeuvre. Therefore this will contribute to the current knowledge on how in-game scenarios affect the movement dynamics and human loading.

The selection of the surface properties was based on the results of the focus group and questionnaire, as well as on previous research and the selected movements. The results of this study showed that the traction and surface hardness was related to a perceived increased loading on the body and injury risk. Related to the selected movements it was expected that the surface hardness would mainly affect the movement dynamics and human loading of the jump / land movement, whereas the traction of the surface would mainly have an effect on the stop and turn. Regarding the traction the choice was made to modify the rotational traction of the surfaces due to the large rotational component present in the stop and turn. Furthermore, previous research that included a 180° turn mainly found effects related to the rotational traction conditions of the shoe-surface interface (Stefanyshyn et al., 2010).

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5. EVALUATION OF PRESSURE INSOLES

5.1 Introduction

Concerning the collection of ground reaction force (GRF) data during the player movement study, it was highlighted in §3.4.5 that while force platforms are considered to be a gold standard in biomechanical research they put restrictions on the movements due to limitations in size. The largest force platforms currently available are restricted to a size of: 60 x 90 cm (Kistler), 90 x 90 cm (Bertec) and 120 x 120 cm (AMTI). As a result, the area in which a movement has to be executed is limited, which could influence the execution of the movement due to players focussing to land on the force platform (Abendroth-Smith, 1996). Furthermore, the use of a large force platform has the limitation that the accuracy of the centre of pressure decreases with an increase in size (Bobbert & Schamhardt, 1990). Finally, in combination with artificial turf surfaces the force platform measures the ground reaction force underneath the artificial turf and not directly underneath the foot, which may not completely reflect the forces that act on the body.

Pressure insoles could provide a solution for these limitations. Since the insoles are placed in the shoe data can be collected in any location, also because the data collection unit is small and easy to transport. This could help with the test design of the player movement study as the location of where the movements are executed is not dictated by a force platform, which may allow the use of more complex in-game scenarios. On the other hand, there are also some limitations to the use of pressure insoles. First of all the pressure insoles only provide information on the forces perpendicular to the sensor surface and the sampling rate of pressure insoles (50 – 200 Hz) is generally lower than that of force platforms (1000 Hz) (Queen et al., 2007; Wong et al., 2007). Also, while some previous studies have used Tekscan F-scan pressure insoles, which were available at Loughborough University, during running and claimed accurate results (Verdejo & Mills, 2004), others have indicated some issues (e.g. durability, temperature sensitivity) that might affect the reliability of the pressure insoles (Luo et al., 1998; Woodburn & Helliwell, 1997; Morin et al., 2001; Sih, 2001). Therefore the pressure insoles need to be investigated to determine if they would be a reliable measurement tool for the player movement study. This addresses objective 4 of this thesis (Chapter 1), which involves designing an experimental study to measure the player kinematics and kinetics on the different surfaces and in-game scenarios.

The aims of this study involve evaluating four different aspects of the Tekscan F-scan (#3000) pressure insoles during running (Figure 5.1). The first aim was to evaluate how well the pressure insoles were able to produce the same output during consecutive trials (repeatability). The second aim was to evaluate how well the pressure insoles were able to produce the same output during a single prolonged trial (reliability). Leading from this the third aim was to evaluate the ability of the pressure insoles to withstand wear and tear during the prolonged trial (durability). The final aim was to evaluate the accuracy of the pressure insoles by comparing the output of the insoles to that of a force platform. If the different tested aspects of the Tekscan F-scan pressure insoles proved to be within acceptable limits (± 2.5%), they could be used during the player movement study to collect GRF data, and movements and in-game scenarios selected for the player movement study would not be restricted by the size and location of a force platform.

This chapter first discusses the methodology of the tests performed to evaluate the repeatability, reliability and durability of the pressure insoles. Following this the results of the different tests are presented, followed by a discussion on the main findings of this study and a conclusion.

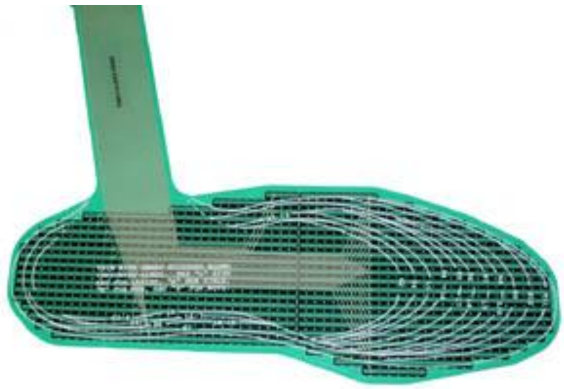

Figure 5.1. Tekscan F-scan #3000 pressure insoles were used in all tests. The insoles can be trimmed to the shoe size of the subjects, have 3.9 sensels/cm^2 and a pressure range of 75 – 125 psi.

5.2 Methodology

To meet the aims set for this study Tekscan F-scan (#3000) pressure insoles were used with the F-scan mobile system (Tekscan Inc., South Boston, MA, USA) during two different treadmill tests. Both treadmill tests were performed by a 23 year old male athlete (body mass 100 kg), who provided informed consent and ethical clearance was gained from Loughborough University Ethical Advisory Committee. Before each test a new pressure insole, cut to the shoe size (UK 12) of the subject, was equilibrated in an airbladder calibration system at 20 PSI. After the equilibration the insole was placed in his right shoe

(Nike Air Max) and the subject performed a step calibration. For the step calibration the subject had to shift the weight from his left foot onto his right foot as described in the F-Scan Mobile Research 6.30 software. With the help of this and the weight of the subject the software calibrated the pressure insoles. Following the calibration the subject was asked to have a walk around the lab to 'break in' the insoles with at least 20 steps as described in the F-Scan Mobile Research 6.30 software and to allow the subject to become accustomed to the equipment.

In order for the pressure insoles to be a valuable addition to the experimental design of the player movement study it had to be sure that their output is similar during repeated trials. The repeatability of the pressure insoles was assessed by having the subject run a series of 5 x 90 second run on a treadmill at 9 km/h. Pressure data was collected from 60 – 75 s into each run at 200 Hz. After each run the pressure insole was removed from the shoe and put back in again to replicate a completely new trial. Repeatability was assessed by comparing the pressure insole output in all five runs.

Apart from a good repeatability the output of the insoles also had to be consistent over a prolonged period of time. With respect to the experimental design of the player movement study a good reliability and durability of the insoles means that the pressure insoles do not have to be replaced or recalibrated during a test session with a player. The reliability and durability of the pressure insoles were assessed during a 24 minute run on a treadmill at 9 km/h. During this test the pressure insole remained in the shoe of the subject for the entire time. Pressure data was collected for 15 seconds at 1, 5, 10 and 23 minutes into the run. Reliability and durability of the pressure insole output was assessed by comparing the output from the four collection points and examining the pressure insoles for damage afterwards, both visually and by checking the insoles with an air bladder for any missing data points of the individual sensels.

As an extra measure to investigate the reliability and accuracy of the pressure insoles the subject was asked to walk twice across a force platform (9281 CA, Kistler Instrument AG, Switzerland, 1000 Hz) and to perform two vertical squat jumps on top of the force platform before and after each treadmill tests. For both movements the subject had to hit the force platform with the right foot, in which the pressure insole was placed. As the force platform is considered a gold standard this allowed for comparing the pressure insole data with the force platform data to see if the output of the pressure insole changed because of external factors, like difference in technique, or because of factors related to the pressure insoles, like wear. In addition to this, the force platform data was used to perform a frame calibration after the data collection to see if any differences between the pressure insole output and the force platform could be corrected with other data. The frame calibration was performed by calibrating a frame of the pressure insole force curve with the corresponding value of the force platform.

The pressure data from the insoles was analysed using F-scan mobile research 6.30. The output curves of both tests over the entire foot of each data collection were compared as this gave an overall picture of the foot strike. In addition to this, the pressure insole data was divided into a forefoot and rearfoot section for the first test to examine if there was any difference between different regions of the foot. The forefoot section comprised of the region of the foot from the distal phalanges to the metatarsalphalangeal joints, the rearfoot region comprised the rest of the foot from the metatarsalphalangeal joints to the calcaneus (Figure 5.2). The repeatability and reliability of the pressure insoles was quantified as the percentile change in peak force output over all data collection points of the treadmill tests. The durability of the insoles was also assessed by examining the changes in sensel output before and after the treadmill tests over the entire insole under uniform pressure in the airbladder. Extra attention was paid to amount of sensels that stopped producing output after the test. Finally, the shape of the force curves (qualitatively) and peak values (quantitatively) of the pressure insole data and force platform data of walks and squat jumps were compared with each other to quantify the accuracy of the pressure insoles. No statistical tests were performed as clear differences were present in the data collected.

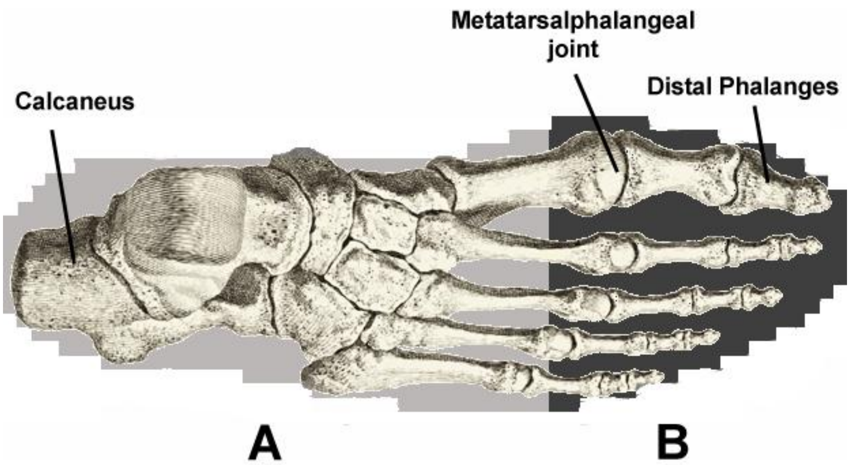

Figure 5.2. Division of the pressure insole used for comparison of foot regions; forefoot region (B), from distal phalanges to just after metatarsalphalangeal joints, and rearfoot region (A), from metatarsalphalangeal joints to calcaneus

5.3 Results

5.3.1 Repeatability

The force curves from the pressure insole (based on the step calibration) showed that with each run the output decreased substantially, with a 41% drop of the peak force between the first and the last run (Figure 5.3). A similar decrease in force output of the pressure insole was found for both the forefoot and rearfoot regions of the insole (Figure 5.4). Despite the change in magnitude of the force the shape of all three force curves appeared reasonably consistent across trials, suggesting that the relative sensitivity of the sensels decreased but that the course of the curve was not affected by this.

The air bladder calibration system pre versus post test comparison indicated that the forefoot region had degraded more than the rear foot as the output of those cells was less than in other regions under the same pressure (Figure 5.5). In addition to this 1.2% of all sensels (nine in the forefoot and two in the rearfoot region) stopped producing any output, indicating wear of the insole after the five runs.

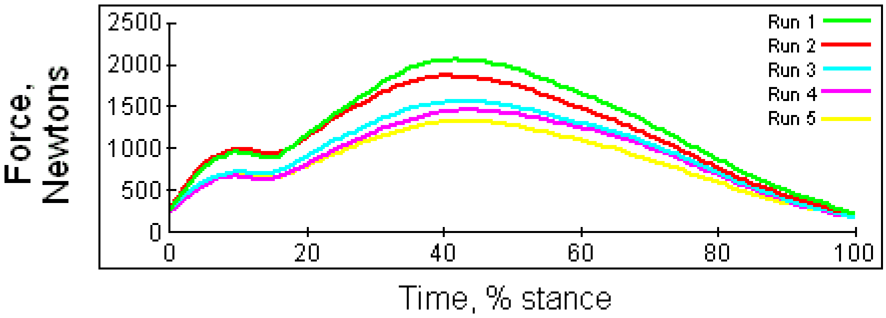

Figure 5.3. Force as a percentage of the stance phase for each of the 5 x 1.5 minute runs. During the test the test the output of the pressure insole decreased gradually.

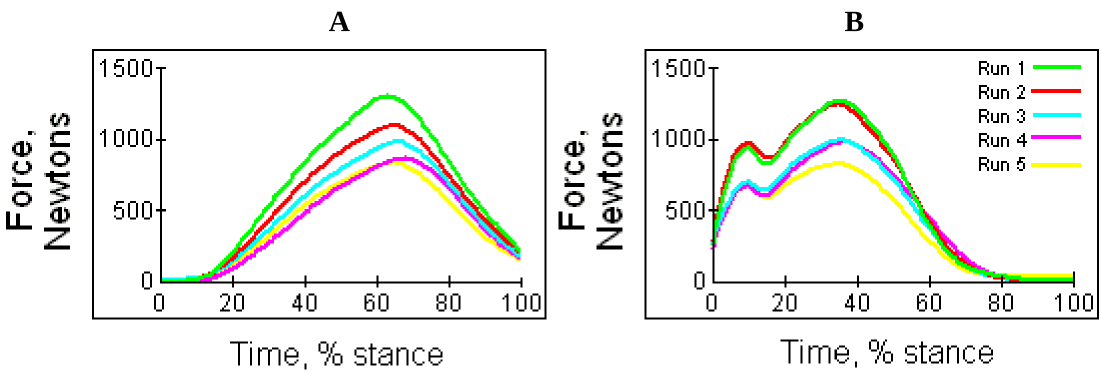

Figure 5.4. Force as a percentage of the stance phase in the forefoot (A) and rearfoot (B) region of the insole for each of the 5 x 1.5 minute runs. The output of the insoles decreased both regions of the insoles, suggesting that the decrease was not region specific

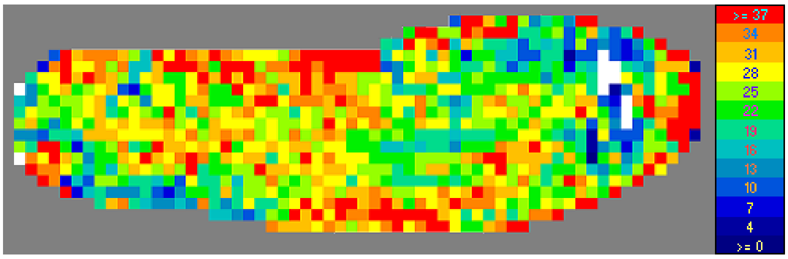

Figure 5.5. Putting the insole in the airbladder calibration system with an equal pressure distribution after the test showed the degradation of the sensels was not uniform. The blue regions indicated a lower output than the red regions. Eleven sensels (white) stopped producing any output after the treadmill test, which is the equivalent to 1.2% of the sensels in the cut insole.

5.3.2 Reliability and Durability

The force curves from the pressure insole (based on the step calibration) showed a 47% decrease in peak force during the 24 minute run (Figure 5.6). This was similar to the decrease found in the repeatability test. During the 24 minute run the insole shifted backwards inside the shoe of the subject. This caused the rearfoot section of the insole to deform together with the lower part of the cuff that connects the insole to the data collection device (Figure 5.7). The pre and post test comparison with the airbladder calibration system showed that 8.4% of the sensels in the insoles stopped producing any output after the 24 minute run (Figure 5.8). Of these, 89.5% were located in three rows, suggesting that this was related to the deformation of the insoles.

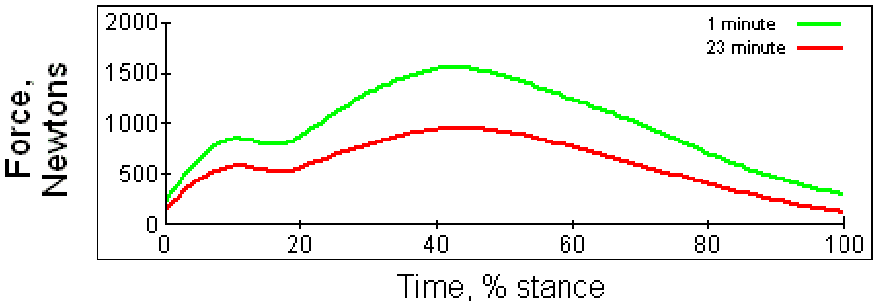

Figure 5.6. Force as a percentage of the stance phase at 1 and 23 minutes into the reliability test on the treadmill. During the test the test the output of the pressure insole decreased gradually.

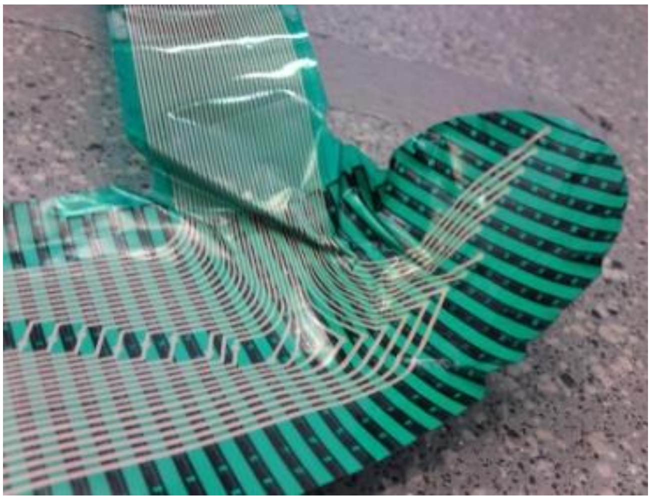

Figure 5.7. The pressure insole was deformed as a result of a shift inside the shoe of the subject during the 24 minute run. The deformation mainly took place around the cuff and the heel area of the insole.

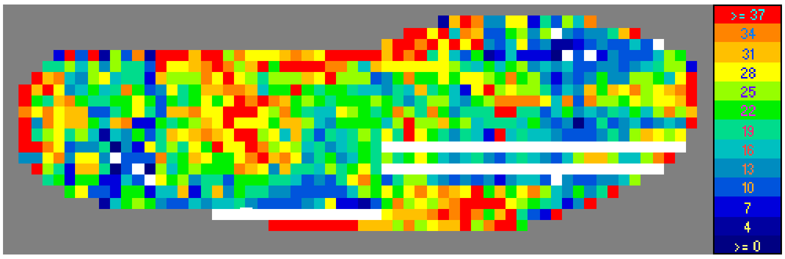

Figure 5.8. Putting the insole in the airbladder calibration system with an equal pressure distribution after the test showed the degradation of the sensels was not uniform. The blue regions indicated a lower output than the red regions. Of the 906 sensels 76 (white) stopped producing any output after the treadmill test, which is the equivalent to 8.4% of the sensels in the cut insole, of which 89.6% was located in three rows.

5.3.3 Accuracy

As the pressure insole during the reliability test suffered from deformation and failing sensels the choice was made to discard the walking and jumping trials after the reliability test. Comparing the pre and post repeatability test force curves from the pressure insole during both the walks and jumps on the force platform showed a similar decrease in peak force as observed during both running tests (Figure 5.9A,C). The force curves generated by the force platform showed similar force profiles in the pre and post tests (Figure 5.9B,D).

During the walks before the running tests the output from the pressure insoles did not show the typical vGRF profile during walking, as observed with the force platform (Figure 5.9A), whereas the walks after the runs did have this two peak profile (Figure 5.9A) (Winter, 1984). Regarding the jumps on the force platform, the force profiles from the pressure insoles were similar to those measured with the force platform. A comparison between the forces measured with the pressure insoles and force platform showed a difference in magnitude both for the walks and jumps (Table 5.1, Table 5.2). This discrepancy between the force platform and pressure insoles could be resolved by using a frame calibration based on the force platform data (Figure 5.10).

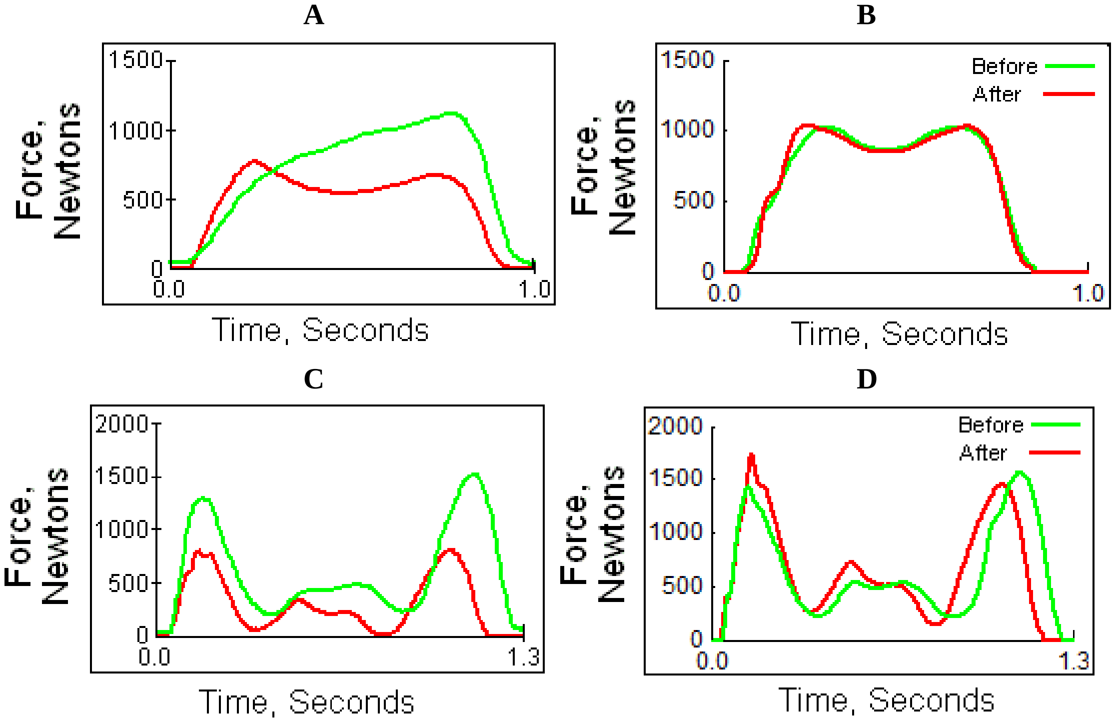

Figure 5.9. Force-time profiles of the walking (A,B) and jumping (C,D) trials before and after the repeatability tests show a similar degradation of the pressure insoles (A,C) as found during the treadmill tests. The force-time profiles of the force platform were similar before and after the test for both movements (B,D).

Table 5.1. Comparison of the push off peak the walking trials before (trial 1 and 2) both treadmill tests between force platform and pressure insole (based on step calibration)

Test		**Repeatability**		**Reliability**	
Step calibration	**Trial**	1	2	1	2
	Force platform	1007	992	986	1024
	Pressure insole	1111	1093	806	805

Table 5.2. Comparison of the first and second force peak of the jump trials between the force platform and pressure insole (based on step calibration) before both treadmill tests (trial 1 and 2)

Test		**Repeatability**				**Reliability**			
Step calibration	**Trial**	1	1	2	2	1	1	2	2
	Peak	1	2	1	2	1	2	1	2
	Force platform	1426	1568	1611	1403	1742	1454	1649	1436
	Pressure insole	1292	1527	1271	1251	1285	1141	1237	1157

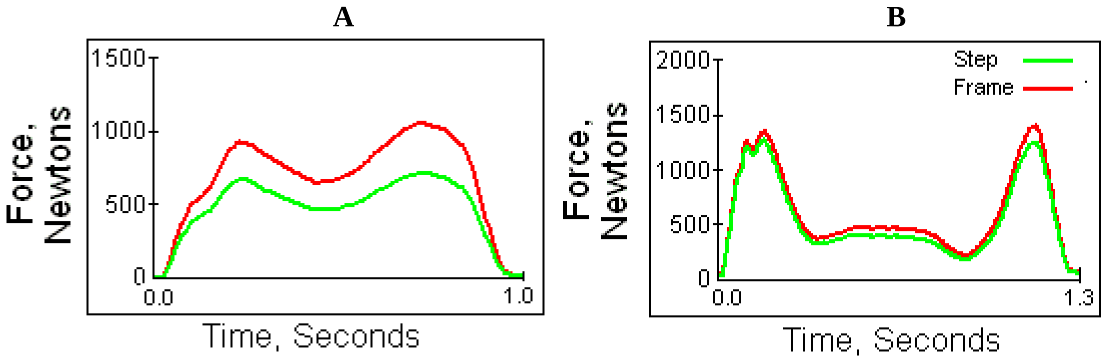

Figure 5.10. Example of the difference between the step calibration and the frame calibration of the pressure insoles for the walking (A) and jumping (B) trials.

5.4 Discussion

The objective of this study was to determine if the Tekscan F-scan (#3000) would be a reliable measurement tool for the player movement study. This was done by assessing the repeatability, reliability and durability during two treadmill tests, and the accuracy of the insoles by walking and jumping trials before and after the treadmill tests. Both treadmill tests showed a decrease of the pressure insole output. This decrease was also present in the pre and post walking and jumping tests. These results suggest that the pressure insoles need additional work, like frequent recalibration, in order for them to be a valuable addition to the experimental design of the player movement study.

The decrease in pressure insole output during both treadmill tests showed that the sensitivity of the Tekscan F-scan pressure insoles degrades rapidly during running. The force platform data suggests that the decrease is related to the pressure insoles as force platform data was similar before and after the runs. This indicates a limited reliability during prolonged use, but also a limited repeatability when the insoles are used multiple times. It has to be noted that the repeatability of the insoles might increase by recalibrating the pressure insoles regularly. The difference in output present between the first and second run of the 5 x 1.5 minute run suggests that recalibration would be needed after each trial. For the experimental design of the player movement study this means that extra time would be required in order to cope with the decreased sensitivity of the insole.

Recalibrating the pressure insoles after each trial puts restrictions on the applicability of the pressure insoles. During field tests a step calibration would be the most practical means of calibrating the pressure insoles. However, performing a step calibration after each trial leads to a substantial increase of the time needed for each trial. The effect of this would either be a substantial increase of the time needed per subject or a restriction of the number of trials executed per subject. Both effects are not preferable. Another issue involving the step calibration is the limited reliability of the calibration itself. Comparing the output of the pressure insoles during the walks across the force platform before both tests shows an average difference in the force reading of almost 300 N, while the average difference between the force platform readings was only 5 N (Table 5.1). On top of this, the difference between the output of the pressure insoles and that of the force platform varied between 100 – 200 N for the walking trials and between 41 – 457 N for the squat jumps. Besides all of this it would not be possible to use a step calibration during a prolonged trial, which makes it necessary to use short trials during any type of test. As such, the recalibration would not be an issue for the experimental design of the player movement study as the trials were short. Therefore the added time requirement and the calibration reliability are the main issues with regards to the player movement study

Not being able to do a step calibration during prolonged trials could be resolved by using the frame calibration afterwards. Though to perform a frame calibration afterwards additional data is needed from another source, e.g. force platform. While this has the advantage that the pressure insole is calibrated to an accurate force reading, this can put restrictions on the test environment as the other equipment has to be incorporated, which negates one of the strengths of the pressure insoles.

The calibration of the pressure insoles was one of the weaknesses of this study as both the step calibration and frame calibration the insoles are based on a single calibration point. Previous studies have shown that a calibration using multiple points and variable loads can be more accurate (Brimacombe et al., 2009). However, the main aim of this study was to examine the repeatability, reliability and durability of the pressure insole output. For this the single point calibration is sufficient as the deterioration in sensitivity of the pressure insoles during running is the same regardless of the calibration method, which supports the findings of previous studies (Woodburn & Helliwell, 1997; Sih, 2001).

Beside issues concerning the reliability, repeatability and calibration the pressure insoles lacked robustness. The insoles were damaged easily due to a backwards shift inside the shoe during the 24 minute run causing 8.4% of sensels to stop producing any output. This was likely caused by the folds around the cuff as the F-Scan Mobile Research 6.30 documentation states that the pressure insoles should not be folded. This damage to the pressure insoles may be prevented to some extent by attaching the pressure insole to the sole of the shoe as this will reduce the chance of the insole moving around in the shoe and folds occurring in the pressure insole. However, during high impact movements, which put a lot of strain on the insoles, some movement of the insole and consequent damage appears inevitable. As a result during the player movement study the insoles would have to be checked for damage and possibly replaced on a regular basis.

5.4.1 Limitations

Considering this study several limitations can be identified regarding the study design. During the repeatability test the insoles could have been recalibrated every time they were taken out of the shoe and put back in. This could have provided insight into if frequent recalibration would resolve some of the identified limitations of the pressure insoles.

Another limitation of the study design can be found in the fact that the results are based on a limited number of tests and for example no tests were performed on consecutive days to evaluate if the results of the pressure insoles would be repeatable in that way. However, testing with a larger number for pressure insoles and test retest reliability would have been the following steps to the tests presented in this chapter if the outcomes of these tests had shown that the pressure insoles were reliable enough to make a valuable addition to the study design of the player movement study.

5.5 Conclusions

In conclusion, the limitations of the Tekscan F-scan pressure insoles make them unsuitable as a measurement tool for use in the player movement study. Using a single calibration the results of the pressure insoles lack reliability and repeatability. Frequent recalibration may increase the reliability and repeatability, but this negates the advantages of using the pressure insoles as they could only be used either during short trials or in combination with other equipment like a force platform. Furthermore the pressure insoles lack durability with sensel damage occurring after only a few minutes of running during the repeatability test and visible damage to the insole following the 24 minute run of the reliability test.

Regarding the test design for the player movement study, dealing with the limitations of the pressure insoles would require recalibrating the pressure insoles after each trial, or collecting GRF data with a force platform. This was undesirable as in combination with four different surface conditions and two in-game scenario conditions the duration of each test session would become too long. Therefore the choice was made to use a force platform to collect GRF data. This would put restrictions on the movements and in-game scenarios used for the player movement study. However, this was not considered to be a major issue as previous studies also used a force platform in combination with similar movements and in-game scenarios (McLean et al., 2004; Ford et al., 2005).

5.6 References

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6. SURFACE DESIGN

6.1 Introduction

To extend the current knowledge and understanding of the effects of surface properties on player movement dynamics, the choice was made in Chapter 3 to design surfaces with specific levels of surface hardness and rotational traction. The aim was to design surfaces close to upper and lower limits of the standards set by FIFA to gain insight into how the changes in these properties affect the human movement dynamics during selected movements. The choice for the surface hardness and rotational traction was made as the literature review showed that these are key properties, and also the player focus group and questionnaire used in Chapter 4 showed that these properties may affect the movement dynamics.

The choice for the combination of surface properties was made as the literature review (Chapter 2) showed that both the surface hardness and rotational traction can affect the human movement dynamics. Therefore, it was expected that the properties may influence each other and show an interaction effect. To quantify the surface properties the choice was made in Chapter 3 to use the standard test devices as specified in the FIFA guidelines to ensure the properties were specified in a similar manner. This allowed that the outcomes of the player movement study (Chapter 7) could be related to the standards used in industry.

Regarding the surface design it was discussed in Chapter 3 that the range of each property has to be safe for the participants of the player movement study. Therefore, the choice was made to design surfaces with properties close the limits of the standards set by FIFA as this is the expected range to which soccer players are exposed to on artificial turf, and therefore it was assumed to be safe. Furthermore, the surfaces for this study were ideally required to have a similar appearance to avoid any effects of visual perception of the players during the trials. In addition, the surface hardness and rotational traction properties were required to be maintained during the player movement study to ensure the properties would remain consistent throughout the player movement study, as a previous study showed that the state of the infill can affect the surface properties (Severn, 2010).

The first aim of this chapter was to create four different surfaces with different hardness and rotational traction values to be used during the player movement study. This addresses objective 3 of this thesis (Chapter 1) for which it was considered important that the surfaces with a different hardness have similar rotational traction values, and the surfaces with a different rotational traction have a similar hardness (Table 6.1). This would make it easier to relate findings during the player movement study to either a change in hardness or rotational traction and identify any interaction effects.

Table 6.1. Different surface properties selected to be used in combination with the selected movements.

Surfaces		Rotational traction	
		High	**Low**
Hardness	**Hard**	Hard – High	Hard – Low
	Soft	Soft – High	Soft – Low

The second aim of this chapter was to investigate how to control the surface properties during testing so there would be no appreciable change when the surfaces are disturbed by player movement or by movement of the surface itself. This addresses objective 5 of this thesis (Chapter 1) and was considered important as controlling the surface properties would ensure the conditions were similar for all subjects in the player movement study.

This chapter first discusses the methodology used for designing surfaces with different properties and for tests on how to maintain these surface properties. Following this, the results of the surface design and maintenance tests are presented, followed by a discussion on the main findings of this study and a conclusion.

6.2 Methodology

6.2.1 Selection of Hardness and Rotational Traction Values

As mentioned, the choice was made in Chapter 3 to design surfaces with different hardness and rotational traction values close to the limits of the FIFA standards. This ensured that the surface properties were safe for the participants of the player movement study. Furthermore, the use of surfaces close to the limits of the FIFA standards during the player movement study would provide insight into the variation in human movement dynamics possible during soccer related movements

The FIFA approval system makes use of two different qualifications, namely: FIFA one star for recreational use and FIFA two star for professional use (Table 6.2) (Appendix C) (FIFA, 2012a). The goal for the surface hardness was to create surfaces near the lower and upper limit of the FIFA qualifications, while maintaining a similar level of rotational traction. For the rotational traction the goal was to create surfaces with as low and as high as possible rotational traction value, while staying within the FIFA qualifications, and maintain a similar level of hardness.

Table 6.2. Standards set by FIFA for rotational traction and shock absorption: One Star for recreational use and Two Star for professional use (FIFA, 2012a).

FIFA Qualification	One Star	Two Star
Rotational traction	25 – 50 Nm	30 – 45 Nm
Shock Absorption	55 – 70 %	60 – 70 %

6.2.2 Equipment

As the FIFA standards were used for the design of the surfaces the choice was made to use the same methods as described in the FIFA guidelines to ensure that the properties were specified in a similar manner. To measure surface hardness an Advanced Artificial Athlete (AAA) (Deltec Metaal, Duiven, the Netherlands) was used (Figure 6.1). The AAA works on the principle that a 20 ± 0.1 kg weight is dropped vertically from a height of 55 ± 5 mm above the surface. Underneath the weight a spring (2200 N/mm) with a test foot (100 mm diameter) is attached and a uni-axial accelerometer (9600 Hz) is attached on top of the weight (FIFA, 2012b). FIFA guidelines specify three repeat measurements to be taken with the AAA at time intervals of 60 ± 5 s.

The hardness is determined by averaging the last two measurements on each location. The hardness (force reduction (FR)) is calculated by the maximal force measured (Fmax) on the test sample compared to the maximal force measured on a concrete surface, with the help of peak acceleration during impact (Gmax), derived from the accelerometer data, mass of the falling weight (m) and acceleration by gravity (g). The measurement uncertainty of the AAA is ± 2% (FIFA, 2012b).

$$FR = \left(1 - \frac{F_{\max\,(testpiece)}}{F_{\max(concrete)}}\right) \bullet 100\%$$

$$F_{max} = G_{max} \bullet \mathrm{m} \bullet \mathrm{g}$$

To measure the rotational traction of the surfaces the standard test method of FIFA was used (FIFA, 2012b). The rotational traction test works on the principle that a studded test foot which is loaded up to a weight of 46 ± 2 kg is dropped from a height of 60 ± 5 mm above the surface and rotated at a speed of 12 rev/min until the test foot moves and has reached a minimal rotation of 45° (Figure 6.2) (FIFA, 2012b). The test foot itself comprised of a metal disc with a diameter of 145 ± 10 mm with six football studs (11 mm long) spaced equally at 46 ± 1 mm from the centre of the disc (Figure 6.2). During the drop and rotation of the test foot the test device was kept vertically as specified by the FIFA guidelines. After the minimum 45° rotation of the test foot the peak torque is taken as a measure for the rotational traction of the surface. The measurement uncertainty of the rotational traction device is ± 2 Nm (FIFA, 2012b).

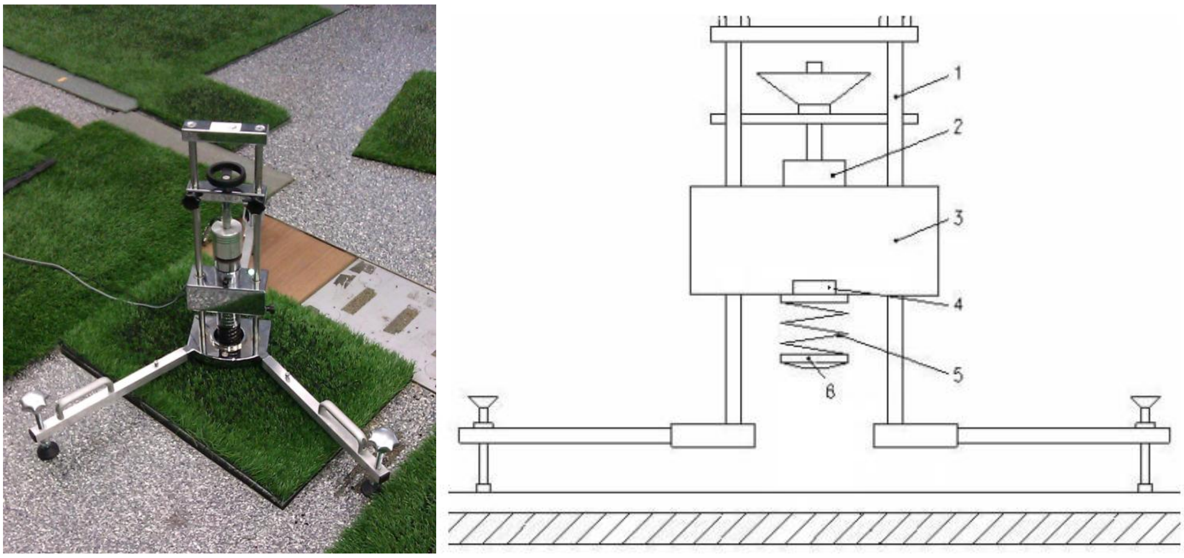

Figure 6.1. Advanced Artificial Athlete used to measure the hardness of the surface and schematic overview with a: 1: guide for the falling mass 2: electric magnet 3: falling mass 4: accelerometer 5: spring 6: test foot (FIFA, 2012b).

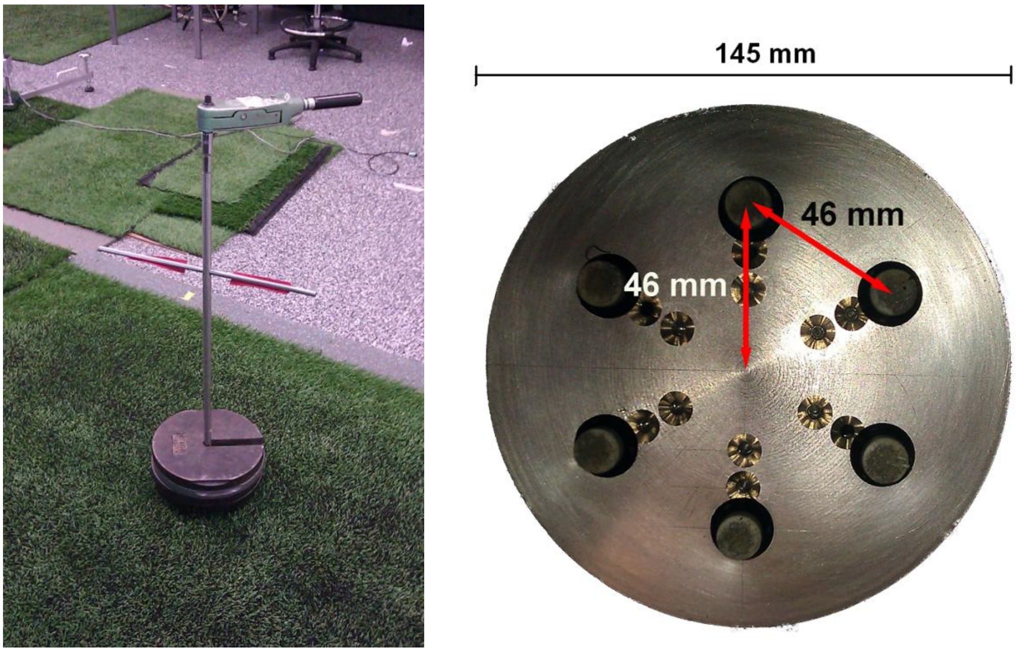

Figure 6.2. Rotational traction device (left) used to measure the rotational resistance of the surfaces with a studded metal test foot (right).

In addition to the AAA and the rotational traction tests the infill depth was measured in the same location as the tests were performed and in additional locations when the disturbance of the surface affected the entire surface sample. This choice was made in §3.3.5 as it was believed that the infill could provide an extra measure of the disturbance and recovery of the infill. The infill depth was measured with a depth gauge meter of which the base was pushed through the infill until the backing of the carpet was reached (Figure 6.3). Following this the top was slid down to the top of the infill, while making sure that none of the fibres were stuck between the infill and the top of the depth gauge meter. The average of at least three measurements was taken per location to come to an accurate infill depth as measurements in the same location typically varied by 1 – 2 mm. The measurement uncertainty of the depth gauge meter was therefore set at 2 mm

The surface design tests for both rotational traction as the AAA, were performed on 1 x 1 m test samples of artificial turf. These test samples were divided into nine sections in which measurements could be taken (Figure 6.4). This allowed the surface properties to be measured across the entire surface while allowing at least 10 cm between test locations and 10 cm from the side of the test sample as prescribed in the FIFA guidelines (FIFA, 2012b). This is necessary as near the edge of the samples part of the infill might drop out and affect the results.

Figure 6.3. Depth gauge meter used to measure the infill depth. The base was pushed through the infill to the backing of the carpet after which the top (black) was slid down to the top of the infill to determine the infill depth

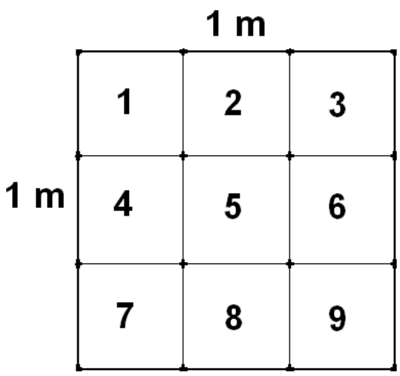

Figure 6.4. Grid used to determine the surface properties. The grid allowed the surface properties to be measured across the sample and provide at least 10 cm between test locations and 10 cm from the side of the test sample as prescribed in the FIFA guidelines.

6.2.3 Materials

With regards to the materials to use for the surface design it was decided in Chapter 3 to use as similar as possible materials in order to minimise differences in the appearance of the different surfaces. Both the surface hardness and rotational traction properties can be modified by making changes to the infill. Infill depth for the hardness and infill bulk density, which is affected by the infill type, size, shape, and infill depth, for the rotational traction (Severn, 2010). The surface hardness can also be modified with the use of a shockpad (Ferris et al., 1998; Meijer et al., 2007; Severn, 2010; Fleming, 2011).

As a base for the surface sample design a surface was selected from a previous study by Severn (2010) that provided detailed information on the materials used as well as information on the rotational traction properties of the surface. Based on this information the choice was made to use a Tiger Turf Soccer Real 50 MS carpet (Appendix D) for all the measurements and modify the surface properties with the help of the infill and shockpads.

For the infill, 0.2 – 0.7 mm silica sand was used as well as two different grades of styrene-butadiene-rubber (SBR) (1 – 3 mm, and 2 – 8 mm) (Figure 6.5). SBR was chosen in §3.3.4 as it is used more commonly in the industry than other types of rubber polymer infill and freely available in different grades. Also, using SBR made sure that the surfaces during the player movement study looked alike. The different grades used affected the appearance somewhat, but this could only be seen through close up examination of the surfaces.

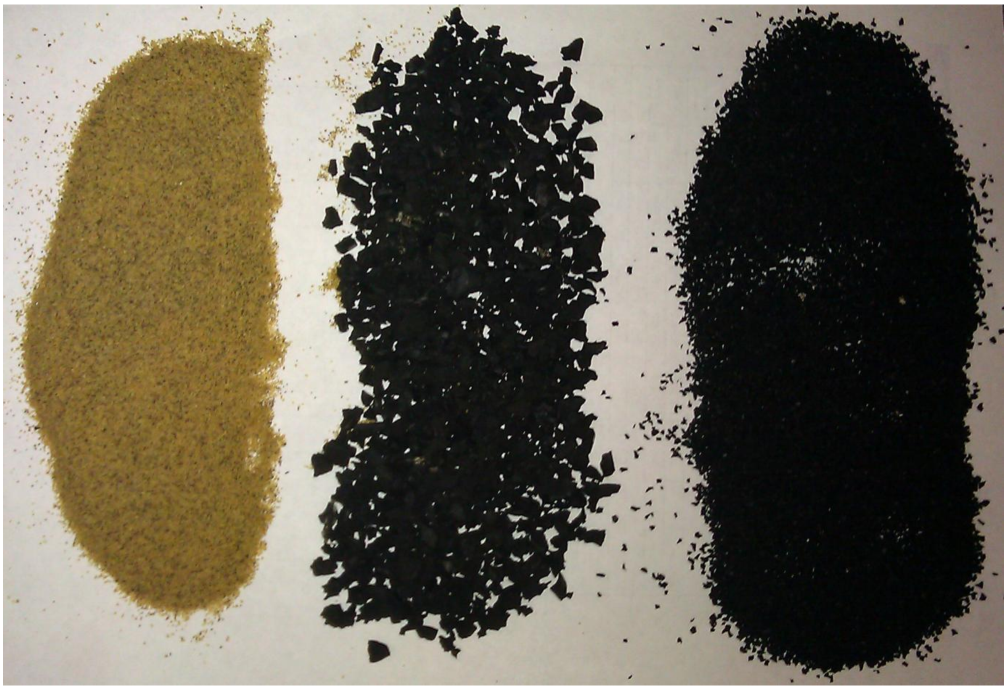

Figure 6.5. Infill materials used to create different surfaces: 0.2 – 0.7 mm silica sand (left), 2 – 8 mm SBR (middle) and 1 – 3 mm SBR (right).

The shockpads used were a rubber granules bound with polyurethane 14 mm thick Regupol® 6010 SP (Berleburger. Germany) shockpad (Appendix D) and a 12 mm thick re-bounce® uni F82.16 (Recticel, Belgium) made of polyurethane flexible foam (Appendix D). Both shockpads were prefabricated, which ensured that the thickness of the shockpads was consistent over the entire surface area. The consistent thickness in combination with the similar material over the entire shockpad also ensured a similar behaviour over the entire surface area.

6.2.4 Surface Sample Design

The first part of the surface design was aimed at manipulating the rotational traction values of the surface, through modifying the infill. The hardness was modified afterwards through the shockpad layer. To modify the rotational traction of the surface different amounts of sand 0 – 22 kg and SBR 0 – 20 kg per square metre were added to the surfaces (Table 6.3). For the SBR different grades were also used. On all surfaces the rotational traction was measured in five locations on the 1 m^2 test samples (location 1, 3, 5, 7, 9 (Figure 6.4)).

Table 6.3. Infill quantities used for surfaces for the eight surfaces used in the rotational traction tests. For all surfaces a 1 x 1 m Tiger Turf Soccer Real 50 MS carpet was used without a shockpad. Surface 1, 3, 5 and 8 were also used in subsequent tests with the AAA and on controlling the surface properties.

Surface	Sand	SBR	Surface	Sand	SBR
1*	*10 kg*	*10 kg, 1 – 3 mm*	**5**	*10 kg*	*12.5 kg, 1 – 3 mm*
2	0 kg	2 kg, 1 – 3 mm	**6**	10 kg	14 kg, 1 – 3 mm
3	*22 kg*	*2.5 kg, 1 – 3 mm*	**7**	10 kg	9 kg, 2 – 8 mm
4	10 kg	0 kg	**8**	*10 kg*	*7 kg, 2 – 8 mm*

* Surface with standard infill quantities based on manufacturing guidelines

The surface with 10 kg of sand and 10 kg of 1 – 3 mm SBR was considered as the standard surface as this met the manufacturer’s guidelines and resembled the surface selected as a base for the rest of the surfaces. In an attempt to modify the rotational traction the amount of sand was modified on three surfaces in combination with little (2 – 2.5 kg) or no SBR (Surface 2, 3 and 4 (Table 6.3)). The rationale behind this was that the bulk density of sand was assumed to be larger than that of SBR due to the smaller grade. Therefore, it was thought that the rotational traction would increase with an increase in sand.

On surface 5 and 6 the quantity of SBR infill was increased, with respect to surface 1 (Table 6.3). The rationale for this was that the of use larger amounts of SBR would cause the infill to be looser and as a result the studs would be able to move more easily through the infill, resulting in lower rotational traction values. For surface 7 and 8 a larger grade of SBR was used in an attempt to reduce the bulk density of the surface and reduce the rotational traction, whereas between surface 7 and 8 different amounts of SBR were used to create a looser infill (Table 6.3). Compared to the standard surface, surface 7 had a similar SBR weight (9 kg versus 10 kg), whereas surface 8 had a similar infill depth.

After selecting surfaces from the rotational traction tests, the effect of a shockpad was firstly tested on the standard surface (surface 1) to examine which of the available shockpads had the largest effect on the FR. The measurements with the AAA were taken in five locations (location: 1, 3, 5, 7, 9 (Figure 6.4)). After establishing the effect of the different shockpads, the shockpad with the largest difference in FR between the condition with and without a shockpad was selected for measurements in combination with the other surfaces selected from the rotational traction.

6.2.5 Maintaining Surface Properties

An important aspect for the player movement study was controlling the surface properties to ensure that the properties would remain consistent over the entire test period. To investigate what methods would be necessary to control the surface properties during the player movement test several tests were conducted in an attempt to disturb or condition the surfaces in a manner similar to what they would be exposed to in the player movement study. This was done with the help of a hand pulled roller, repeated impacts (with the AAA and human impacts), and moving the surface samples across the floor.

The hand pulled roller was used to condition the surface. This is required in the FIFA guidelines and a previous study by Severn (2010) found that the infill depth of a surface decreases, and the bulk density increases, with increasing number of rolls. As the literature review showed that the infill depth and bulk density can affect the surface properties it was expected that the surface properties would change as a result of the rolls.

The roller had a weight of 30 ± 0.5 kg, a diameter of 118 ± 5 mm and studs mounted on it in a specific pattern (Figure 6.6). For the tests the same definition of a cycle was used as in the FIFA guidelines, namely: “one cycle comprises one outward and one return path” (FIFA, 2012b). The effects of rolling on the rotational traction were tested on surface 1 and 5 (Table 6.3). These surfaces were selected to investigate if the rolling had a different effect on surfaces with a different rotational traction. The choice to do this only on surfaces with the 1

– 3 mm SBR was made as it was assumed that compaction would have a larger effect on the smaller grade of SBR. Rotational traction and infill depth measurements were taken at 0 and 50 cycles in location 1, 7, 9 of the test grid (Figure 6.4). The 50 cycles were selected as this is the minimum set by FIFA (FIFA, 2012b).

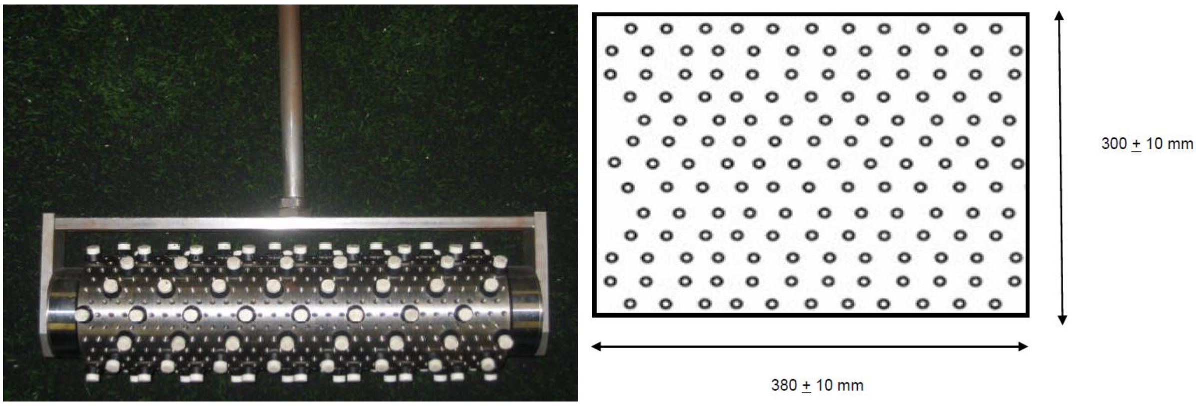

Figure 6.6. Studded roller (left) used in FIFA guidelines to condition the surfaces to simulate the use of the surface. The studs are placed on the roller in a specific pattern (right) (FIFA, 2012b)

The effects of rolling on the FR were tested on surface 1 in combination with the Recticel shockpad (Table 6.3). AAA and infill depth measurements were taken at 0, 50 and 100 cycles in location 4, 5, 6 of the test grid (Figure 6.4). The extra 50 cycles on top of the minimum set by FIFA was chosen as it was expected that the FR would be more sensitive to changes in infill depth than the rotational traction.

The goal of the repeated impact tests was to disturb the surface in a small area, as during the player movement study the movements would also be performed in a small area (i.e. on a force platform). The effects of the repeated impacts on the rotational traction and FR were investigated with different tests on the standard surface (surface 1 (Table 6.3)). For the rotational traction the test involved a subject (100 kg) hopping across the surface on flat trainers with two feet to compact the surface with a vertical component and move the infill with a horizontal component. Furthermore, the pathway across the surface would provide different test locations (4, 5, 6 (Figure 6.4)), which would be wide enough for the rotational traction device due to the two footed hops (Figure 6.7). The infill depth was measured in the same locations. The hops across the surface were 3 – 4 cm high and with each hop the subject progressed approximately 5 cm forward during which the entire foot of the subject made contact with the surface. One hopping cycle was defined as the outward path, making the return path the second cycle.

The rotational traction and infill depth were measured at 0, 10, 30, 60, and 100 cycles to investigate how the increments in impacts affected the rotational traction properties.

Following each measurement the surface was restored by redistributing the infill by light brushing in order to make the surface level. This was followed by another measurement in the same locations to investigate the effects of redistributing the infill.

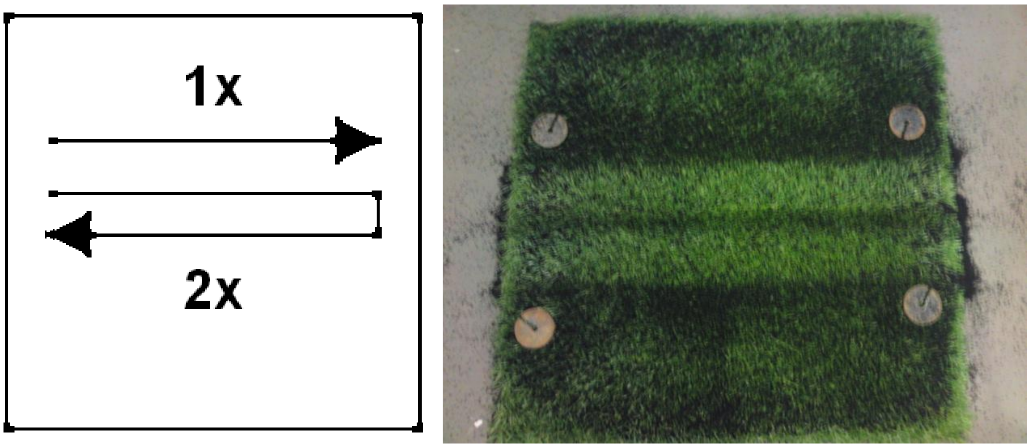

Figure 6.7. Example of two hopping cycles (left) and hopping path on surface (right) for the test with the rotational traction device.

The repeated impacts to investigate the effects on hardness were constrained to a smaller area and involved both a subject in flat trainers hopping, 3 – 4 cm high, on one leg to resemble a human impact, and repeated impacts with an AAA to have standardised impact conditions. For the human impact test the subject hopped for a total of 90 repetitions in the same location on the standard surface (surface 1 (Table 6.3)) with the Recticel shockpad, with FR and infill depth measurements being taken at 0, 10, 20, 30, 40, 50, 70 and 90 hops. During the first 50 hops the surface was not restored to gain insight into the change of infill depth and the effect this had on the FR. After the 50 hops the surface was restored with similar light brushing as for the rotational traction test, after which the infill depth and FR was measured again. The 2 x 20 hops after this were done to investigate if the change in surface properties would be similar after restoring the surface as at the start of the test.

For the test with the AAA, surface 1 and surface 8 (Table 6.3) were used in combination with and without the Recticel shockpad. This test involved a total of 27 repeated impacts in the same location, which resembled nine tests following the FIFA procedures. The number of repeated impacts is substantially less than the 90 impacts of the human, but as the impact was in exactly the same location fewer impacts were deemed necessary, also as the AAA would provide continuous feedback on the changes in FR. After 18 impacts the surfaces were restored, the infill depth measured and another 9 impacts were performed to investigate if the change in surface properties would be similar after restoring the surface as at the start of the test. The surfaces were restored only once as it was assumed that the four different surfaces would provide sufficient knowledge on how well the surfaces could be restored, and how they respond after redistributing the infill with light brushing.

The final test for controlling the surface properties involved moving the surface samples across the floor. This test was performed as moving the surfaces was a necessary part of the player movement study to modify the surface conditions during the test sessions. The main concerns for moving the surfaces were: sand infill coming out at the bottom of the carpet, as there are holes in the carpet to help the drainage of the pitch; and both sand and rubber infill coming out from the sides. The test was performed with a standard surface (surface 3 (Table 6.3)), which was moved across the floor in a straight line for 0, 1, 1.5, 3, and 6 m, making a total of 11.5 m. To move the surface the test sample was lifted approximately 2 cm on the side to which it would be moved and then pulled smoothly across the floor in an effort to keep the disturbance of the surface to a minimum. Following each move the rotational traction was measured at three locations on the surface (location 1, 5 and 9 (Figure 6.4)) and the infill depth in five locations (location 1, 3, 5, 7 and 9 of Figure 6.4) to determine if the infill depth had changed across the test sample during movement. The FR was not measured as it was assumed that the rotational traction and infill depth would provide sufficient insight in any disturbances in the surface properties.

6.3 Results

6.3.1 Rotational Traction and AAA Surface Sample Design Tests

During the rotational traction test, values between 21 and 61 Nm were obtained with the different quantities and grades of infill (Table 6.4). The standard surface with 10 kg sand and 10 kg 1 – 3 mm SBR had an average rotational resistance of 38 Nm. Increasing the amount of SBR as well as using a larger grade of SBR led to a decrease in the rotational traction values. Increasing the amount of sand in the surface increased the rotational resistance substantially. The infill depth of the surfaces varied with the amount of infill, with the quantities and grades of SBR having the largest effect on the infill depth. Of the eight surfaces surface 1, 3 and 8 were selected to be tested with the AAA as these created a large range of rotational traction values while keeping the infill depth, and thus the appearance, the same (Table 6.4).

The AAA test for the different shockpad conditions showed that the use of a shockpad increases the FR values substantially. The difference in FR between the surface without and with a shockpad was approximately 13 – 15% (Table 6.5). A small difference was found between the two shockpads for the FR (2%). Overall the largest difference existed between the surface without a shockpad and the surface with the Recticel shockpad. Therefore the Recticel shockpad was selected to be used in the further tests. The average infill depths of all three conditions were similar.

Table 6.4. Results of the rotational traction test on surfaces with different quantities of infill and different grades of SBR (Average + SD of 5 locations).

Surface	Sand (kg)	SBR (kg)	SBR (Grade mm)	Rotational Traction (Nm)	Infill depth (mm)
1*	10	10	1 – 3	38.0 ± 1.9	30.6 ± 0.8
2	0	2	1 – 3	21.2 ± 1.4	10.5 ± 0.4
3*	22	2.5	1 – 3	61.3 ± 2.3	29.7 ± 0.6
4	10	0	–	40.8 ± 6.4	11.1 ± 1.4
5	10	12.5	1 – 3	32.6 ± 2.6	36.6 ± 1.0
6	10	14	1 – 3	30.0 ± 1.2	39.0 ± 1.0
7	10	9	2 – 8	27.2 ± 1.7	39.4 ± 0.4
8*	10	7	2 – 8	29.3 ± 1.2	31.4 ± 0.5

* Surfaces selected for AAA test

The comparison test of the three surfaces selected during the rotational traction test showed the surface with 22 kg of sand had substantially lower FR values compared to the other two surfaces with the shockpad (Table 6.6). As a result, the choice was made not to measure surface 3 without a shockpad. The other two surfaces, both with and without the shockpad, had similar FR values. The average infill depth was similar for all surfaces.

Table 6.5. Results on effect of different shockpad conditions on AAA results (Average ± SD of 5 locations). For all conditions a surface with a standard infill (10 kg sand; 10 kg 1 – 3 mm SBR) was used.

Surface	Shockpad	Force Reduction (%)	Infill depth (mm)
1	**None**	54.2 ± 2.0	30.3 ± 0.7
	Berleburger	67.2 ± 0.3	30.3 ± 0.3
	Recticel	69.3 ± 1.2	30.7 ± 0.7

Table 6.6. Results of AAA measurements on surfaces selected after testing with the rotational traction device (Average ± SD of 5 locations). All surfaces were measured in combination with a Recticel shockpad. Surface 1 and 8 were also measured without a shockpad.

Surface	Sand (kg)	SBR (kg)	SBR (Grade mm)	Shockpad	Force Reduction (%)	Infill depth (mm)
1	10	10	1 – 3	No	52.3 ± 1.8	30.0 ± 0.5
				Yes	68.7 ± 0.6	30.6 ± 0.3
3	22	2.5	1 – 3	Yes	58.5 ± 0.6	29.7 ± 0.6
8	10	7	2 – 8	No	51.5 ± 1.6	30.7 ± 0.6
				Yes	68.0 ± 0.9	31.4 ± 0.5

Based on the results of the rotational traction and AAA test four surfaces, surface 1 and 8 with and without a shockpad, were selected to be taken forward to the player movement study (Table 6.7). These four surfaces met the set objectives and two had a difference in rotational traction, while maintaining a similar hardness, and two had a difference in hardness, while maintaining a similar rotational traction. Furthermore, all four surfaces had a similar infill depth ensuring a similar appearance.

Table 6.7. Surfaces selected to be taken forward to the player movement study. The surfaces with a different hardness maintained similar rotational traction properties, whereas the surfaces with a different rotational traction maintained similar hardness properties.

Properties		**High traction**	**Low traction**
		38 Nm	**29 Nm**
Hard (No shockpad)	**FR: ~ 52%**	Sand: 10 kg SBR: 10 kg 1 – 3 mm	Sand: 10 kg SBR: 7 kg 2 – 8 mm
Soft (Shockpad)	**FR: ~ 68%**	Sand: 10 kg SBR: 10 kg 1 – 3 mm	Sand: 10 kg SBR: 7 kg 2 – 8 mm

6.3.2 Maintaining Surface Properties

6.3.2.1 Rolling

Rolling the surfaces had a limited effect on the rotational traction and infill depth. The average infill depth decreased 1.3 – 1.7 mm on both surfaces (Table 6.8). The average rotational traction decreased 1.6 Nm on surface 3, but on surface 4 no change in rotational traction was present before and after rolling.

For the AAA results the FR values reduced by 1.3% over the 100 rolls (Table 6.9). The infill depth decreased on average by 1.9 mm after 50 rolls and stayed at a similar level after 100 rolls.

Table 6.8. Effect of rolling the surface for 50 cycles on the rotational traction values and infill depth of the surface (Average ± SD of 3 locations).

Surface	**Sand (kg)**	**SBR (kg)**	**SBR (Grade mm)**	**Rolling (Cycles)**	**Rotational Traction (Nm)**	**Infill depth (mm)**
1	10	10	1 – 3	0	38.0 ± 1.9	30.6 ± 0.8
				50	36.4 ± 2.3	28.8 ± 1.4
5	10	12.5	1 – 3	0	32.6 ± 2.6	36.6 ± 1.0
				50	32.4 ± 2.3	35.3 ± 1.2

Table 6.9. Effect of rolling the surface for 50 and 100 cycles on AAA results and infill depth (Average ± SD of 3 locations). Measurements were taken on a surface with standard infill quantities (10 kg sand; 10 kg 1 – 3 mm SBR) and with a Recticel shockpad

Rolling (Cycles)	Force Reduction (%)	Infill depth (mm)
0	69.5 ± 1.0	31.6 ± 1.0
50	68.8 ± 0.8	29.7 ± 0.7
100	68.2 ± 1.0	29.7 ± 0.3

6.3.2.2 Repeated Impacts

During the hopping cycles the rotational traction values decreased in all three locations with an average decrease of 3 Nm (Figure 6.8A). Over the 40 hopping cycles the average infill depth decreased from 31 mm to 27 mm (Figure 6.9). Restoring the surfaces by redistributing the infill with light brushing after the hopping cycles restored the rotational traction to similar values as at the start of the test (Figure 6.8B).

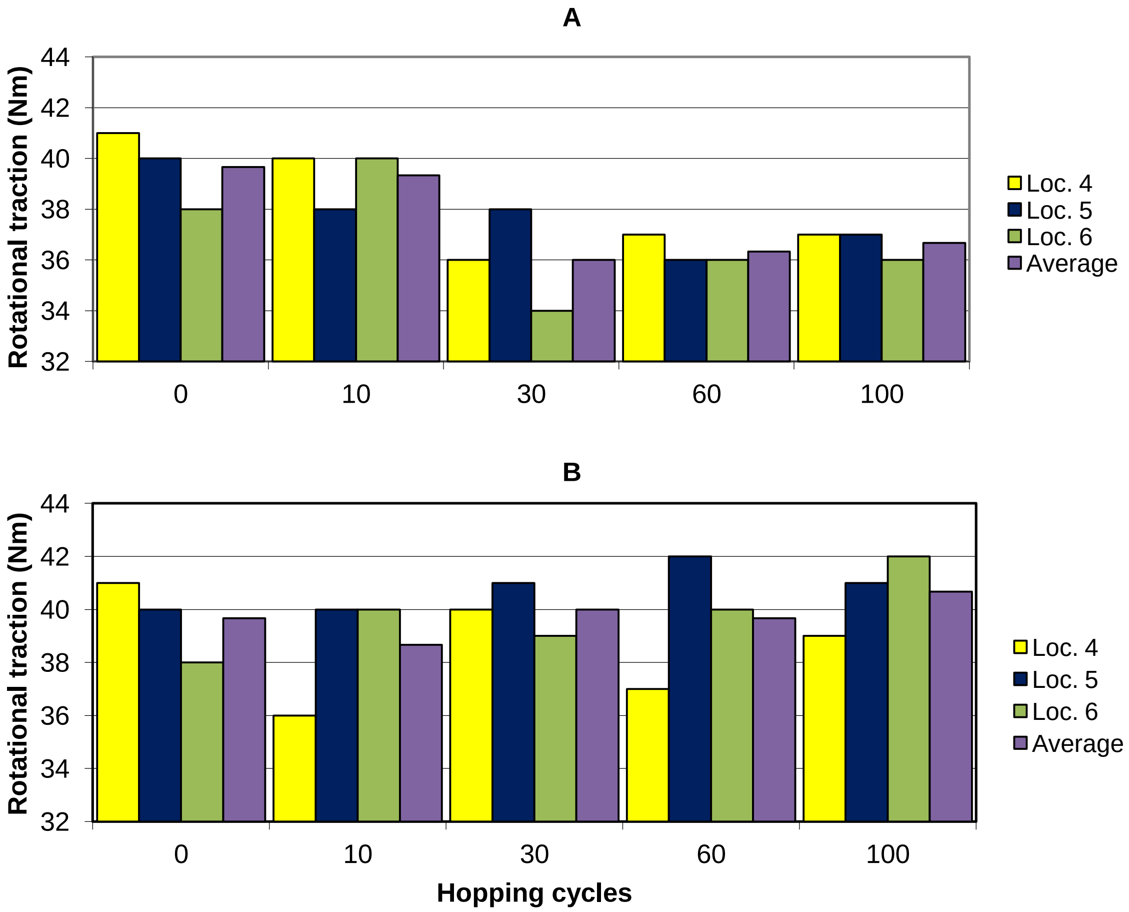

Figure 6.8. Effect of hopping cycles on rotational traction values (A) and rotational traction values after the surface was restored by redistributing the infill with light brushing (B).

During the hopping test in a single location the FR gradually decreased by 4% after 50 hops (Table 6.10). The infill depth decreased over 7 mm during the 50 hops. After restoring the surface by redistributing the infill with light brushing all properties were restored close to the start values. The FR values were even 2% higher after restoring than at the start of the test. After restoration the properties changed in a similar pattern as during the hops at the start of the test.

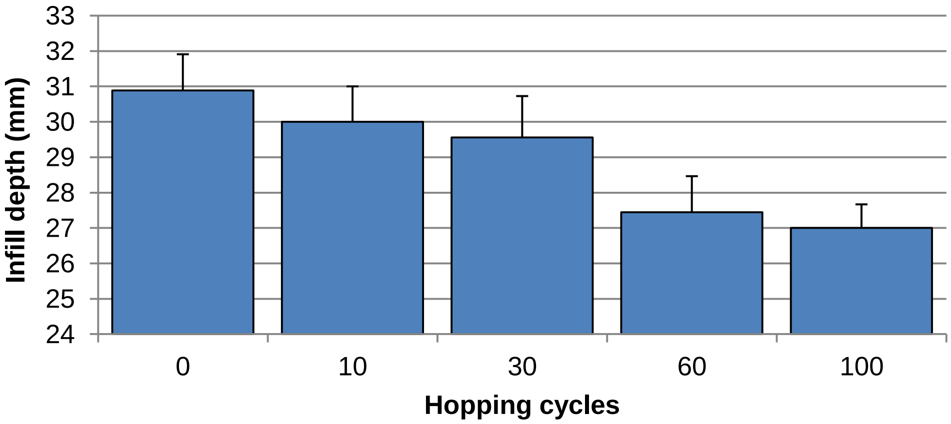

Figure 6.9. Effect of hopping cycles on the average infill depth of the surface

Table 6.10. Effect of repeated impacts by hopping on AAA results and infill depth of surface. Surface was restored by light brushing after 50 hops.

Hops	**Force Reduction (%)**	**Infill Depth (mm)**
0	66.5	30.0
10	65.0	30.0
20	64.5	25.7
30	64.0	25.0
40	63.0	24.3
50	62.5	23.7
Restored	68.5	30.3
20[1]	66.5	30.3
40[2]	65.0	27.7

1= 70 hops in total 2= 90 hops in total

The repeated impacts with the AAA affected the FR more on the surfaces without the shockpad than the surfaces with a shockpad (Table 6.11). The infill depth of the surfaces decreased up to 6.4 mm during the first 18 impacts (Table 6.11). Restoring the surface by redistributing the infill by light brushing after 18 impacts brought the FR and infill depth of all four surfaces close to the start values. After restoring the surface the properties responded in a similar way as during the first impacts.

Table 6.11. Effect of repeated impacts with the AAA on the force reduction results on two different surfaces both with and without shockpad. Surfaces were restored by light brushing of the SBR infill after 18 impacts.

Impact	Force Reduction (%)				Infill depth (mm)			
	1 – 3 mm SBR		2 – 8 mm SBR		1 – 3 mm SBR		2 – 8 mm SBR	
	No	Shockpad	No	Shockpad	No	Shockpad	No	Shockpad
1-3	50.5	69.5	51.5	66.5	29.3	30.3	30.7	31.0
4-6	49.5	69.0	50.0	64.5	26.0	28.0	27.3	27.0
7-9	48.0	68.0	48.0	65	25.3	27.0	26.0	26.3
10-12	47.0	68.0	48.0	64.6	24.0	26.0	25.3	25.3
13-15	46.5	67.5	47.0	64.0	24.0	24.7	24.3	24.7
16-18	45.5	68.0	48.0	64.0	23.3	24.0	24.3	24.7
Surfaces restored								
19-21	48.5	69.5	51.0	67.5	29.3	30.0	30.3	31.7
22-24	47.0	68.0	48.5	66.0	25.3	28.0	26.0	27.0
25-27	46.5	68.0	47	65.5	24.3	26.3	25.3	26.3

6.3.2.3 Surface Movement

During the movement test small changes were found for both the rotational traction values and the infill depth with maximum average differences of 2.3 Nm and 1.5 mm (Figure 6.10). The changes, both for the rotational traction and infill depth, were within the expected measurement uncertainty of the equipment (§6.2.2).

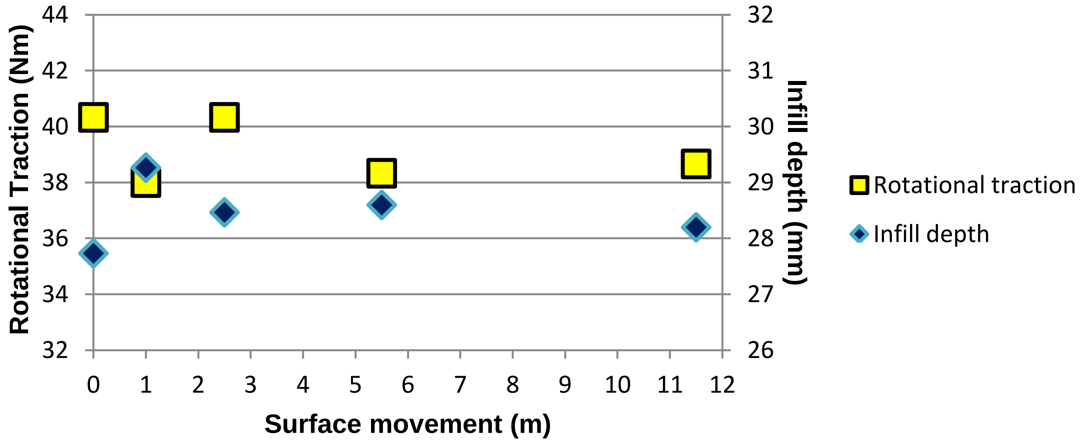

Figure 6.10. Results for the rotational traction values and infill depth of the surface when moving the surface across the floor of the lab.

6.4 Discussion

The main aim of this study was to create four surfaces with specific rotational traction and hardness properties for use in the player movement study. For this the surfaces with a difference in rotational traction were required to have similar hardness properties, and the surfaces with a difference in hardness were required to have similar rotational traction properties.

The secondary aim was to investigate how to maintain the surface properties during testing so there would be no appreciable change when the surfaces are disturbed by player movement, mechanical tests or by moving the surface itself. During the different tests to disturb the surfaces the surfaces were restored close to their original values by redistributing the infill by light brushing. Moving the surfaces had no substantial effect on the surface properties.

6.4.1 Surface Sample Design

During the design phase four different surfaces were designed for use during the player movement study (Table 6.7). Two surfaces had a different hardness, while maintaining a similar rotational traction, and two had different rotational traction values, while maintaining a similar hardness. In addition to this, the infill depth of the four surfaces were similar ensuring a similar appearance and as the surface properties were close to the limits of the standards set by FIFA it was assumed they are safe for use during the player movement study.

The rotational traction properties were modified by using different amounts and ratios of sand and SBR infill, as well as different grades of SBR. The hardness of the surfaces was mainly modified by using a shockpad, but the infill also had an influence on the FR. For the rotational traction the particle size and quantity of the infill and infill depth were the main factors that determined the rotational traction properties of the surfaces. Comparing surfaces with a similar infill depth (surface 1, 3 and 8) showed that the highest rotational traction was found on the surface with more than double the amount of sand (surface 3), which has the smallest particle size. The lowest rotational traction was found on the surface with the largest SBR grade (surface 8). While surface 1 and 8 also contained 10 kg of sand, the infill depth of surface 4 showed that that the sand only comprised the first ~11 mm of infill. Therefore the studs of the test device would not be in contact with the sand as the remaining ~ 20 mm is more than the stud length of 11 mm. The change in rotational traction between these surfaces therefore seems to be related to the bulk density, caused by the different infill type and size which has been identified in previous research to affect the bulk density (Severn, 2010).

In addition to the different grades the infill depth also influenced the rotational traction. For surfaces with more SBR infill the rotational traction gradually decreased. With an infill depth of ~ 39 mm the rotational traction of the surfaces with 1 – 3 mm SBR decreased approximately 8 Nm compared to the standard surface with an infill depth of ~30 mm. The same effect was found on the surfaces with 2 – 8 mm SBR which decreased with approximately 2 Nm when the infill depth increased to ~39 mm. As the particle size remained the same on these surfaces it is thought that this change is caused by the infill being looser on the top of the surface when the infill depth gets closer to the pile height of the carpet (50 mm). This causes the infill to move around more easily when the test foot is rotated, leading to a lower rotational traction. A similar effect was found in a previous study on second generation sand filled artificial turf, which reported that the rotational traction decreased, and the infill produced less resistant to movement with an increased infill depth (James & McLeod, 2008). Based on the rotational traction results surface 1, 3 and 8 were selected to be taken forward to the AAA test as they covered a range (29.3 – 61.3 Nm) of rotational traction values and the similar infill depth ensured a similar appearance.

The results with the AAA on the three selected surfaces showed that the surfaces with similar infill depths of sand (~10 mm) and SBR (~20 mm) resulted in similar FR values (surface 1 and 8). That the FR values of surface 1 and 8 were similar was unexpected as it was thought that the ability of the SBR to compress was more dependent on the amount of SBR (mass) than on the volume of SBR. However, this did mean that the appearance of the different surfaces would be the same while the hardness and rotational traction properties were manipulated. The hardness of the surfaces was manipulated with the use of the Recticel shockpad. This meant that both surface 1 and 8 had a FR of ~52% without the use of a shockpad and a FR of ~68% with the use of a shockpad, which in both cases was near the limits of the FIFA one star qualification (55 – 70%). The FR of surface 3 was substantially lower (~10%) than the other two surfaces with a shockpad and was therefore not included in the further tests. This is caused by the large amount of sand infill in this surface (22.5 kg), which is not compressible like the SBR.

Apart from creating four different surfaces for the player movement study an important outcome also was that the measurements both of the AAA and the rotational traction device were repeatable across the test sample. For both types of measurements the standard deviation across the measurements was within the 2% and 2 Nm expected measurement uncertainty (FIFA, 2012b). With regards to the player movement study this means that measurements can be taken in fewer locations under the assumption that the surface with similar infill ratios and with or without a shockpad will behave in a similar manner across the entire surface. This will save time as fewer measurements have to be taken and has the advantage that the surface will be disturbed less by the measurement equipment.

Concluding from this, the aim of the design phase to create four surfaces, two with different rotational traction properties, while maintaining a similar hardness, and two with different hardness properties, while maintaining a similar rotational traction has been met (Table 6.7). The hardness of the surfaces covered the limits of the FIFA one star qualification, whereas the rotational traction of the surfaces covered a large part of the FIFA two star qualification. The hypotheses on the effects of these surface properties on the movement dynamics and human loading during the player movement study are presented in §3.5.1.

6.4.2 Maintaining the Surface Properties

The aim of the surface maintenance tests was to investigate how to maintain the surface properties during testing so there would be no appreciable change when the surfaces are disturbed by player movement, mechanical testing or by movement of the surface itself. This was investigated with three different tests in an attempt to disturb and condition the surface and one test during which the surface was moved across the floor. The repeated impact tests managed to disturb the surface properties substantially with changes for the rotational traction, FR and infill depth. Redistributing the infill through light brushing made it possible to recover the properties to the original values. In the tests with the studded roller to condition the surface and moving the surfaces across the floor, the change in properties were limited.

The repeated impacts by hopping across the surface caused the rotational traction to drop by an average of 3 Nm after a total of 100 cycles. While this is close to the expected measurement uncertainty of 2 Nm the fact that the decrease was present in all three locations suggests that the decrease was caused by the hops, rather than the measurement device. The repeated impacts by hopping on the surface and AAA impacts caused the FR to drop 4% after 50 hops, and on average 3% (on all four surfaces) after 18 impacts. During the impact tests the infill depth of the surface decreased from 3.9 to 6.3 mm. This suggests that the infill of the surface compacted as a result of the hops and the AAA impacts. For the rotational traction measurements a possible mechanism may have been that it was harder for the studs to penetrate the compacted infill, causing less infill to grip the studs and reducing the rotational traction. With regards to the FR the ability of the infill to compress during impact will have decreased, leading to a harder surface.

During all impact tests it was possible to restore the surface properties to the original values by redistributing the infill with light brushing. Furthermore the infill depth and FR responded in a similar manner after restoring the surface as at the start of the test. In addition to this a comparison between the hopping test and the repeated impacts with the AAA showed that during both tests a 6.3 mm decrease in infill depth led to a similar decrease in FR (3 – 4%). The observation that the FR decreased in a similar manner during separate tests with a similar decrease in infill depth, and that restoring the infill depth to the original values also restored the FR and rotational traction to their original values suggests that the infill depth is a good precursor for the amount of disturbance and change in surface properties. Using the infill depth as a precursor for the change in surface properties during the player movement study had the advantage that fewer measurements would be needed with the AAA and rotational traction device, saving time and avoiding the surfaces to be disturbed by the test equipment. However, measuring the rotational traction and hardness of the surface would still be required on a regular basis to ensure that surface properties remain at a similar level throughout the test period.

As due to player movement the infill depth could decrease by infill being lost from the surface a target value was determined with the help of the control results. This value was set at 2 mm, as for both the FR and rotational traction the change was within the expected measurement uncertainty when the infill depth decreased with 2 mm. Therefore if the infill depth on average changed more than 2 mm across the surface it was topped up to the original levels to ensure similar surface properties.

Of the remaining tests, rolling the surface and moving the surface across the floor had limited effects on the surface properties. The change in infill depth was limited to an average change of 1.7 mm, whereas the rotational traction changed 0.9 Nm and the FR 0.7% after 50 rolls and 0.6% after 100 rolls. These results are quite different compared to a previous study by Severn (2010) which found increases in FR and rotational traction after 50 rolls, with the rotational traction increasing by up to 6 Nm. Also, after 100 rolls the infill depth on average decreased by 6 mm, whereas in this study the infill depth did not change more than 1.7 mm. A possible explanation for this is that in the study by Severn (2010) the surfaces were raked at the start of the test, which has not been done in this study. This may have caused the infill in the surface to be looser at the start of the test and therefore affect the properties and making the infill more sensitive to rolling the studded roller. Despite the difference in results the main outcome is that the effect of rolling on the surface properties was limited. Also, the repeated impact tests showed that the surfaces behaved consistently and could be restored to their original values with light maintenance without being conditioned with the studded roller, making conditioning the surfaces with the studded roller during the player movement study not necessary.

Moving the surface across the floor had no effect on the infill depth. The rotational traction decreased a maximum of 1.7 Nm overall. However, as the change in rotational traction was not consistent during the movement and the 1.7 Nm was within the expected measurement uncertainty it was concluded that moving the surfaces across the floor had no effect on the surface properties. Therefore the surfaces could be moved during the player movement study with the assumption that the properties did not change.

6.5 Conclusions

During the design phase the goal was met to create four different surfaces with two different hardness values, while maintaining a similar rotational traction, and two different rotational traction values, while maintaining a similar hardness (Table 6.7). The FR values of the surfaces cover the limits of the FIFA one star qualification, whereas the rotational traction values cover a large part of the FIFA two star qualification. As a result, using these surfaces for the player movement studies provided insight in how the FIFA standards affect the human dynamics during soccer relevant movements. That the surface properties were close to the limits of the FIFA standards ensured they are similar to the conditions soccer players are typically exposed to and therefore do not create an added injury risk. Furthermore, the appearance of the four surfaces was similar due to the materials used and equal infill depth.

The design phase showed that the traction of a surface can be modified by changing the grade and quantities of the infill. For which at a similar infill depth a lower grade increased the traction and a higher grade lowered it. Regarding the FR the tests showed that the FR values of surfaces with a similar infill depth, but different grade, were similar, despite the mass of the infill being different. This indicated that the infill depth of the SBR had a greater effect on the FR than the mass of the SBR. The maintenance tests showed that during the player movement study the surfaces can be maintained by redistributing the infill with light brushing and that the infill depth can be used as a precursor of changes of the surface properties. As a consequence the surfaces can be monitored during the player movement study by measuring the infill depth regularly, meaning that rotational traction and FR measurements can be taken less frequently assuming that the surface properties are equal with a similar infill depth. Finally the tests showed that the surfaces in the player movement study can be moved across the floor without disturbing the surface properties.

6.6 References

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7. PLAYER MOVEMENT STUDY

7.1 Introduction

In the literature review (Chapter 2) several gaps of knowledge were identified concerning the movements and surfaces used in previous studies. These helped form the base for the research philosophy in Chapter 3. From the player focus group and questionnaire (Chapter 4) the stop and turn and stop-jump, including related in-game scenarios (a simulated opponent and heading a ball) were selected for this player movement study. Furthermore, four different surfaces were designed (Chapter 6) with different hardness and rotational traction values.

This chapter addresses objective 5 of this thesis (Chapter 1) which involves measuring the effects of controlled surface properties and the effect in-game scenarios on player kinematics and loading during selected soccer movements. This chapter first presents the methods used to collect data on the effects of different surface conditions and in-game scenarios on human movement dynamics during a stop and turn (ST) and a jumping / heading (JH) manoeuvre, followed by the results obtained from this player movement study, which are used in Chapter 8 to answer hypotheses formulated in Chapter 3.

7.2 Methodology

7.2.1 Subjects

Sixteen male players were recruited from the first, second and third Loughborough University soccer teams. The choice was made to recruit the players from these teams as this ensured that the players had a good level and experience (>10 years) in playing soccer, and the players would already be able to perform the required movements in a natural and consistent way. Furthermore, it also ensured that the players had experience with playing on artificial turf as there were two artificial turf pitches on campus on which the players train multiple times per week.

The recruited players were on average 20 ± 1 years old, had an average body mass of 74.7 ± 6.6 kg, and an average height of 178.0 ± 4.8 cm. The average overall playing experience of the players was 13.6 ± 2.1 years and 6.4 ± 3.7 years of playing on artificial turf. The exposure of the players during a season was 6.0 ± 2.7 hours of training and 2.2 ± 2.3 hours of playing recreationally per week (Table 7.1). Furthermore, they played on average

6.6 ± 2.3 matches per month, of which the majority were played on natural grass. All participants signed an informed consent form and declared to be free of any major injuries for at least 6 months prior to the test. Ethical clearance was gained from Loughborough University Ethical Advisory Committee.

Table 7.1. Detailed overview of exposure of all 16 participants in test per surface type (Mean + SD)

Exposure	Natural grass	Artificial turf
Training (hours / week)	1.1 ± 1.6	4.9 ± 1.8
Matches (per month)	5.2 ± 2.3	1.4 ± 1.5
Recreational (hours / week	0.7 ± 1.1	1.5 ± 1.4

7.2.2 Lab Set-up

The lab set-up involved the runway, with the ability to change the surface conditions, and the data collection methods to collect biomechanical data as determined in Chapter 3. The set-up for the runway and the data collection methods are discussed in the following sections.

7.2.2.1 Runway

The complete runway used was 12 m long and 1.5 m wide and divided into four sections: run-up area (1), pre-movement area (2), force platform area (3), and extra area (4) (Figure 7.1). Of these, areas (2), (3) and (4) were used for both movements, whereas the run-up area was only used for the ST.

To alter the surface conditions only section (2) and (3) of the runway were changed during the test (Figure 7.1). This meant that the properties of section 1 of the runway were different to the area in which the ST and JH manoeuvres had to be performed. However, in Chapter 3 it was discussed that this should not to be a problem as a previous study on running showed that humans are able to adjust their movement dynamics for their first step on a new surface (D. Ferris et al., 1999). It was assumed that in the 2.1 m long section (2) the players would have to make at least two steps while decelerating, giving them sufficient space to adjust before making the stop and turn on top of the force platform.

The properties of the extra area behind the force platform were also different to the pre-movement and force platform area. The purpose of this area was only to provide an area with artificial turf in case the subjects were not able to perform the movements on the force platform(s) and to provide an area for the simulated opponent in the in-game scenario.

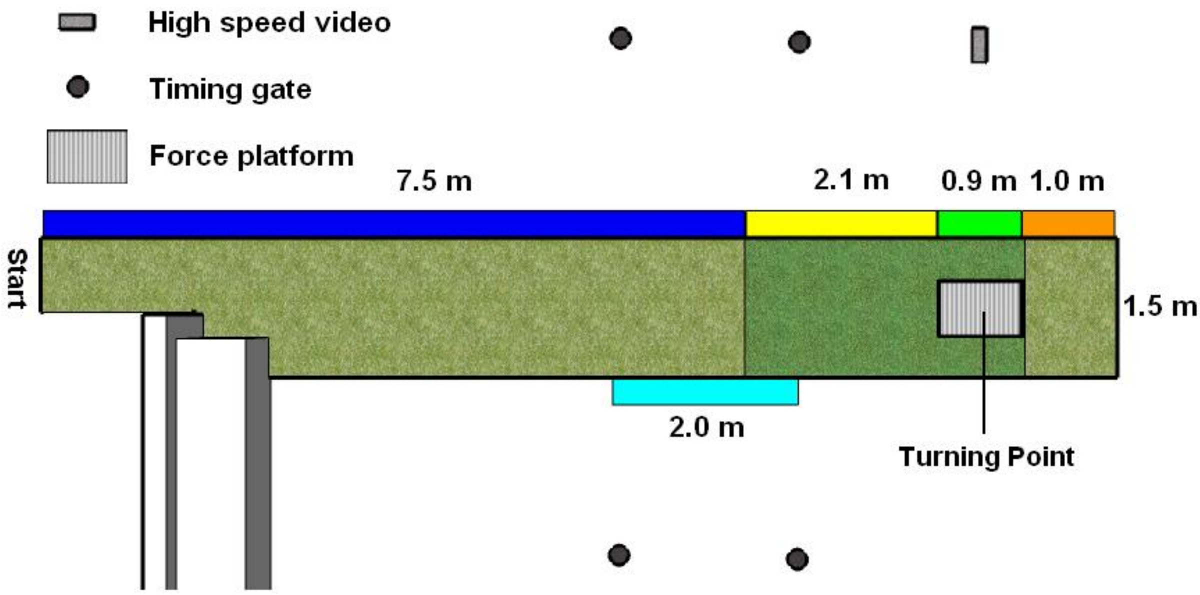


Figure 7.1. Scaled overview of set-up for biomechanical tests of runway, large force platform, timing gates and high speed video. The run-way was divided into four sections: (1) an 7.5 m run-up area (blue), (2) 2.1 m pre-movement area (yellow), (3) 0.9 m force platform area (green) and (4) 1 m extra area (orange). The surfaces in the pre-movement area and force platform area, highlighted in dark green, were changed in a randomised order in each test session to modify the surface conditions. For the ST timing gates were used over a 2 m long area to measure the approach speed of the players (cyan).

7.2.2.2 Data Collection

In chapter 3 the choice was made to use a Vicon 3D motion analysis system (Vicon, Oxford, United Kingdom) to track the movements of the players, and in Chapter 5 the choice was made to use the force platforms to collect the ground reaction force (GRF) data. In addition to this timing gates were used during the ST to monitor the approach speed of the players, whereas a high speed video camera was used to get detailed feedback on the contact of the foot with the surface during the ST.

The Vicon 3D motion analysis system consisted of 12 cameras (MX T20 and MX T40, 500 Hz) that were positioned to cover the force platforms and surrounding area where the subjects had to perform the movements (Figure 7.2). Eleven of these were mounted on rails on the ceiling of the lab and could be moved around to get the best possible positions. The final camera was placed on a tripod on the ground to increase the probability that all body markers were tracked during the turning and flexing of the upper body during the ST (Figure 7.3, Figure 7.4). The global axes of the Vicon system are presented in Figure 7.2-7.4.

The force platforms (Kistler Instrument AG, Winterthur, Switzerland) were located in the middle of the runway (Figure 7.2). This allowed for enough space to the sides for the players to move freely, which was mainly relevant for the ST as while the players were required to make a 180° turn as it was thought that a limited turning space may lead to an unnatural movement. In Chapter 3 the choice was made to use the large force platform (0.9 x 0.6 m, 9287 BA, 1000 Hz) during the ST as its location allowed for a longer runway and its size would reduce the risk of the players aiming to land on the force platform. The large force platform did have the disadvantage that only the final step of the ST could be measured, but the run-up space towards the small force platforms was considered too short for the players to accelerate and decelerate for the ST. For the JH the choice was made in Chapter 3 to use the combination of the large and small (0.6 x 0.4 m, 9281 CA, 1000 Hz) force platform as this created the largest surface area for both feet to land. The coordinates of the force platform are presented in Figure 7.5.

The high speed video camera (Fastcam Ultima APX, Photron, USA, 125 Hz) was aimed to the side of the force platform at a distance of approximately 2 m for additional feedback on what happened at the shoe surface interface (Figure 7.2-7.4). This was mainly important for the ST manoeuvre to get insight into the landing of the foot and a qualitative estimate of the amount of foot rotation during ground contact.

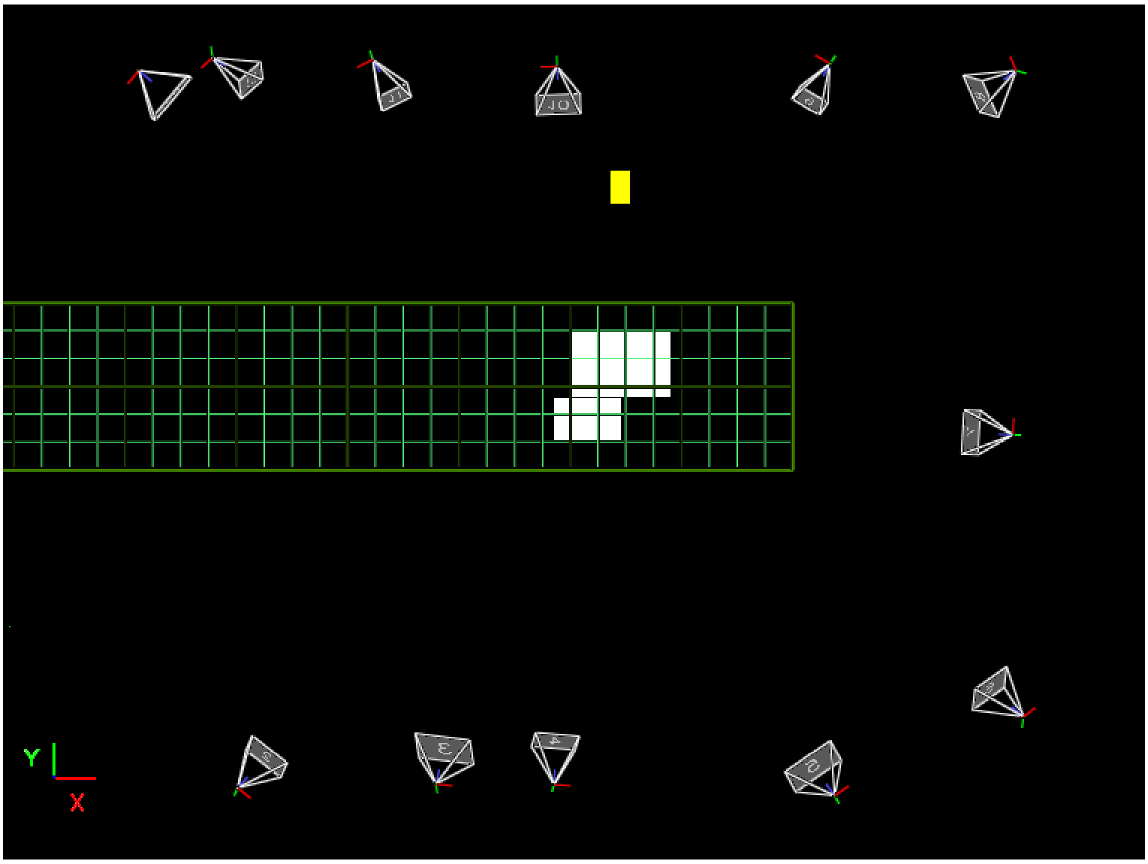


Figure 7.2. Top view of camera exact camera locations taken from Vicon Nexus software. The 12 Vicon cameras were positioned to cover the force platforms and surrounding area where the subjects had to perform the movements. The yellow rectangle indicates the location of the high speed video camera used which was aimed to the side of the force platforms as an additional feedback on what happened in the shoe-surface interface.

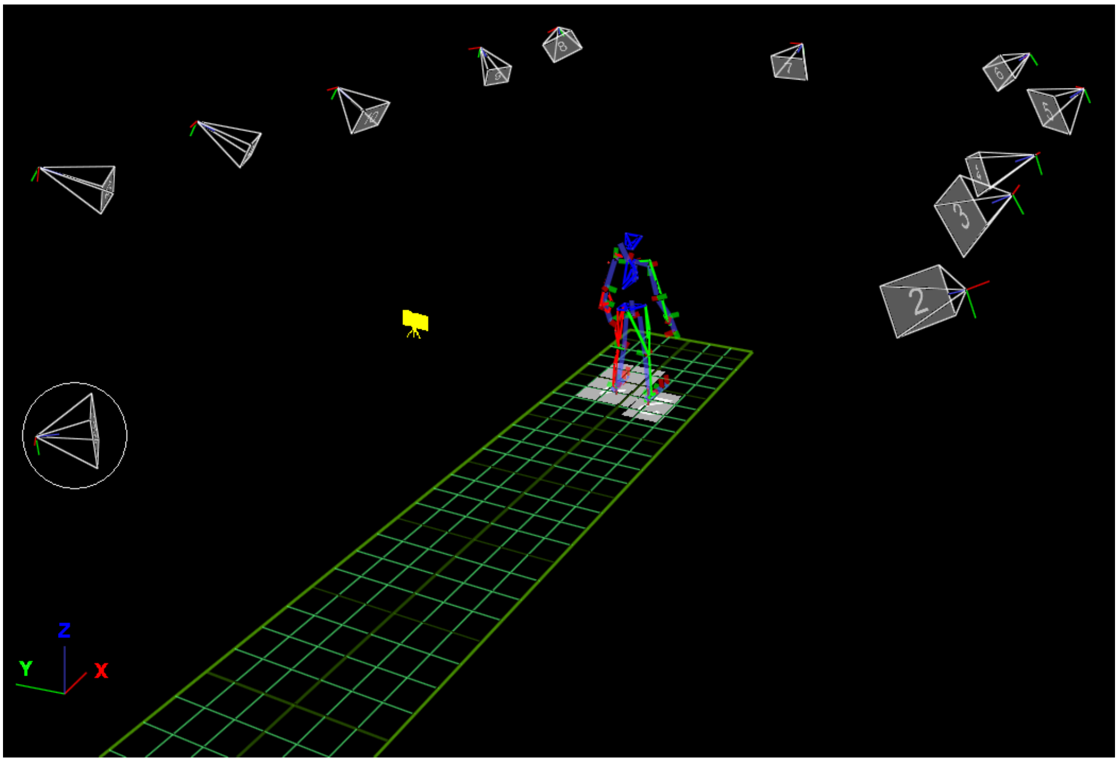


Figure 7.3. Overview from rear side of the Vicon camera locations in the lab. The circled camera was mounted on a tripod to track the markers from a lower angle. All other cameras were mounted on rails across the ceiling. The yellow rectangle indicates the location of the high speed video camera used which was aimed to the side of the force platforms as an additional feedback on what happened in the shoe-surface interface.

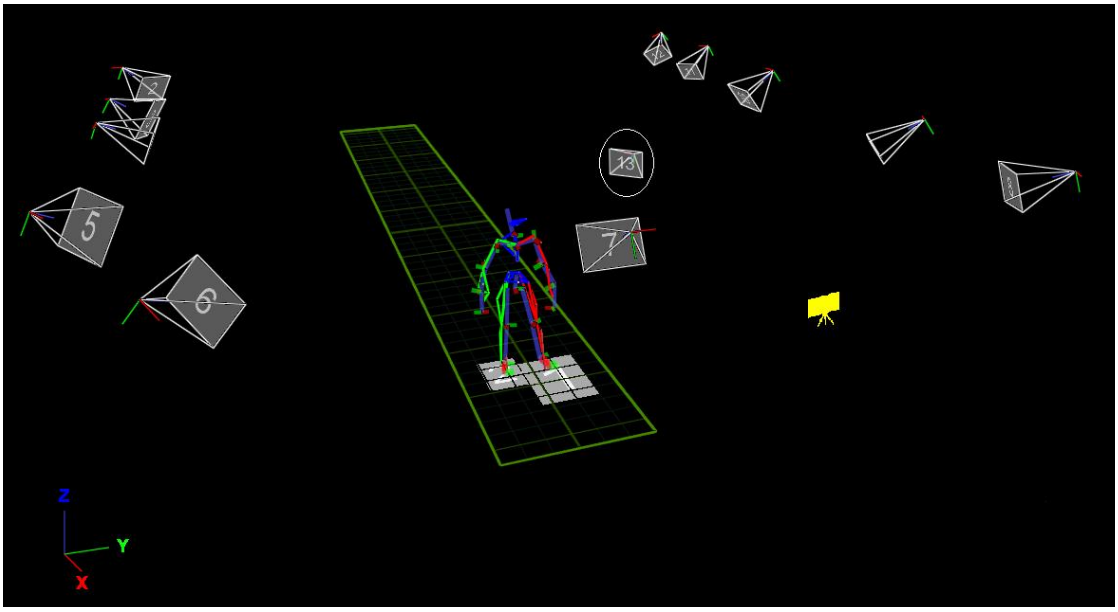


Figure 7.4. Overview from front side of the Vicon camera locations in the lab. The circled camera was mounted on a tripod to track the markers from a lower angle. All other cameras were mounted on rails across the ceiling. The yellow rectangle indicates the location of the high speed video camera used which was aimed to the side of the force platforms as an additional feedback on what happened in the shoe-surface interface.

Timing gates (Smartspeed, Fusion Sport, Coopers Plains, Australia) were used, placed 2 m apart, to measure the approach speed of the players during the ST (Figure 7.1). This distance was chosen as the approach towards the force platform was too short for the subjects to run at a steady speed and therefore the players would reach top speed prior to deceleration. The 2 m distance provided an insight into the average top speed the players reached just before decelerating for the stop and turn. Furthermore, the timing gates were placed at 1.5 m before the force platform as preliminary tests showed that this distance would provide sufficient space for the players to decelerate to the force platform where they had to turn. Also, the location of the timing gates created a clear visual point for the players from where they were allowed to decelerate for the ST.

Figure 7.5. Kistler 9287 BA force platform including the force coordinates: z (vertical), y (anterior / posterior, x (medial / lateral)

7.2.3 Surfaces

In Chapter 3 it was decided to create surfaces with different hardness and rotational traction properties. Following this four surfaces were created in Chapter 6 with the help of a Tiger Turf Soccer Real 50 MS carpet (Appendix D), different grades of styrene-butadiene-rubber, 1 – 3 mm and 1 – 8 mm, 0.2 – 0.7 mm silica sand, and a 12 mm thick re-bounce® uni F82.16 (Recticel) shockpad (Appendix D). The details on the surfaces and properties are presented in Table 7.2.

Table 7.2. The four surfaces created in Chapter 6 for use during the selected movements with rubber infill quantities per m^2 and force reduction (hardness) and rotational traction values found in Chapter 6. For all surfaces a Tiger Turf Soccer Real 50 MS carpet was used and all surfaces contained 10 kg of sand per m^2.

Surface	Rubber per m^2	Shockpad	Force Reduction (%)	Rotational traction (Nm)
Hard / High (HAhi)	10 kg, 1 – 3 mm	No	52.3 ± 1.8	38.0 ± 1.9
Hard / Low (HAlo)	7 kg, 2 – 8 mm	No	51.5 ± 1.6	29.3 ± 1.2
Soft / High (SOhi)	10 kg, 1 – 3 mm	Yes	68.7 ± 0.6	38.0 ± 1.9
Soft / Low (SOlo)	7 kg, 2 – 8 mm	Yes	68.0 ± 0.9	29.3 ± 1.2

A spreader was used for the distribution of the infill across the runway (Figure 7.6), this ensured that the sand and rubber infill was evenly spread over the entire surface area, resulting in consistent surface properties.

Figure 7.6. Spreader used to distribute sand and rubber infill evenly during surface preparation

7.2.3.1 Surface Control

One of the objectives of this research was to measure the effects of controlled surface properties on the player kinematics and loading. To control the surface properties during the sessions the choice was made in Chapter 3 to measure the surface properties regularly; whereas Chapter 6 showed that the infill depth is a good precursor for any changes in the surface properties.

In addition to measuring the surface properties and infill depth regularly, the surfaces were also maintained regularly. The entire runway was brushed at the start of each test day, typically after every two to three subjects, to keep the infill even and loose to prevent it from compacting. The samples of artificial turf on top of the force platform(s) were lightly brushed after each subject. This was done as it was assumed that these surfaces were disturbed the most by the different movements. Furthermore, Chapter 6 showed that the surface properties could be recovered to their original values by light brushing, which would ensure similar surface properties for all players. The infill depth was measured in five random locations with a depth gauge meter after each subject, typically after every 10 – 15 trials, plus the surfaces were topped up if the decrease in infill depth got close to 2 mm, based on the findings in Chapter 6.

In addition to the maintenance and measuring of the infill depth, the surface properties were measured with an Advanced Artificial Athlete (AAA) and rotational traction device (RT) at the end of each test day, typically after every two to three subjects, according to the principles described in §6.2.2 (Figure 7.7). This choice was made as measuring the surface properties after each subject would be too time consuming, whereas it was still deemed necessary to monitor the surface properties at regular intervals to ensure similar surface conditions throughout the test period.

To determine the surface properties, measurements were performed in three locations with the rotational traction device and two with the AAA. For both measurements, one location was in the centre of the large force platform. This location was chosen as the samples on the force platform(s) would be disturbed the most as the movements had to be performed on this. The choice for using only a single location was made as this would keep the disturbance by the mechanical measurement devices to a minimum.

For the rest of the runway the surface properties were measured in the pre-movement area as the surface in this area was the same as that on the force platform (Figure 7.1). All measurements were taken in the expected path of approach the players would take for each movement. The hardness was measured in a single location in the middle of the pre-movement area, whereas the rotational traction was measured in two locations (Figure 7.8). Based on the findings in Chapter 6 it was assumed that these measurement locations would provide a good insight into the changes in surface properties over the entire surface.

Figure 7.7. The advanced artificial athlete (AAA) and rotational traction device used for measurements on the hardness (force reduction) and rotational traction properties of the surfaces

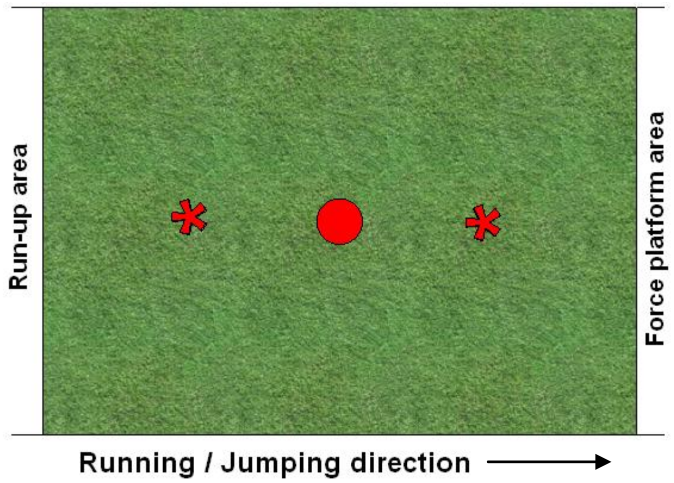


Figure 7.8. Test locations for measurements with the AAA (O) and rotational traction device (*) in the pre-movement area of the runway

7.2.4 Biomechanics

A Vicon 3D motion analysis system was used to track the movements of the players based on markers placed on the body. From these markers the joint angles can be determined which are required to calculate the joint moments with the help of the GRF data and anthropometrics of the subject (see §7.2.5.2). The following section discusses possible marker sets which are needed to track movements with the Vicon system.

7.2.4.1 Marker Set and Placement

In Chapter 3 it was decided to track the entire body during the selected movements. To do this several marker sets were available of which the standard plug-in-gait marker set as provided with the Vicon system was selected. This choice was made as previous studies on similar movements made use of this marker set, either full body or lower limb, or slight variations (Kaila, 2007; Besier et al., 2001; Chan, Huang, Chang & Kernozek, 2009a; McLean et al., 2004; Chappell et al., 2005; Sell et al., 2007).

The full body plug-in-gait marker set consisted of 39 markers of which 16 were placed on the lower limbs and 23 on the upper body, creating the following segments: head, thorax, left / right humerus, left / right radius, left / right hand, pelvis, left / right femur, left / right tibia, and left / right foot (Figure 7.9). Information of the location of the 39 markers is given in Table 7.3 and more detailed information on the placement is available in Appendix E. Table 7.4 gives an overview of the joints considered in this study and their related segments.

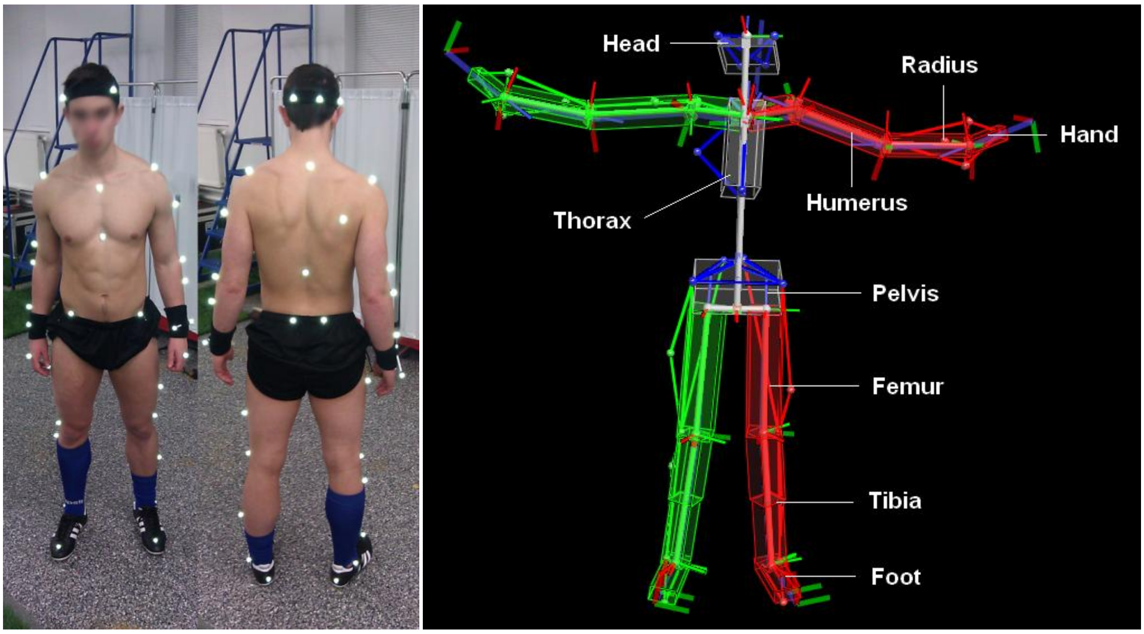


Figure 7.9. Marker placement of plug-in-gait set on test subject (left) and segments created in the Vicon Nexus software (right)

Table 7.3. Overview of the 39 markers, comprising the plug-in-gait marker set, that were placed on the players to track their body during the different movements

	Marker	**Definition**	**Location**
Head	**L / RFHD**	Left / Right front head	Left / Right temple
	L / RBHD	Left / Right back head	Left / Right back of head in horizontal plane of FHD
Torso	**C7**	7th Cervical vertebrae	Base of neck
	T10	10th Thoracic vertebrae	Lower back
	CLAV	Clavicle	Suprasternal notch
	STRN	Sternum	Xiphoid process of sternum
	RBAK	Right back	Middle of right scapula
Arms	**L / RSHO**	Left / Right shoulder	Left / Right acromio-clavicular joint
	L / RUPA	Left / Right upperarm	Outside left / right upper arm between SHO and ELB
	L / RELB	Left / Right elbow	Left / Right lateral epicondyle
	L / RFRA	Left / Right forearm	Outside left / right lower arm between ELB and WRA / B
	L / RWRA	Left / Right wrist	Left / Right thumb side of wrist bar posterior of wrist
	L / RWRB	Left / Right wrist	Left / Right pinkie side of wrist bar posterior of wrist
	L / RFIN	Left / Right finger	Just below dorsum of the second metacarpal left / right hand
Hips	**L / RASI**	Left / Right ASIS	Left / Right anterior superior iliac spine
	L / RPSI	Left / Right PSIS	Left / Right posterior superior iliac spine
Leg	**L / RTHI**	Left / Right thigh	Left / Right lateral part of thigh between ASI and KNE
	L / RKNE	Left / Right knee	Left / Right lateral epicondyle
	L / RTIB	Left / Right tibial wand	Left / Right Lateral part of lower leg between KNE and ANK
Feet	**L / RANK**	Left / Right ankle	Left / Right lateral malleolus
	L / RHEE	Left / Right heel	Left / Right calcaneus
	L / RTOE	Left / Right toe	On top of second metatarsal head left / right foot

Table 7.4. Overview of joints considered in this study and between which segments they are located

Joint	Proximal Segment	Distal Segment
Ankle	Foot	Tibia
Knee	Tibia	Femur
Hip	Femur	Pelvis
Spine	Pelvis	Spine

7.2.5 Test Protocols

The ST and JH test were performed by all 16 subjects in two separate sessions with at least one day between sessions to provide players with sufficient rest and prevent them being fatigued during the second test session. The following subsections discuss the preparations that had to be done before the tests with regards to the data collection and players, and the test protocols for the ST and JH regarding instructions for the players and the set-up of the in-game scenarios.

7.2.5.1 Data Collection Preparation

To ensure the quality of the collected data several steps were performed at the start of each test day. Doing this at the start of each test day meant that this was typically done after every two to three subjects. First of all the location and working of the high speed video camera and timing gates were checked. For the high speed video camera it was also checked that it was aimed properly to the force platform and that it was recording at 125 Hz. The charge of the light emitting units of the timing gates was checked and other spare units were on charge in case any of the units ran out of energy.

Following this the Vicon system was calibrated with both a static and dynamic calibration. The static calibration was done so the Vicon Nexus software could calculate the origin of the capture volume and determine the orientation of the 3D work space. For this the calibration wand was placed in the corner of the large force platform (Figure 7.10). The purpose of the dynamic calibration was for the Vicon Nexus software to calculate the relative positions and orientations of the 12 cameras used in the setup, as well as linearise the cameras. To do this the calibration wand was waved throughout the capture volume until all cameras captured 2000 frames of the wand.

Finally the working of the force platform(s) was checked with the help of the Vicon Nexus software. This was done by someone moving over the force platform in different locations to check if the centre of pressure of the force platform was accurate. Furthermore the force platforms were reset before each trial to minimise noise in the collected GRF data and to ensure the force reading was 0 N when no force was applied.

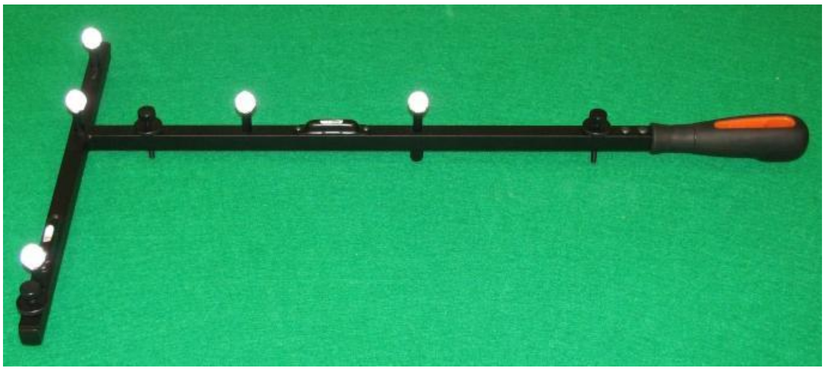


Figure 7.10. Calibration wand used for both the static and dynamic calibration of the Vicon 3D motion capture system.

7.2.5.2 Player Preparation

The first step of the player preparation was providing all players with Adidas Copa Mundial boots (Figure 7.11). These boots were provided to make sure that the shoe-surface test conditions were similar for all players as a difference in footwear could have an effect on the interaction of the shoe with the different surfaces leading to differences in experienced hardness and traction. The Adidas Copa Mundial boots were chosen as the boots have been on the market since 1979 and are therefore considered to be a standard in soccer. Furthermore, the boots use circular studs of a similar size to that of the rotational traction device and so it was assumed that the different surfaces had a similar interaction with the boots as on the rotational traction device. The players were asked to wear the boots on at least one occasion before their test session in order for them to get used to the boots. The players were provided with soccer socks to increase the natural feel of test and to allow for cutting holes in the socks for placement of the markers directly on the skin on the lower legs and ankle.

At the start of the first session the players were presented with an information sheet about the study. After reading this they were allowed to ask any questions and they signed an informed consent form. They also filled out a medical questionnaire, to make sure they did not have any medical conditions that could affect their performance, and a general questionnaire, to gain information on their soccer experience and exposure to natural grass and artificial turf surfaces (Appendix F). Thereafter the players changed into shorts and put on the socks and soccer boots provided.

Figure 7.11. The Adidas Copa Mundial soccer boots were provided to all players to ensure similar properties of the shoe-surface interface for all participants of the study.

The following step in the preparation was placing the 39 markers of the plug-in-gait marker set on the body of the player (Figure 7.9). All marker locations were marked with a black pen to make sure they could be placed in the same location in the event any would come off during the test. The following anthropometric measurements were taken: body length, body mass, leg length, knee width, ankle width, shoulder offset, elbow width, and wrist width. With these measurements the Vicon Nexus software was able to calculate characteristics of the different body segments, which are needed for calculating the joint moments with the use of the inverse dynamics. After the anthropometric measurements and marker placement a static trial was taken of the player standing in a T-pose in order to label all markers correctly (Figure 7.12).

For the final stage of preparation the players were asked to perform a short self-selected warm-up for which they could use the run-up area of the runway (Figure 7.1). While this had some limitations in respect to their normal warm-up routine it allowed the players to warm-up in a manner they were comfortable with. Furthermore, it also allowed them to get an initial feel of the lab set-up before executing the specific movements.

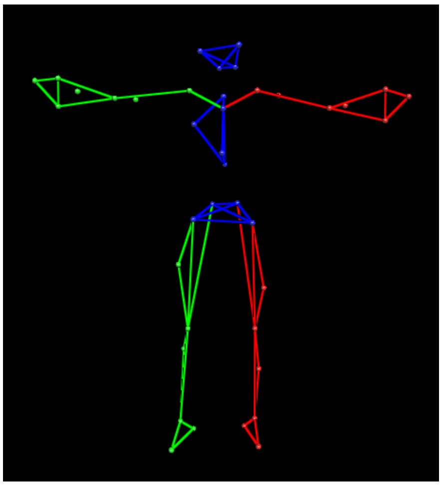


Figure 7.12. T-pose used for the static trial at the start of each test session for labelling the markers

7.2.5.3 Stop and Turn

For the ST the players were instructed to start at the beginning of the runway and accelerate towards the timing gates (Figure 7.1). Between the timing gates they were required to reach a speed between 12 – 14.5 km/h for a trial to be valid. This speed and range was based on the speeds used in previous studies on cutting and turning manoeuvres (Nyland et al., 1999; McLean et al., 2004; Kaila, 2007; Sigward & Powers, 2006; Dempsey et al., 2007; Besier et al., 2001; Stefanyshyn et al., 2010). The players were instructed to start decelerating at the second timing gate, after which they had to land with their preferred foot (13 used their right foot, 3 their left foot) on the artificial turf covering the force platform and turn 180° (Figure 7.13, Figure 7.14). After the turn they were instructed to accelerate back towards the first timing gates as if they had to chase a ball or opponent, or were chased by an opponent (Figure 7.1). The subjects were required to use the same turning foot throughout the test and were only allowed to hit the force platform area with their turning foot. After receiving these instructions the players were allowed to make three trial runs to get used to the set-up and required running speed. The players were not given any trial runs to familiarise to the different surface conditions. To further add to the in-game scenario a simulated opponent was included to the set-up. This entailed a person standing approximately 5 - 10 cm behind the force platform (Figure 7.15). The simulated opponent was instructed to only stand behind the force platform.

Figure 7.13. Rear view sequence of the final approach of the stop and turn manoeuvre on the pre-movement section of the runway, the turn on the force platform area and acceleration in the opposite direction of the approach (Figure 7.1), including the simulated opponent used for the in-game scenario.

On each surface condition five valid trials were required with and without the simulated opponent making a total of 10 valid trials per surface. This number was based on the number of trials typically used in similar studies (D. Ferris et al., 1999; Chappell et al., 2005; Wannop et al., 2010; Stefanyshyn et al., 2010). Furthermore, the number of trials meant that a larger number of trials were available to compare the data between surface condition (10 trials per surface) and in-game conditions (20 trials per in-game condition). In addition to this the number of trials was still small enough to prevent fatigue for the players as well as large enough to have a sufficient number of trials during data collection (a minimum of 6 per surface condition and 12 per in-game scenario) in the event some did not produce valid data, for example because of missing marker trajectories. The order of the trials with and without a simulated opponent was randomised for all players, as was the order of surfaces. A trial was valid if the player reached the correct speed between the timing gates, landed with the whole foot on the force platform and no markers were lost during the movement. After each surface condition, the pre-movement and force platform area of the runway were changed to a new surface. The randomisation was done to prevent that any effects found between surface conditions would be related to fatigue or practice. Players had approximately 1 minute rest between trials and approximately 5 – 10 minutes between surface conditions.

Figure 7.14. Front view sequence of the turning part of the stop and turn, including the simulated opponent used for the in-game scenario

During the change of surface conditions the players were asked to indicate on a visual analogue scale how they perceived both the traction and the hardness of the surface condition they had just experienced. The visual analogue scale was chosen as the relation between the surfaces was of interest rather than the absolute rating. Furthermore, the analogue scale made it easy for the players to compare between the surfaces as they only had to rate four surfaces. At the end of the test the player was asked which of the four surfaces they liked and disliked the most to get insight into the surface preferences of the players.

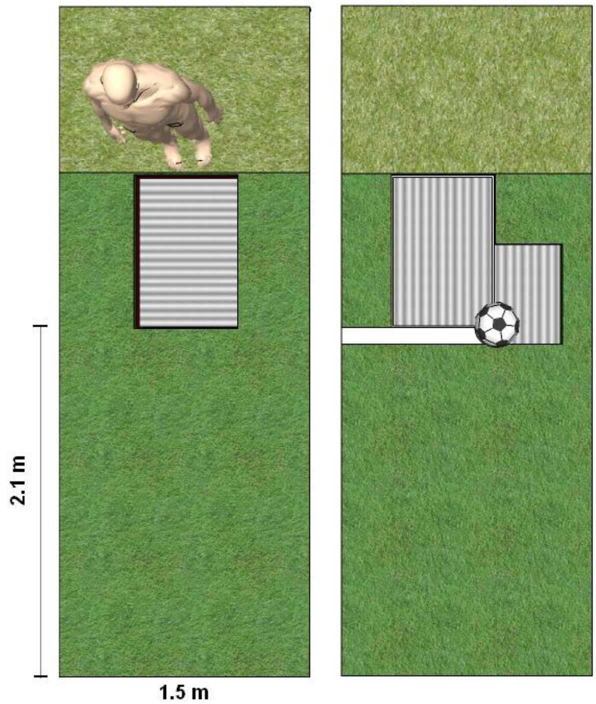


Figure 7.15. Overview of the set-up of in-game scenarios used, both images represent the pre-movement, force platform and extra area of the runway (Figure 7.1). The left image represents the in-game scenario for the stop and turn for which a simulated opponent stood 5 – 10 cm behind the force platform. The right image represents the in-game scenario for the jumping / heading trials for which a ball was suspended from the ceiling at the maximal vertical stop jump height of each player.

7.2.5.4 Jumping / Heading

For the JH the players were instructed to start at the beginning of the pre-movement area of the runway and make two steps, land on both feet and perform a maximal two footed vertical stop jump (Figure 7.16-7.18). While during a match situation they might often take off with just one foot, the two foot take off was chosen in Chapter 3 as it was believed this would result in a more controlled manoeuvre. During the landing the players had to land with their right foot on the small force platform and with their left foot on the large force platform (Figure 7.15). A trial was invalid if one of their feet, or a part of it, did not land on the force platform.

The in-game scenario was created by suspending a ball from the ceiling which they had to head at maximal jump height (Figure 7.15). The maximum jump height of the players was determined by having the players perform a maximal vertical stop jump. If it was thought that the player could jump higher they were given additional instructions, after which they had to perform another maximal vertical stop jump. When the ball was in place the players performed another maximal vertical stop jump to make sure that the ball was placed at the right height.

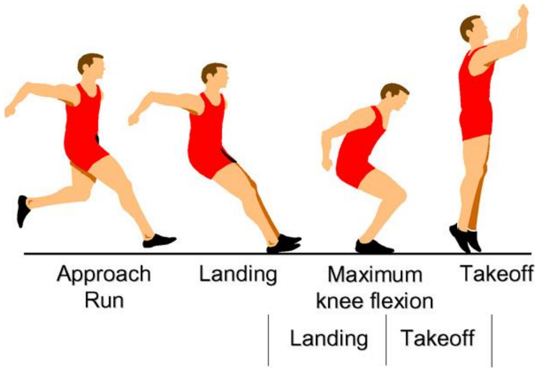


Figure 7.16. Representation of the stop jump used for the jumping / heading trials. The players were allowed to make two steps (approach run) before landing on both feed and performing a maximal two footed vertical stop jump (Weinhold et al., 2007).

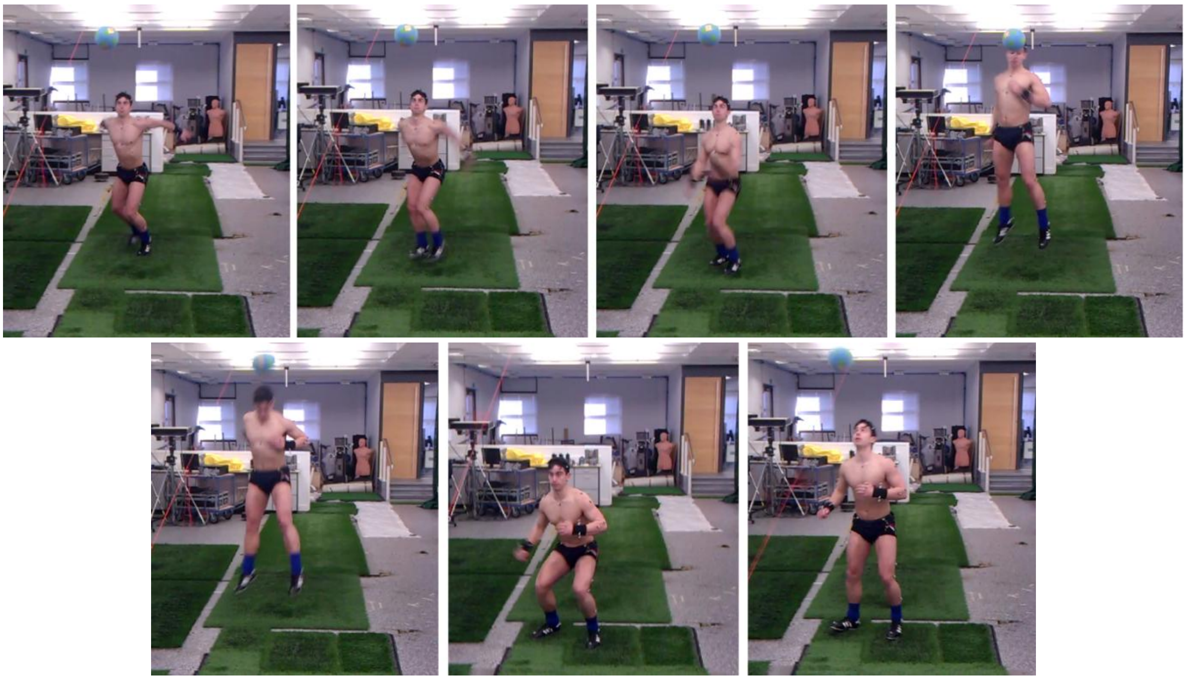


Figure 7.17. Front view sequence of the maximal vertical stop jump and heading manoeuvre. The players had to takeoff with two feet and land with each foot on the appropriate force platform.

Relative to the lab, the ball location was above the front edge of the large force platform and in the middle of both force platforms (Figure 7.15). This location was chosen by studying a slow motion video of a heading movement (Figure 7.19). This video showed that the rear foot of the player landed approximately underneath the location in the air where the ball was headed. However, as the ball would be hanging still in mid-air a more forward motion was expected in this situation, leading to the choice to place the ball above the edge of the force platform, rather than above the centre of the force platform as this would increase the probability of the players landing on the force platform. Several heading trials confirmed the suitability of this location.

The number of valid trials required for all surface and in-game conditions, the amount of rest and the player perception questionnaire were all similar to the ST and is described in the previous section.

Figure 7.18. Side view sequence of the maximal stop jump and heading manoeuvre. The players had to takeoff with two feet and land with each foot on the appropriate force platform

Figure 7.19. Studying a slow motion video of a heading manoeuvre showed that the rear foot landed approximately underneath the location where the ball was headed (http://www.youtube.com/watch?v=5VroNiXG8X4 Channel: BiomechanicsMMU)

7.2.6 Data Processing

Several steps were undertaken in the Vicon Nexus software to process the data collected during the test sessions. The first step was making sure all markers were labelled correctly. For this the core processing function was used, which labelled the markers automatically based on the static trial taken at the start of the test session (Figure 7.12). Following this all labels were checked throughout the entire movement, to ensure the markers were labelled correctly and no unexpected shifts took place in the trajectories. Any discrepancies found during the movement were corrected at this stage and the data was cut to cover the entire movement. For the ST this entailed ~300 frames before initial ground contact and after toe-off, whereas for the JH this entailed ~500 frames before and after initial ground contact.

After this initial step, all unlabeled trajectories were deleted to remove all ghost markers present in the data. The goal of this was to make the dataset cleaner before importing to MATLAB for analysis.

The data was then filtered using a Woltring filtering routine. This routine was used to fill small gaps that existed in the marker trajectories and filter the data over the entire range with a predicted mean square error value of 10 for smooth trajectories. While the Vicon plug-in-gait foundation notes recommended a value between 15 and 20 the choice for a lower value was made to avoid the risk of over smoothing, which could affect the results of the measurements.

After the Woltring filtering routine the 'VPI compatibility Run Dynamic gait model' process was run. This process calculated all joint parameters such as the angles and moments based on the anthropometric measurements, marker trajectories and collected GRF. For this process the standard options as provided in the Vicon Nexus software were used. When the process finished all the calculations, the entire trial was checked once more to ensure all markers were labelled correctly and that no strange shifts took place in the trajectories. If any errors were found, the processing of the trial was redone completely.

The final step in the data processing consisted of exporting the data. The data was exported to both a C3D file and an ASCII file. The C3D file provided an extra back-up of the data that could be read by the Vicon Nexus software, whereas the ASCII file served the purpose of importing it into other software such as Excel and MATLAB for analysis.

7.2.6.1 Body Movement

With the help of the plug-in-gait model and Vicon Nexus software the movement of the joints and joint moments in the lower limbs were calculated. Each joint / segment movement corresponds either to a positive or a negative value. All definitions are presented in Table 7.5. For the lower body the corresponding values of the joint angles and moments were similar, except for the flexion / extension moments which are opposite for the moment**.** The joint angles for the lower limbs are presented in Figure 7.20 and Figure 7.21. In addition to the joint angles, the rotation of the foot segment relative to the global lab coordinate system (Z-axis) was included to gain insight into the amount of rotation of the foot during the ST.

Table 7.5. Movements corresponding to the positive and negative values identified by the plug-in-gait model

Body part		**Angle: Negative**	**Angle: Positive**
Joint	**Ankle**	Plantar Flexion*	Dorsi Flexion*
		Eversion	Inversion
		External Rotation	Internal Rotation
	Knee	Extension*	Flexion*
		Valgus	Varus
		External Rotation	Internal Rotation
	Hip	Extension*	Flexion*
		Abduction	Adduction
		External Rotation	Internal Rotation
	Spine	Extension	Flexion
		Lateral Bend (opposite side of turning direction ST) (left JH)	Lateral Bend (same side of turning direction ST) (right JH)
		Rotation (opposite direction of turning direction ST) (left JH)	Rotation (same direction as turning direction ST) (right JH)
Segment	**Foot**	Rotation in opposite direction of turning direction ST	Rotation in same direction as turning direction ST
	Thorax	Backward Tilt	Forward Tilt
		Lateral Tilt (opposite side of turning direction ST) (left JH)	Lateral Tilt (same side of turning direction ST) (right (JH)
		Rotation (same direction approach ST) (left JH)	Rotation (opposite direction approach ST) (right JH)

* Opposite value for moments

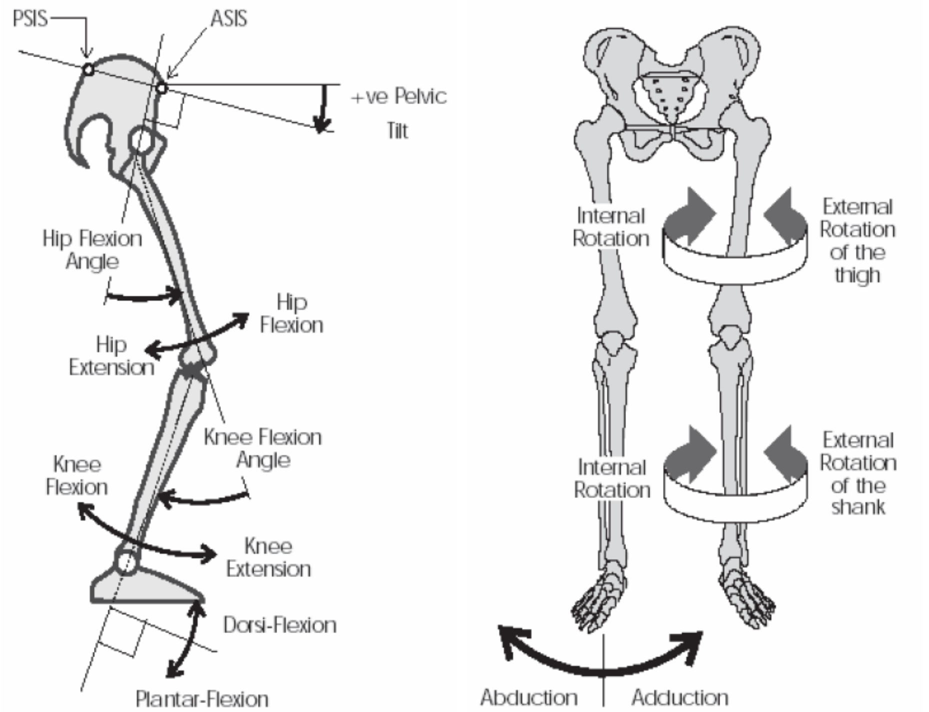


Figure 7.20. Overview of the lower limb movements calculated with the plug-in-gait model (irc-web.co.jp, 2010)

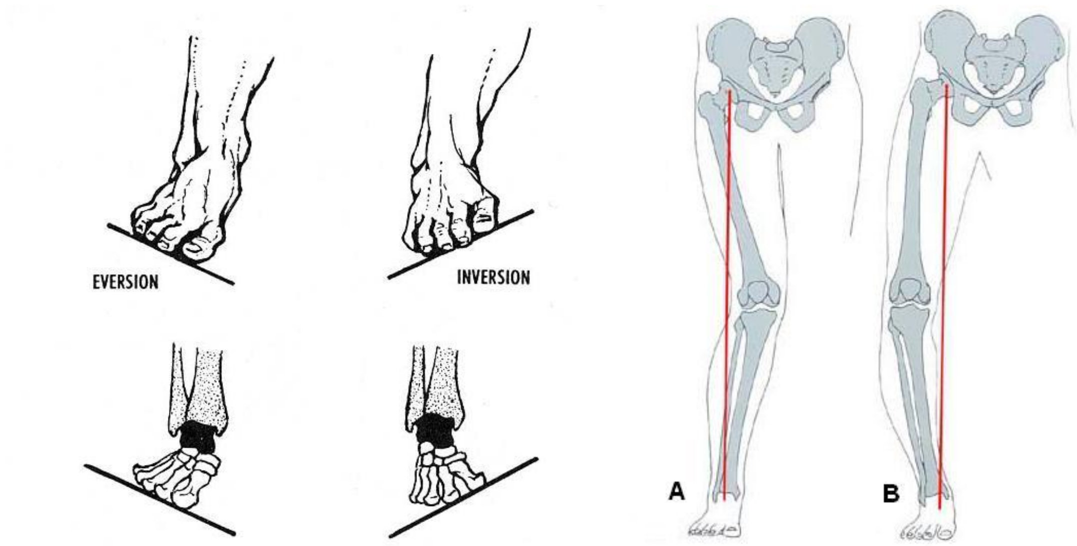


Figure 7.21. Overview of the medial / lateral movements of the ankle (left) and knee (right) joint. In the plug-in-gait model the ankle inversion and knee varus (B) corresponded to a positive value, whereas the ankle eversion and knee valgus (A) corresponded to a negative value. (Image right: www.darthmouth.edu/~humananatomy/figures/chapter_17/17-6.htm, Image left: www.orthopedieherentals.be/index.php?page=ascorrectie-of-osteotomie-van-de-knie-bij-x-of-o-benen)

For the upper body only the joint and segment angles were considered (Table 7.5). The movement of the thorax was determined using the global lab coordinate system as this was a segment, whereas the movement of the spine was determined with proximal and distal segment between which the spine joint was located (Table 7.4). During the ST subjects were instructed to use their preferred foot, which meant that the values for players turning left or right would differ for the lateral and rotational movements of the spine and thorax. Therefore the choice was made to alter the data to give all players the same values (negative / positive). For the spine lateral bend and thorax lateral tilt this meant that a positive value corresponded to a lateral bend / tilt in the same direction as the turn, e.g. left for players turning left (Figure 7.22). A positive value for the rotation of the spine corresponded to a rotation in the same direction as the turn. Regarding the rotation of the thorax a positive value corresponded to the thorax being turned in the opposite direction of the approach, with the 0 point being located on the Y-axis (Figure 7.23). For the JH a spine lateral bend and thorax lateral tilt a positive value corresponded to a bend / tilt to the right. A positive value for the spine and thorax rotation corresponded to a rotation to the right, with the 0 point for the thorax rotation being located on the X-axis (Figure 7.23).

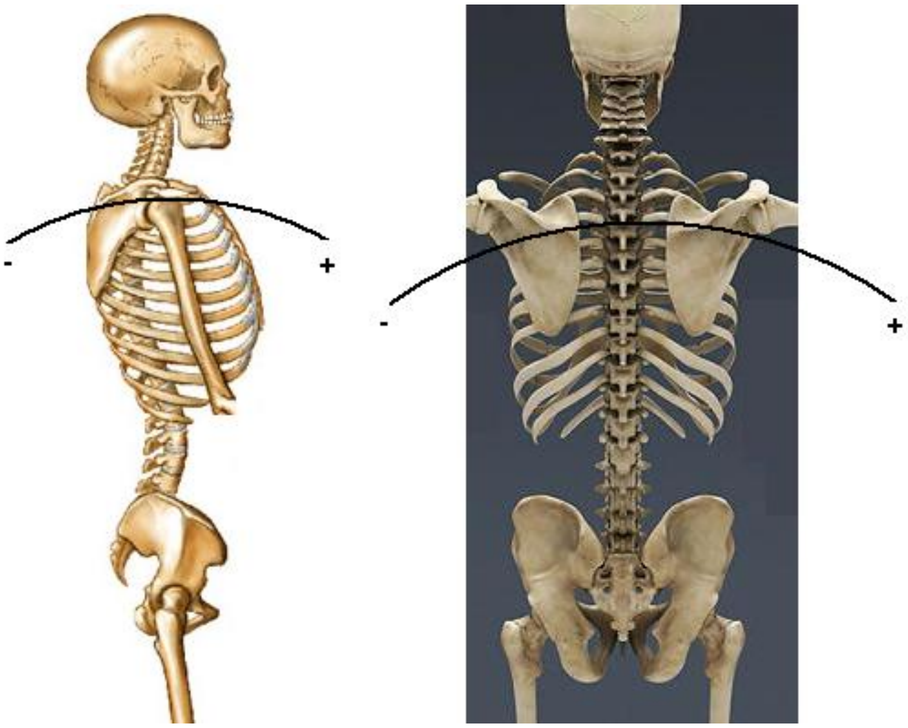


Figure 7.22. Overview of the spine flexion / extension and thorax forward / backward tilt (left) and spine lateral bend and thorax lateral tilt (right). The spine flexion and thorax forward tilt corresponded to a positive value. For the spine lateral bend and thorax lateral tilt a positive value corresponded to a bend / tilt in the same direction as the turn for the ST, e.g. left for players turning left. For the JH a lateral bend / tilt corresponded to a bend / tilt to the right.

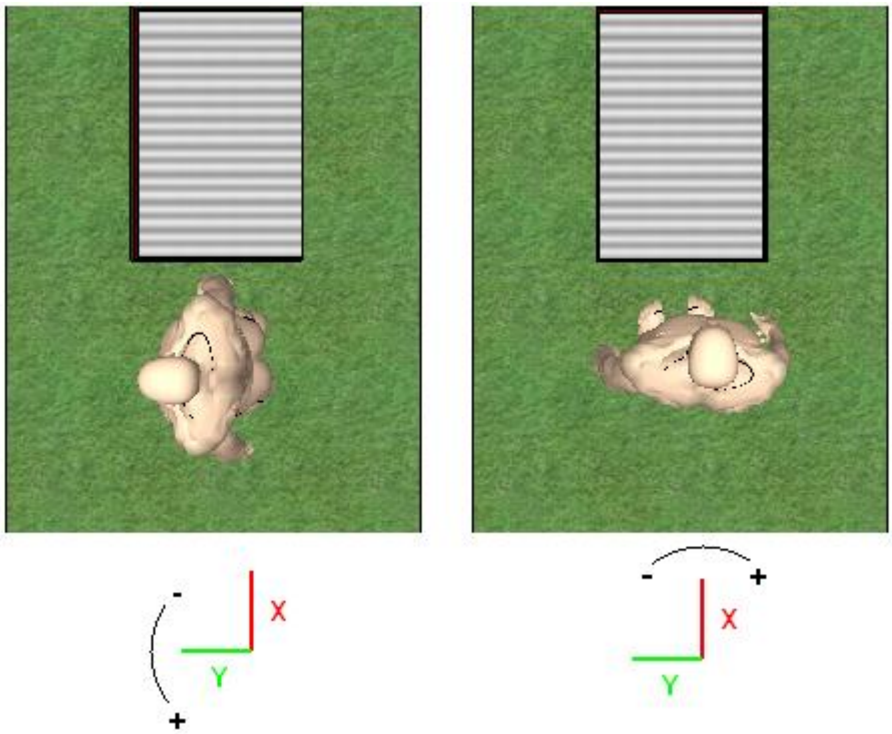


Figure 7.23. Overview of the spine and thorax rotation during the ST (left) and JH (right). During the ST a positive value corresponded to a rotation of the spine to the direction of the turn, whereas for the rotation of the thorax a positive value corresponded to a rotation to the opposite direct of the approach; the 0 point of the turn was located on the Y-axis. During the JH a positive value of the rotation of the spine corresponded to a rotation to the right. This was also the case for the rotation of the thorax; the 0 point was located on the X axis.

7.2.7 Data Analysis

7.2.7.1 Surface Measurements

The results of the surface measurements were analysed using a repeated measures ANOVA (PASW 18, SPSS inc., Chicago, IL, USA). For the infill depth during the ST a one-way repeated measures ANOVA was used, with the surface conditions creating four levels, as the infill depth was only measured on the large force platform. For the JH test a two-way repeated measures ANOVA was used. Again the four surface conditions were used to create four levels, but in addition the two force platform measurement locations formed the second sublevel.

The measurements with the AAA and the RT were analysed with a two way repeated measures ANOVA. In addition to the surface conditions, the test locations were used as sublevels. Subsequently, the AAA test location had two different levels, whereas the RT test location had three different levels. A p-value of 0.05 was used for all these tests.

7.2.7.2 Inclusion Movement Parameters

A selection was made of the measured parameters related to the movements. These can be divided into four different groups: movement control, ground reaction forces, joint angles and joint moments. The movement control parameters include the approach speed for the ST and the jumping height for the JH and had the primary goal to control these possible confounding variables and ensure that the movement conditions were similar on the different surfaces and during the different in-game scenarios.

The ground reaction force data was included as previous studies showed that the surface hardness can affect the vertical ground reaction forces and some studies suggested that high ground reaction forces and loading rates can increase the risk on injuries (Peikenkamp et al., 1998; Milburn & Barry, 1998; D. Ferris et al., 1999; N. Smith et al., 2004; Meijer et al., 2007). Furthermore, the ground contact time could be determined for the ST with the ground reaction force data, which would indicate if the players were able to turn faster on certain surface conditions.

The joint angle data of the lower limbs was included as this provided information on the movement strategy of the lower limb that may be related to higher joint loading and injuries as shown in previous studies (Decker et al., 2003; Chappell et al., 2005; Senter & Hame, 2006). The joint angle data of the upper body was included as previous studies suggested that the upper body can affect the loading of the lower limbs (Dempsey et al., 2007; Blackburn & Padua, 2008). Finally the joint moment data of the lower limbs was included as this provided information on the internal loading of the joints and previous studies have suggested that high joint moments can cause damage to the tissues surrounding the joints (Piziali et al., 1980; Kaila, 2007; Wannop et al., 2010).

7.2.7.3 Stop and Turn

Based on previous studies (Besier et al., 2001; Gehring et al., 2007; Kaila, 2007), the ST data was divided into four phases (Figure 7.24, Figure 7.25). Studies by Besier et al. (2001) and Kaila (2007) looked at cutting manoeuvres and divided the stance phase into three different phases based on the GRF curve: weight acceptance, peak push off, and final push off. However, the curve during the ST was different to that of the cutting manoeuvre with a more extended midstance, which also showed in the force curve presented in a study by Gehring et al. (2007) (Figure 7.24C). Therefore the choice was made to include an extra mid-stance phase for the analysis of the ST (Figure 7.25).

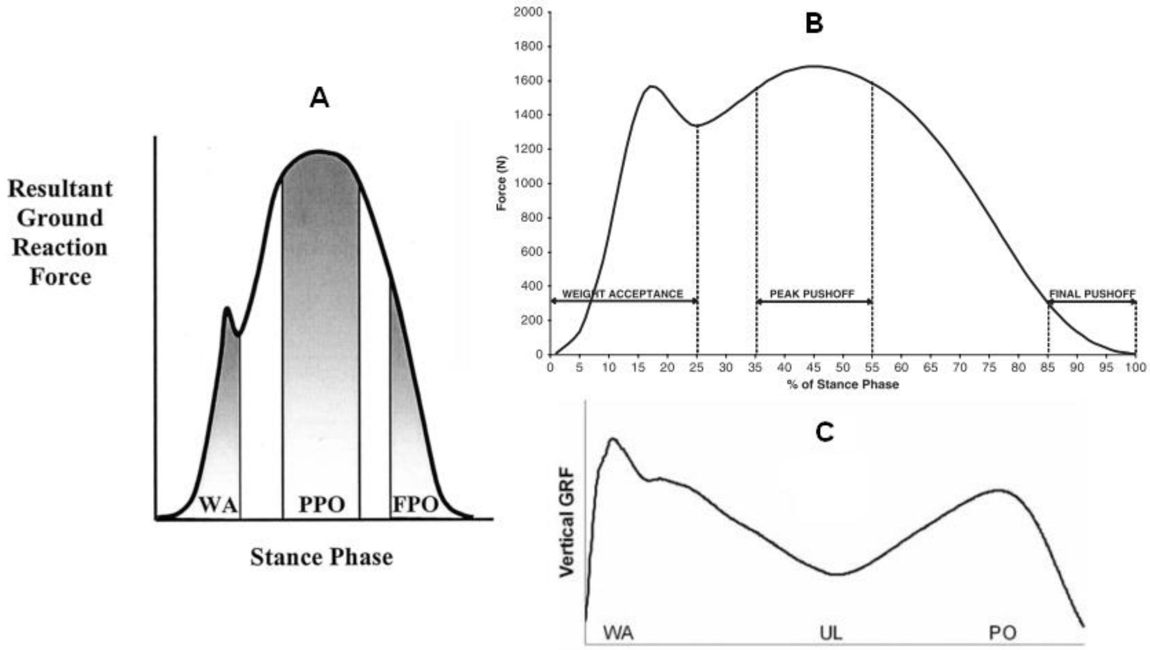


Figure 7.24. Studies by Besier et al. (2001) (A), Kaila (2007) (B) and Gehring et al. (2007) (C) divided the ground contact face of cutting and stop and turn manoeuvres into different phases based on the GRF curve. These studies provided the basis on which the stop and turn manoeuvre was divided into four phases.

The first phase during ground contact was the weight acceptance phase (WA). This phase was similar to previous studies and involved the initial 20% of the stance from the instant of impact (Figure 7.25). The second phase was the mid-stance phase (MS) and was situated from 40 – 60% of the stance phase. The choice for this was based on the fact that during this period the knee reached its maximal flexion angle, which was used as a key parameter in previous studies on cutting manoeuvres (Kaila, 2007; Pollard et al., 2004; Decker et al., 2003). The MS phase was followed by the peak push-off phase (PO) which took place from 70 – 90% of the stance phase. The final 10% of the ST was identified as the final push-off phase (FP). This again was similar to the final phase used in previous studies and was used to gain insight in to what happened during the final part of the ST.

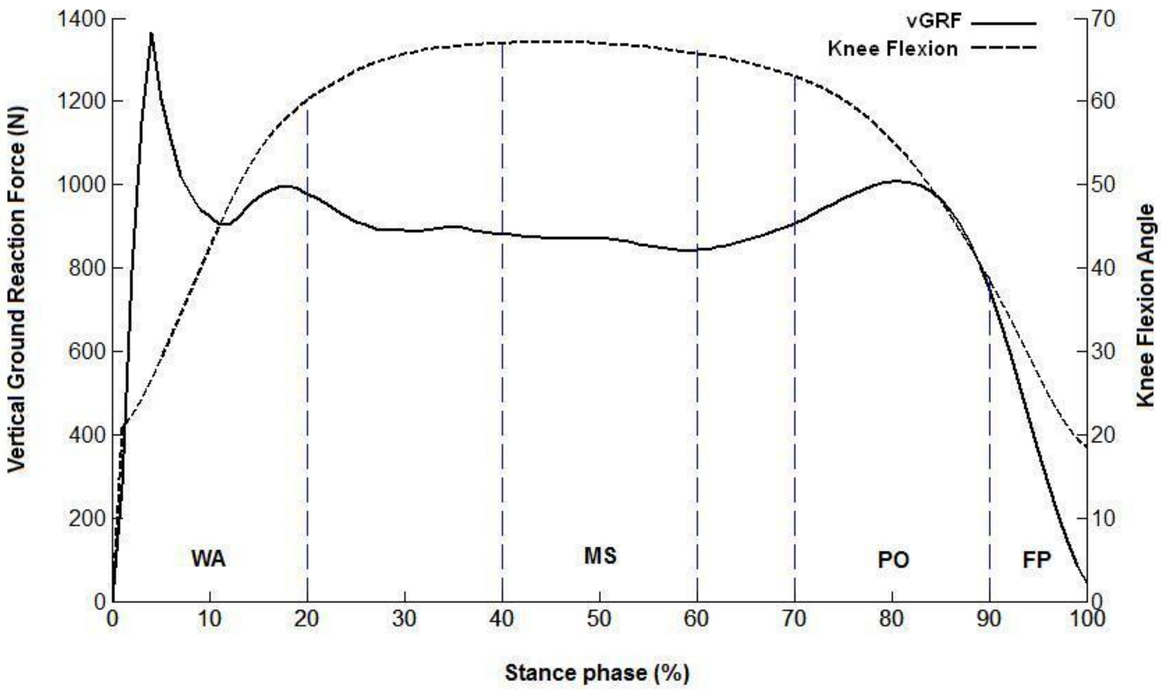


Figure 7.25. Phases used to define the different parts of the stance phase: weight acceptance (WA), mid-stance (MS), peak push off (PO), and final push off (FP). While there was some variation between players when the push off initiated during in the stance phase it took place between 70 and 90% for the majority of the players.

In addition to the stance phases a pre-movement phase (PRE) was included. This phase comprised the 50 ms before the initial impact of the foot with the force platform. The 50 ms was based on previous research which looked at the effects of the joint angles as well as muscle activation during a cutting manoeuvre just before ground contact (Besier et al., 2003). Only the joint angle data was analysed during this phase, it was used to investigate if the players made any movement changes prior to ground contact to adjust for the different surface and in-game conditions.

The stance phase of the ST was determined with the help of the GRF data, for which a threshold of 50 N was used to identify the beginning and end the ground contact during the ST. Following this all data (forces, joint angles and joint moments) was interpolated to a common time base representing the stance phase from 0 – 100%. After interpolation, the phases were determined on the percentages of the set phases and the data was averaged for each phase similar to the method used in a study by Besier et al. (2001) on cutting manoeuvres. This method was chosen as this provides insight into what happens throughout the entire cutting manoeuvre, rather than only at a single point in the movement determined by for example the peak force. Furthermore, using this method for all biomechanical parameters (GRF, joint angles and joint moments) in the set phases helped to relate changes in joint loading to changes in movement strategy and GRF.

In addition to the above described method the choice was made to also analyse the peak vertical impact force that took place during the WA phase of the ST. This choice was made as previous studies have showed that the peak vertical impact force can be affected by changes in surface hardness and some studies have suggested that this may related to the development of injuries (Milburn & Barry, 1998; D. Ferris et al., 1999; Meijer et al., 2007). Within the WA phase the choice was made to also analyse the average loading rate and the peak loading rate of the impact force. This gives insight in how the impact force develops and previous studies have shown that the loading rate can also be affected by the surface hardness and some studies have suggested that a high loading rate of the vertical impact force is related to injuries (Peikenkamp et al., 1998; Milner et al., 2006; Butler et al., 2003; Hreljac, 2004). The average loading rate was determined from initial ground contact to peak impact force and gave an indication of the development of the ground reaction force until the maximum force was reached (Figure 7.26). The peak loading rate was determined as the steepest gradient of the vertical ground reaction force curve and gave an indication of the peak loading during the WA phase (Figure 7.26).

Of the horizontal forces the peak forces were determined during the WA as it was hypothesised that these would be affected by the changes in rotational traction as well as may reflect a faster deceleration by the players during the in-game scenario including the simulated opponent. The loading rates were not determined as the results of this study (§7.3.4) showed that the magnitudes of the horizontal forces were limited.

The statistical analysis of this data was done with a two way repeated measures ANOVA using PASW 18 for which a p-value of 0.05 was used. The first level involved the four surface conditions, whereas the second level was aimed at investigating if the use of a simulated opponent had an effect on any of the parameters. A Mauchly's test of sphericity was first performed and if sphericity was not assumed a Huynh-Feldt correction was used. If a significant difference was present for the repeated measures a post-hoc pairwise comparison test was used to compare the surfaces and in-game conditions to each other. For the pairwise comparison a Bonferroni adjustment was used to correct for multiple comparisons.

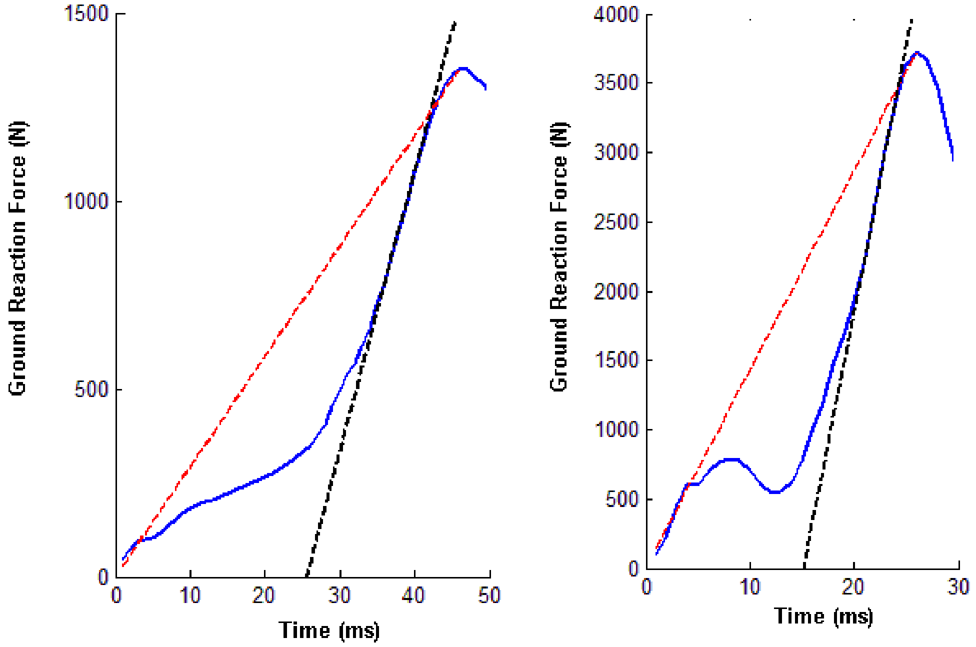


Figure 7.26. Typical vertical GRF curve during the impact of the ST and impact of the landing of the JH (right). The average loading rate was determined from initial contact to peak ground reaction force curve (red dotted line), whereas the peak loading rate was determined as the steepest gradient of the curve (black dotted line).

7.2.7.4 Jumping / Heading

For the JH the data was divided into three phases based on the GRF curve and the knee flexion data (Figure 7.25). This was based on a previous study by Chappell et al. (2005) in which the ground contact was divided into two phases which were interpolated for the ground contact time: landing (included the impact peak of the vGRF curve) and take-off (included the remainder of the curve). However, since in this study the subjects did not make a jump after landing it was not possible to interpolate the data to the ground contact phase. Instead the phases were determined by using clear points in the data.

The first phase used was the impact phase (IMP) (Figure 7.28a). This phase was extended from the initial impact to the peak vertical impact force. The choice for this was made as the impact peak was a clear point in the data and furthermore for some trials it was not possible to identify the entire weight acceptance phase as the vGRF decreased gradually compared with a rapid decrease followed by a small increase of the other trials and the study by Chappell et al. (2005) (Figure 7.28). While this is somewhat similar to the landing phase used by Chappell, it did not include the complete landing phase. However, it was expected that players may adjust their movement strategy during this phase to reduce the effects of the impact.

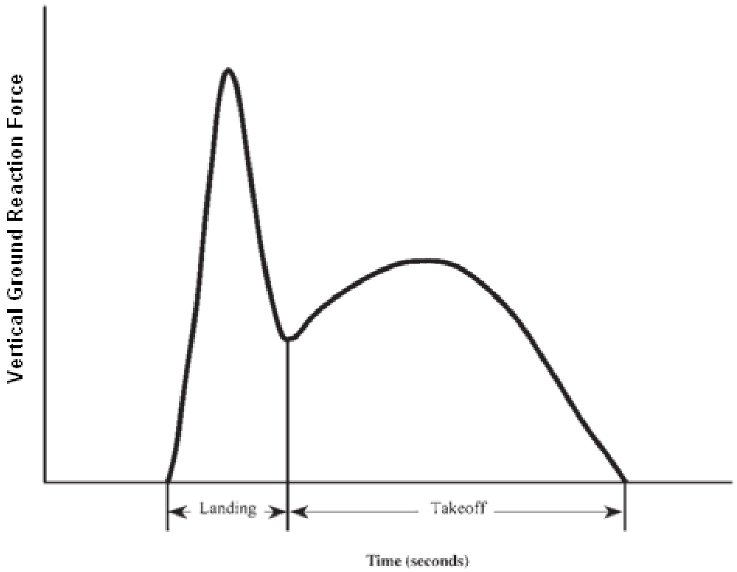


Figure 7.27. A study by Chappell et al. (2005) divided the ground contact after the landing of a jump in a landing phase and takeoff phase based on the vGRF curve. This was used as a basis for dividing the landing after the JH manoeuvre in different phases, with the main difference that the subjects in this study did not have to take off after the landing.

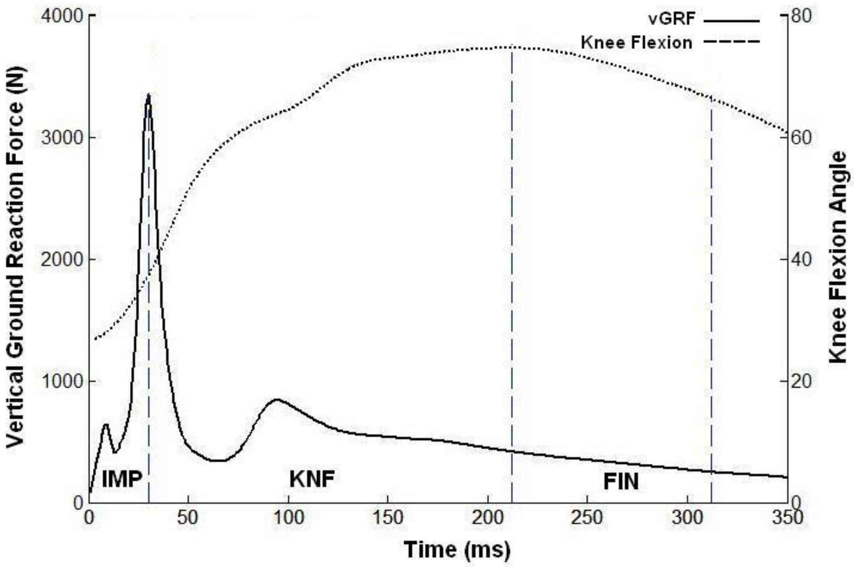
The second phase used was the peak impact – peak knee flexion phase (KNF) (Figure 7.28). Compared to the phases used by Chappell et al. (2005) it could be said that this phase is split between the landing and takeoff phase. However, as this study did not involve a takeoff the phase stands on its own as no takeoff phase can be created. The peak knee flexion was chosen as this has been a key parameter in previous studies and furthermore peak knee flexion has been related to the end of the deceleration phase of the landing in previous studies (Senter & Hame, 2006; Blackburn & Padua, 2008; Pollard et al., 2010).

The final phase (FIN) was determined from peak knee flexion to 100 ms after the peak knee flexion (Figure 7.28). This phase was chosen to investigate what happened to the GRF, joint angles and joint moments after the peak knee flexion had been reached and the impact of the landing absorbed. The time of 100 ms was chosen based on a previous study on landings (Kellis & Kouvelioti, 2009). In addition to the mentioned phases a pre-movement phase (PRE) was used as for the ST analysis. This phase again comprised of the 50 ms before ground contact and was used to investigate if the players made any movement changes before ground contact to adjust for the different surface conditions or in-game scenarios.

All parameters were analysed in a similar manner as described in §7.2.7.3. As for the ST the choice was made to analyse the peak vertical impact force, and the average and peak loading rate of the vertical ground reaction force curve (Figure 7.26). Furthermore, the peak horizontal forces were determined during the landing of the JH manoeuvre to investigate any effects by the changes in traction and in-game scenarios.

For the statistical analysis, similar tests were used as for the ST with the main difference that for the JH a third level was added as data was available for both legs.

A



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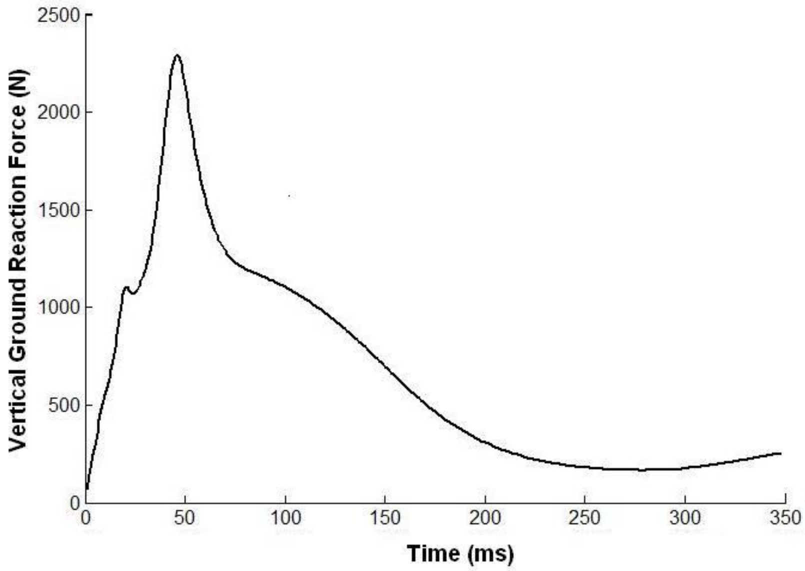


Figure 7.28. Phases used to define the different parts of the stance phase (A): impact (IMP), peak impact to peak knee flexion (KNF), peak knee flexion to peak knee flexion + 100ms (FIN). The choice for the IMP phase was made as for some trials (B) it was difficult to identify the entire landing phase as the vGRF curve decreased gradually compared to the rapid decrease followed by a small increase (A)

7.3 Results

This section presents the results of the ST and JH test. First the surface test results are presented that were collected over the entire test period. This is followed by a section presenting the results on the approach speed and maximal jump height used to control the ST and JH, and a section on the ground contact times during the ST. Following this, the ground reaction force, joint angles, centre of mass (COM) and joint moment data are presented. In each subsection the results of the ST are presented first, followed by the results of the JH.

7.3.1 Surface Measurements

7.3.1.1 Infill Depth

The average infill depth of the surfaces on top of the large force platform varied from 30.0 – 33.7 mm during the ST tests and from 30.3 – 33.3 mm during the JH test (Figure 7.29). The average infill depth of the surfaces on top of the small force platform varied from 30.0 – 32.2 mm during the JH test (Figure 7.29).

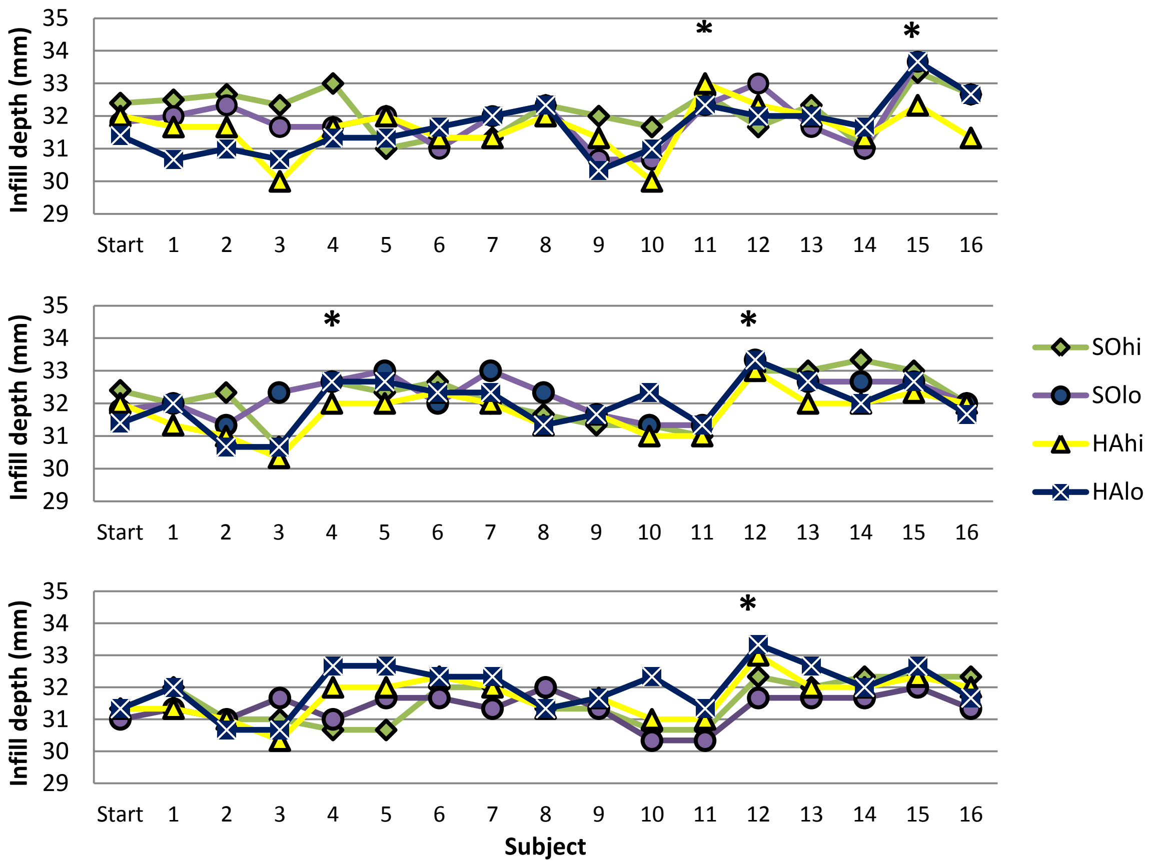


Figure 7.29. Infill depth of surfaces on top of the large force platform during the ST (upper) and JH (middle) test, and on top of the small platform during the JH (lower) test. The top-up occasions are indicated by *.

No significant difference was found for the average infill depth between surfaces during the ST tests. During the JH tests a significant difference was found between some surfaces and between the large and small force platform. The maximal difference between the surfaces (0.6 mm) and force platforms (0.8 mm) were, however, smaller than the predefined 2 mm limit assumed necessary to top up the surfaces. Therefore these differences should have had no effect on either the appearance or properties of the surface. The infill was topped up twice during the ST and JH due to infill being lost from the surfaces through the player movements and moving of the surfaces (Figure 7.30).

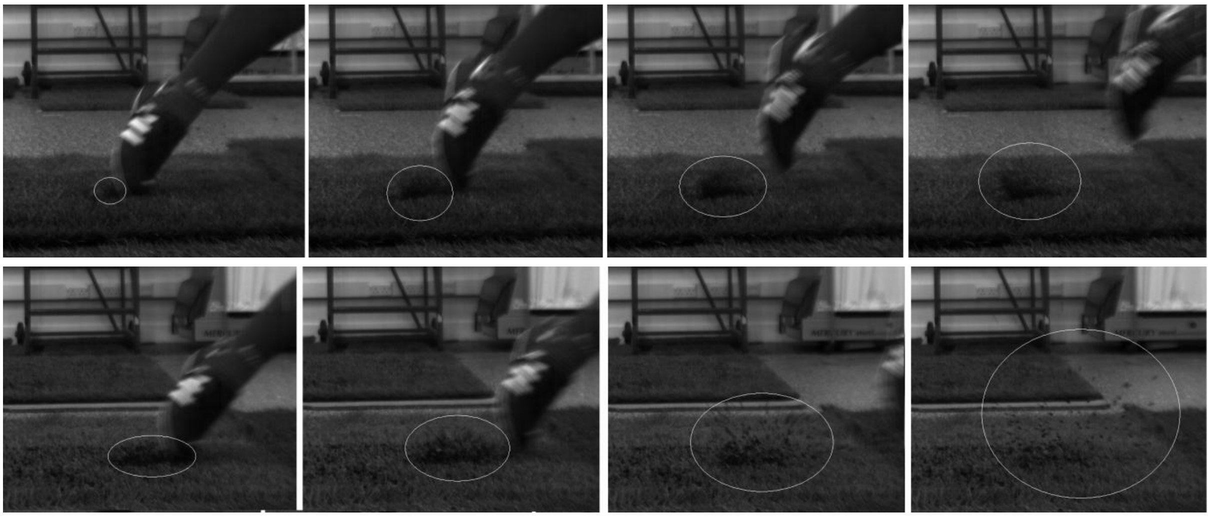


Figure 7.30. The infill of the surfaces was topped up on two occasions over the test period. This was necessary as infill was lost from the surfaces due to the movements. This was both the case for the 1 – 3 mm (upper) and the 2 – 8 mm SBR infill (lower).

7.3.1.2 Rotational Traction

The average rotational traction values of the surfaces were close to the values measured during the design of the surfaces (Chapter 6) (Table 7.2, Figure 7.31). The standard deviation of the rotational traction values over the three test locations during the 16 test days varied from 1.0 – 1.7 Nm, which is within the expected measurement uncertainty of 2 Nm given in the FIFA test guidelines (FIFA, 2012b). The average differences between the surfaces with a high traction and low traction value varied between 9.5 and 10.1 Nm. A significant difference was found between the surfaces with a low traction value (0.6 Nm, p: .000) and between the two locations in the pre-movement area (0.9 Nm, p: .000), but as these differences are small (<10% of the difference between the low and high traction surfaces) and within the measurement uncertainty; therefore it should have minimal effect on the rotational traction experienced by the players. Topping up the surfaces during the test period appeared to have no effect on the rotational traction values (Figure 7.31).

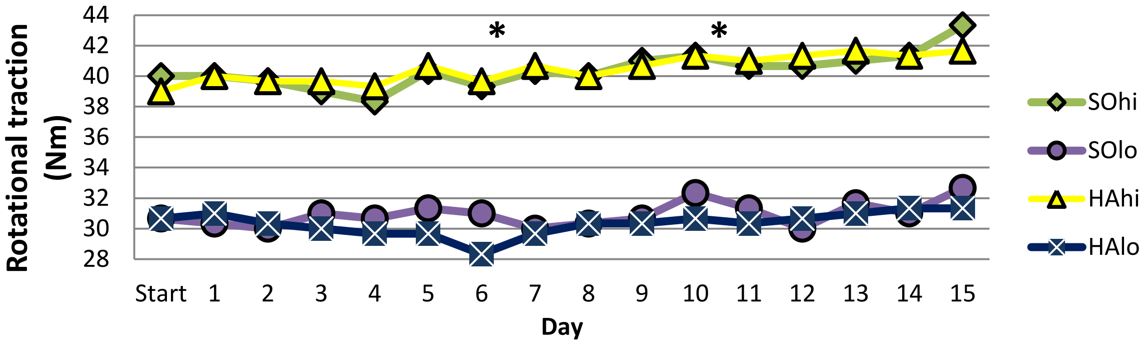


Figure 7.31. Rotational traction results over 15 day test period. RT values stayed at a similar level throughout the test period (* indicates when surfaces were topped up)

7.3.1.3 Force Reduction

The average force reduction (FR) values of the surfaces were close to the values measured during the design of the surfaces (Chapter 6) (Table 7.2, Figure 7.32). The standard deviation of the FR values over the three test locations during the 15 test days varied from 0.7 – 3.6%. The 3.6% variation was slightly higher than the expected measurement uncertainty of 2% as presented in the FIFA test requirements (FIFA, 2012b). Despite this variation there was a clear difference in hardness between the hard and soft surfaces. The average FR difference between soft and hard surfaces varied between 12.3% and 18.8% (Figure 7.32). For the surfaces with a low traction value the average difference was 17.0%, whereas for the surfaces with a high traction value it was 14.2%.

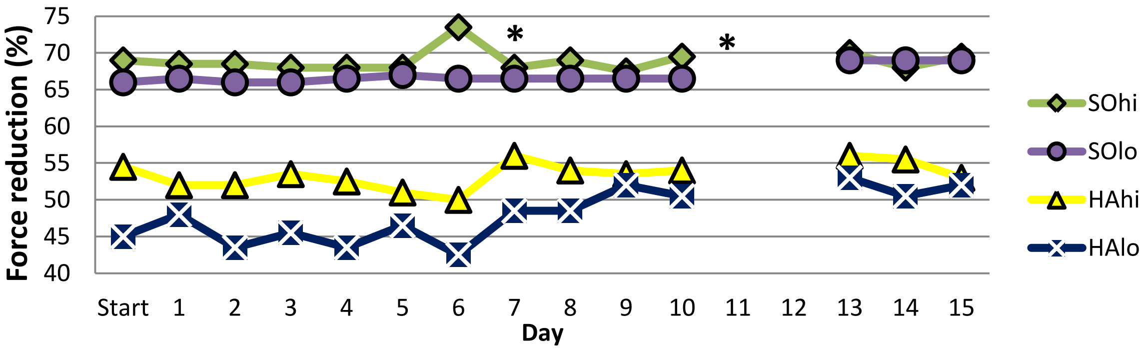


Figure 7.32. AAA results over 15 day test period. FR values stayed at a similar level throughout the test period, no results were available on day 11 and 12 due to a defect on the AAA (* indicates when surfaces were topped up)

Between both soft surfaces a significant difference of 1.9% (p: .000) was found and between both hard surfaces a significant difference of 4.6% (p: .000) was found. For the different test locations a significant difference was found of 1.1% (p: .020). As with the variation the difference between the hard surfaces was higher than the expected measurement error. However, as the difference between the hard and soft surfaces was larger any changes in body dynamics should first be visible between the hard and soft surfaces. Topping up the infill led to an increase in the FR value close to the start values. This effect was mainly visible on the hard surfaces without a shockpad.

7.3.2 Movement Control

The movements of the ST and JH manoeuvres were controlled with different parameters. The ST was controlled by a set approach speed of 3.33 – 4.03 m/s (12 – 14.5 km/h) which was measured during the final 2 m of the approach before deceleration.

The JH was controlled by having the players perform a maximal stop-jump, which for the heading manoeuvres was controlled with the ball height. The maximal jump height was determined with the help of the highest vertical COM location prior to landing.

7.3.2.1 Approach Speed (ST)

The average approach speed on the different surfaces varied from 3.71 – 3.75 m/s and for the in-game conditions 3.72 – 3.73 m/s for the different conditions (Table 7.6). No significant effects were present for surface and in-game conditions.

Table 7.6. Average approach speed (± standard deviation) based on 16 subjects on all four surfaces and both in-game conditions during ST

Surface	HAhi	HAlo	SOhi	SOlo	Opponent	No Opponent
Approach Speed (m/s)	3.71 ± 0.16	3.73 ± 0.18	3.71 ± 0.19	3.75 ± 0.16	3.73 ± 0.66	3.72 ± 0.60

7.3.2.2 Maximal Jumping Height (JH)

The maximal jump heights were similar on all surface conditions and for both in-game conditions. The differences in maximal jump height between the surfaces were maximally 0.6 cm, and not significant, whereas for the in-game scenarios a non significant difference of 0.7 cm was present (Table 7.7).

Table 7.7. Maximal vertical COM (average ± standard deviation) determined over 16 subjects) for the different surface and in-game conditions during JH

Surface	HAhi	HAlo	SOhi	SOlo	Jumping	Heading
Max COM (cm)	156.4 ± 6.7	156.4 ± 6.4	157.0 ± 6.6	156.4 ± 6.0	156.9 ± 6.0	156.2 ± 6.7

7.3.3 Ground Contact Time (ST)

The average ground contact times varied from 470 – 509 ms over all the surfaces with a significantly shorter ground contact time on the HAhi compared to the HAlo surface (24 ms, p: .014) (Figure 7.33). In addition to this the ground contact times were lower on the soft (15 – 22 ms) and high traction surfaces (17 – 24 ms). Though the effects were not significant between all surface conditions. Between the in-game scenarios no significant difference in ground contact time was present.

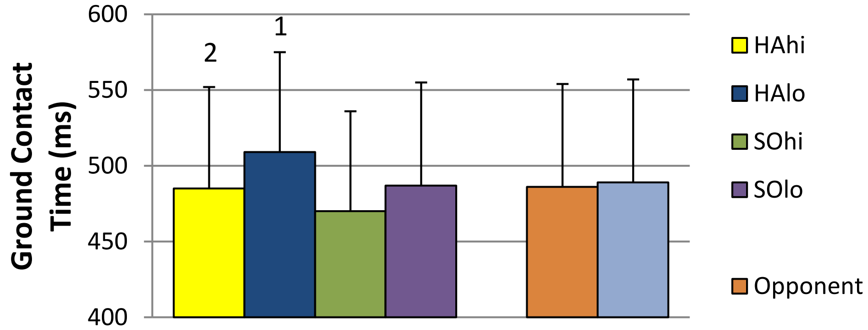


Figure 7.33. Average ground contact time (± standard deviation) of the ST determined over 16 subjects. The ground contact time was significantly higher on the HAlo surface than on the HAhi surface (p: .014). Between the other surfaces and in-game conditions no significant differences were present, but the ground contact times on the soft and high traction surfaces were lower. (1: significant effect HAhi; 2: significant effect HAlo)

7.3.4 Ground Reaction Forces

7.3.4.1 Stop and Turn

During the ST the average vertical GRF (Fz) ranged from 0.309 times the body weight of the subject (BW) during the FP phase to 1.266 BW during the MS phase (Table 7.8). During the MS, PO (p: .039) and FP phase a significant difference was found between the SOhi and HAlo surface with higher Fz on the SOhi surface during MS (0.080 BW, p: .035) and a higher Fz on the HAlo surface during PO (0.067 BW, p: .039) and FP (0.048 BW, p: .034) (Figure 7.35). Between other surface conditions no significant differences were present, but during MS Fz was slightly higher on the high traction and soft surfaces.

Table 7.8. Average GRFs (± standard deviation) based on all trials of 16 subjects during ST

Direction	WA	MS	PO	FP
Fz	1.081 ± 0.178	1.266 ± 0.126	1.116 ± 0.140	0.309 ± 0.074
Fy	0.258 ± 0.058	0.298 ± 0.058	0.268 ± 0.045	0.062 ± 0.022
Fx	0.050 ± 0.033	0.031 ± 0.037	0.030 ± 0.035	-0.007 ± 0.028

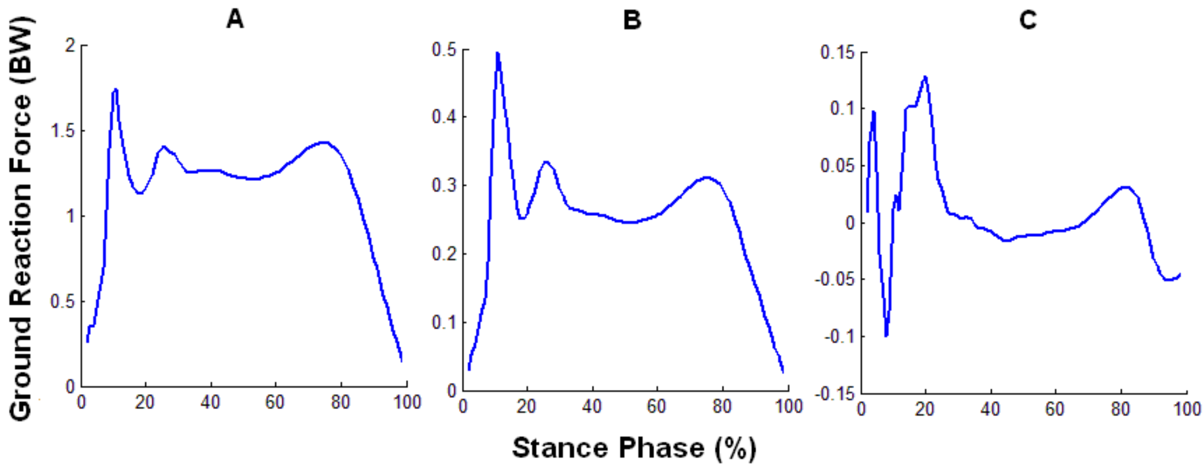


Figure 7.34. Typical GRF curves during the ground contact phase of the ST. A= Fz, B= Fy C= Fx.

The average GRF in the horizontal directions were no higher than 0.298 BW for Fy during the MS phase and 0.050 BW for Fx during the WA phase (Table 7.8). Between the different surface conditions Fy was significantly higher on the HAlo surface compared to the HAhi surface during the FP (0.011 BW, p: .043) (Figure 7.35). For the other surfaces and phases no significant differences were present, but as for Fz the force was slightly higher on the high traction and soft surfaces for Fy during MS.

The inclusion of a simulated opponent had no significant effect on the average GRF in all directions, with a maximal difference of 0.008 BW.

The peak vertical impact force varied between 1.714 and 1.867 BW for the different surface conditions (Figure 7.36). A significant effect was present between the HAhi surface and both soft surfaces (SOhi, p: .022, SOlo, p: .024), for which the peak impact force was increased on the HAhi surface. The HAlo surface showed no significant effects with any of the other surfaces. No effects were present between the in-game conditions for the peak vertical impact force.

The peak forces during the WA phase in the horizontal directions varied between 0.383 and 0.411 BW for Fy (Figure 7.37), 0.118 and 0.138 BW for the positive Fx peak and between -0.036 and -0.048 BW for the negative Fx peak (Figure 7.38). No significant effects were present between any of the surface conditions and in-game scenarios.

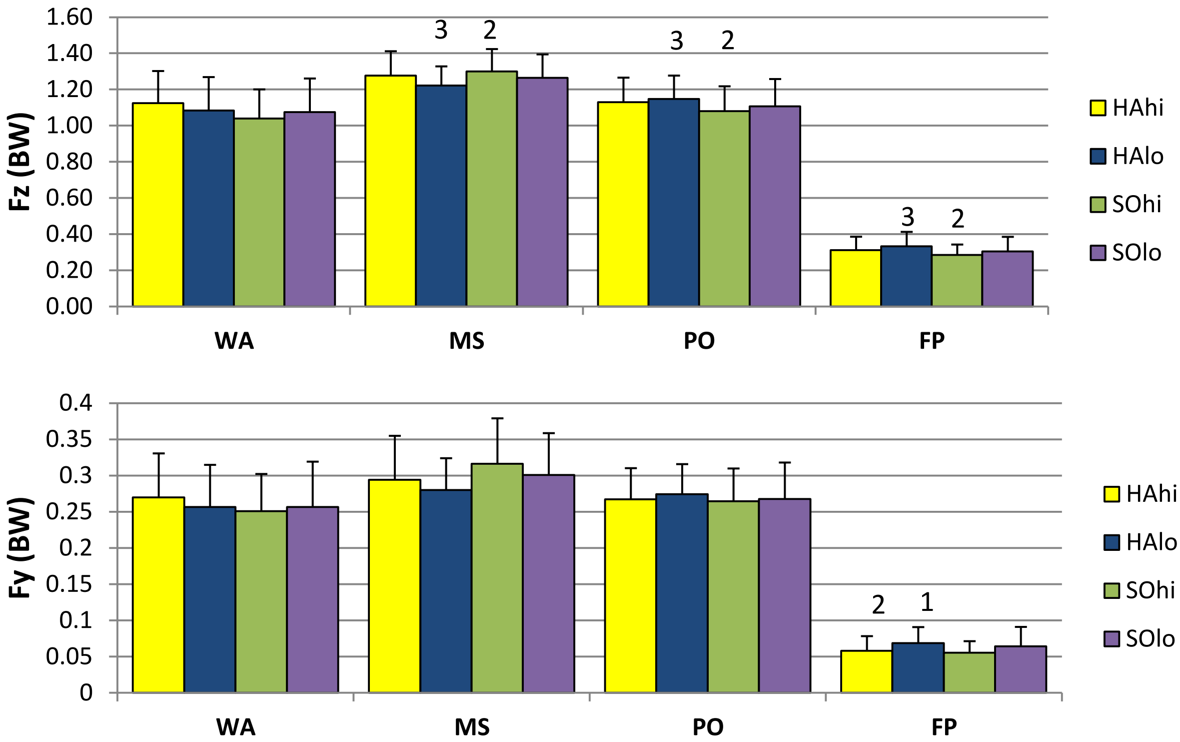


Figure 7.35. Average GRF (± standard deviation) for Fz and Fy during all phases of the ST determined over 16 subjects. For Fz a significant difference was present between the HAlo and SOhi surface during MS (p: .035), PO (p: .039) and FP (p: .034) direction, whereas for Fy a significant difference was present between the HAhi and HAlo surface during FP (p: .034). During MS Fz and Fy were slightly higher on the high traction and soft surfaces. (1: significant effect HAhi; 2: significant effect HAlo; 3: significant effect SOhi)

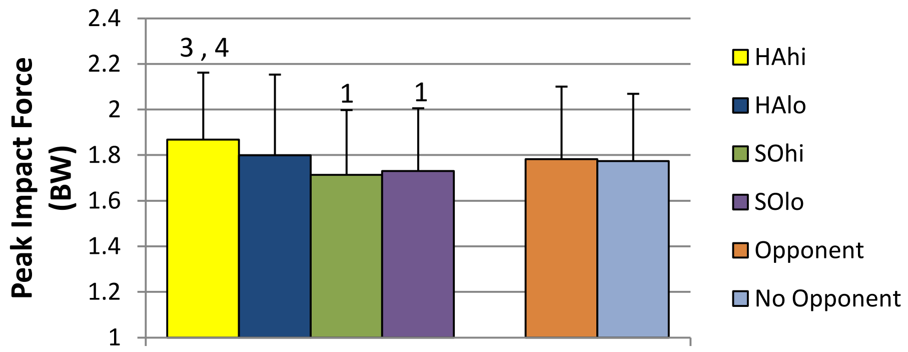


Figure 7.36. Peak vertical impact force (± standard deviation) during WA phase of the ST determined over 16 subjects. Between surface conditions the impact force was significantly higher on the HAhi surface compared to the SOhi (p: .022) and SOlo (p: .024) surface, whereas the HAlo surface did not show any significant effects.

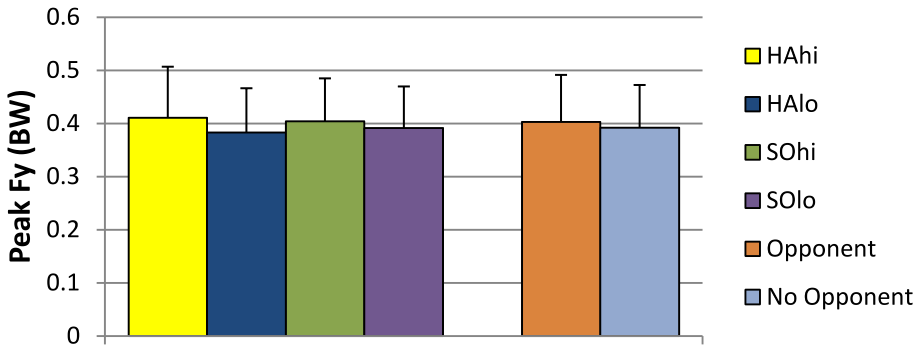


Figure 7.37. Peak force (± standard deviation) of Fy during WA phase of the ST determined over 16 subjects. In this direction no significant effects were present for the surface conditions and in-game scenarios.

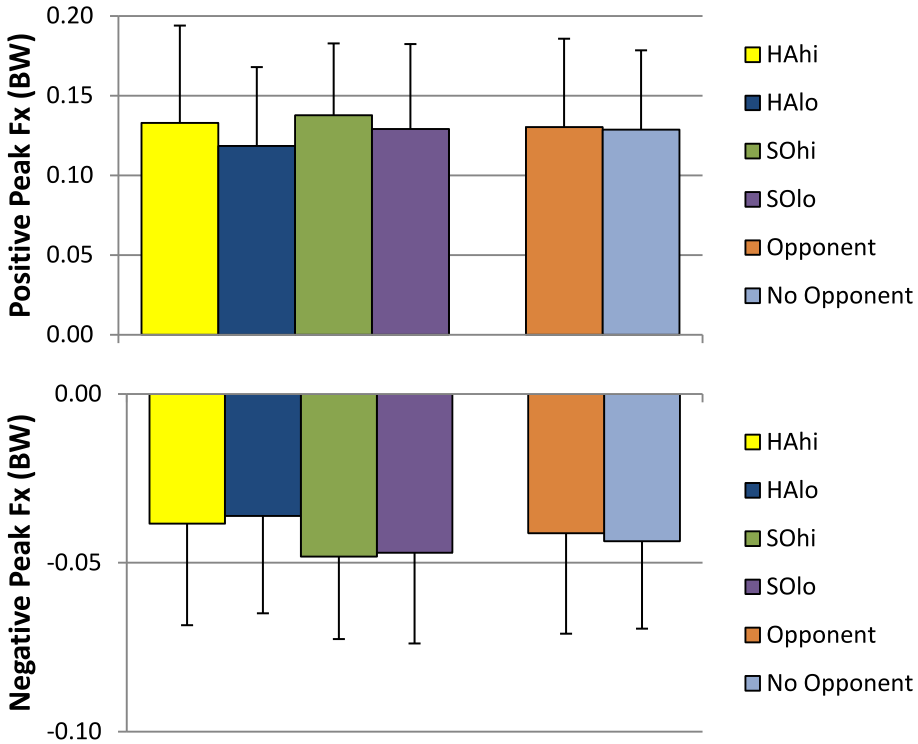


Figure 7.38. Positive and negative peak force (± standard deviation) of Fx during WA phase of the ST determined over 16 subjects. In this direction no significant effects were present for the surface conditions and in-game scenarios.

7.3.4.2 Jumping / Heading

During the JH manoeuvres the average forces varied from 0.067 BW for Fy to 1.579 BW for Fz (Table 7.9). In the horizontal directions the highest forces were present during the KNF phase, whereas for Fz the average force was highest during IMP. Between the surface conditions no significant effects were present (Figure 7.40).

The different in-game scenarios showed significant effects in all directions during the KNF phase of the landing (Figure 7.41). During KNF, Fz was on average 5.8% (p: .010) higher during the heading condition, whereas Fy was on average 12.6% higher (p: .004). The force for Fx was also higher for the heading condition, with a difference of 9.0% (p: .020).

Table 7.9. Average GRF (± standard deviation) based on all trials of 16 subjects during JH

Direction	IMP	KNF	FIN
Fz	1.579 ± 0.318	1.445 ± 0.297	0.877 ± 0.169
Fy	0.125 ± 0.062	0.160 ± 0.062	0.067 ± 0.042
Fx	0.096 ± 0.029	0.118 ± 0.034	0.074 ± 0.027

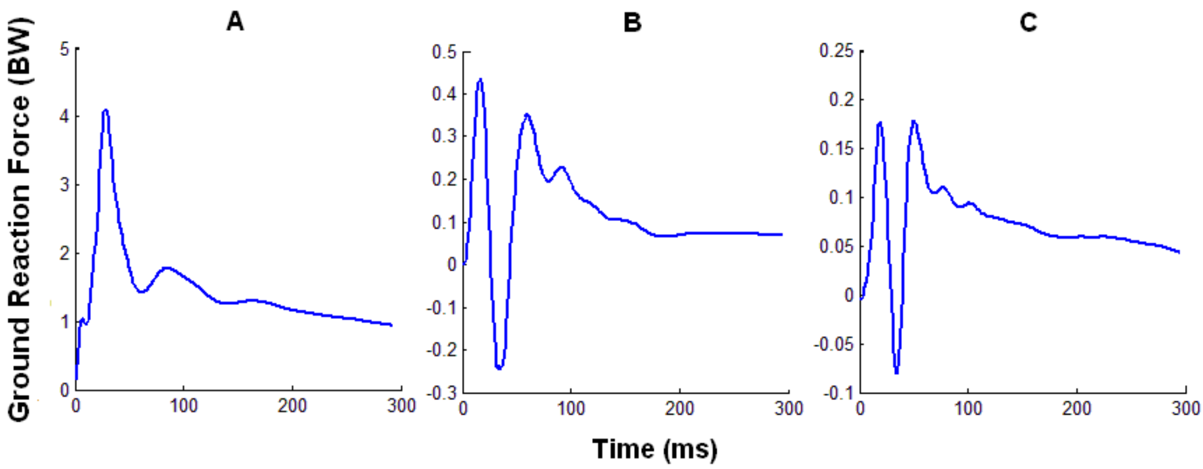


Figure 7.39. Typical GRF curves from the initial impact to the end of the FIN phase of the JH. A= Fz, B= Fy C= Fx.

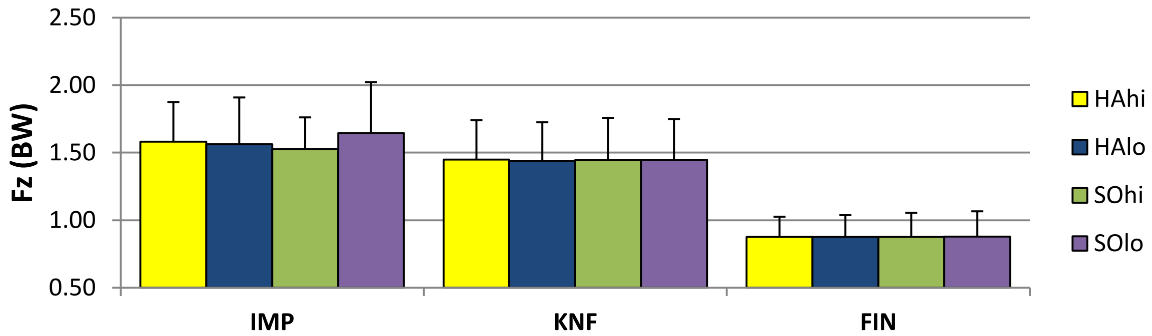


Figure 7.40. Average vertical GRF (± standard deviation) during all phases of the JH determined over 16 subjects. While it was expected that the hardness of the surface would affect the vertical GRF (Fz) no significant difference was present between any of the surfaces.

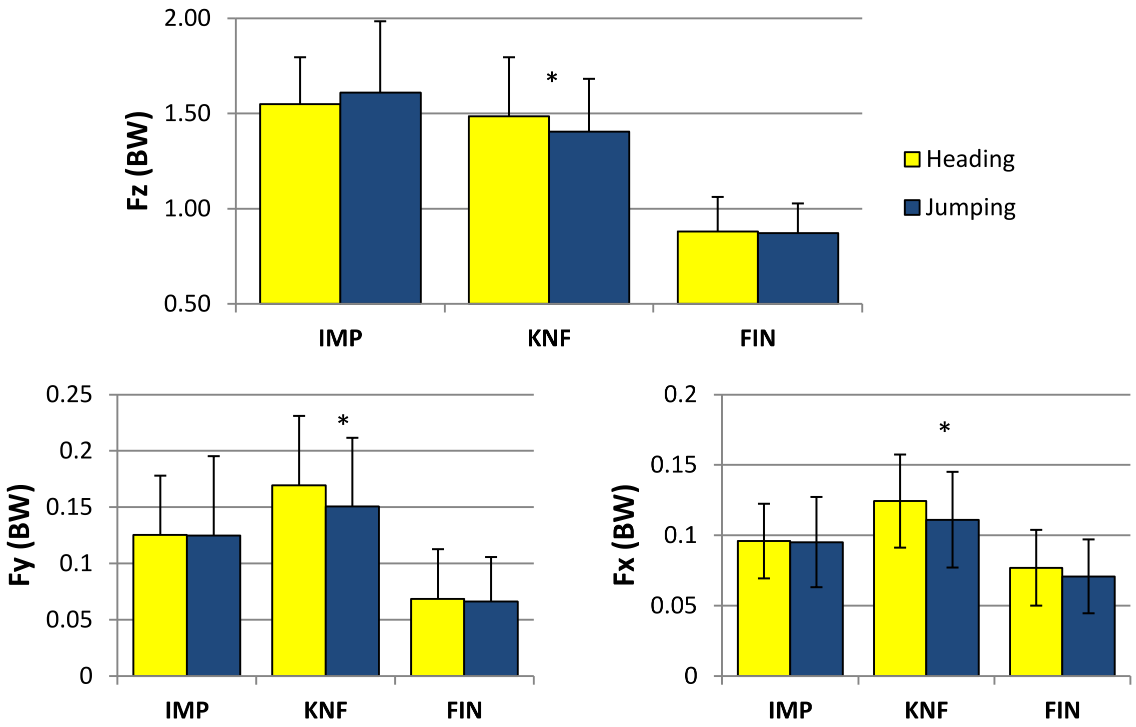


Figure 7.41. Average GRF (± standard deviation) for Fz, Fy, and Fx during all ground contact phases of the JH determined over 16 subjects. In all directions the GRF was significantly higher during the heading condition in the KNF phase. (* significant effect)

The peak impact force varied between 3.883 and 4.368 BW for the different surface conditions (Figure 7.42). The peak impact force was higher on the hard surfaces than on the soft surfaces. Significant effects were present between both hard surfaces and the SOhi surface (HAhi, p: .008, HAlo, p: .004). Furthermore, a significant effect was present between the HAlo and SOlo surface (p: .005), and the difference between the HAhi and SOlo surface approached significance (p: .077). No effects were present between the in-game scenarios.

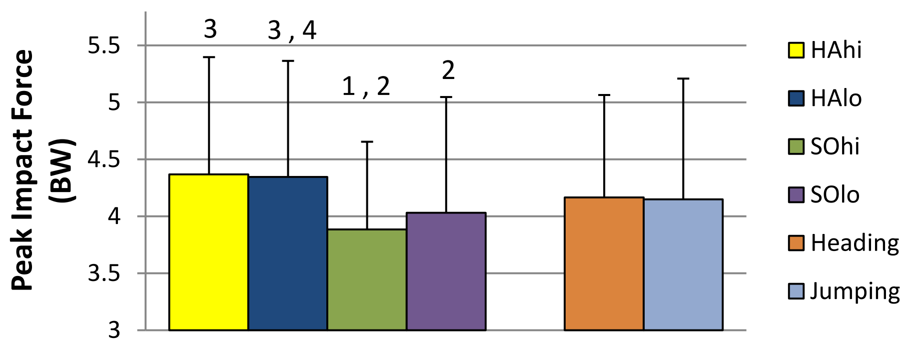


Figure 7.42. Peak vertical impact force (± standard deviation) of the JH determined over 16 subjects. Between surface conditions the impact force was higher on the hard surfaces compared to the soft surfaces with significant differences between the SOhi surface with the HAhi (p: .008) and HAlo (p: .004) surface, and between the SOlo and HAlo surface (p: .005). The difference between the HAhi and SOlo surface approached significance (p: .077).

The peak forces during the horizontal directions varied between 0.377 and 0.564 BW for the positive Fy peak and between -0.345 and -0.388 BW for the negative Fy peak (Figure 7.43). In the Fx direction the peak forces varied between 0.239 and 0.255 BW for the positive Fx peak and between -0.052 and -0.062 BW for the negative Fx peak (Figure 7.44). The surface conditions showed a significant increase for the SOhi surface compared to all other surfaces (HAhi, p: .042; HAlo, p: .007; SOlo, p: .004) for the positive peak force for Fy (Figure 7.43). This increase was no larger than 0.050 BW. No significant effects were present between the surface conditions for the negative Fy peak and the Fx peaks (Figure 7.43, Figure 7.44).

The in-game scenarios showed a significant increase for the positive Fy peak (p: .000) and negative Fx peak (p: .010) during the jumping condition.

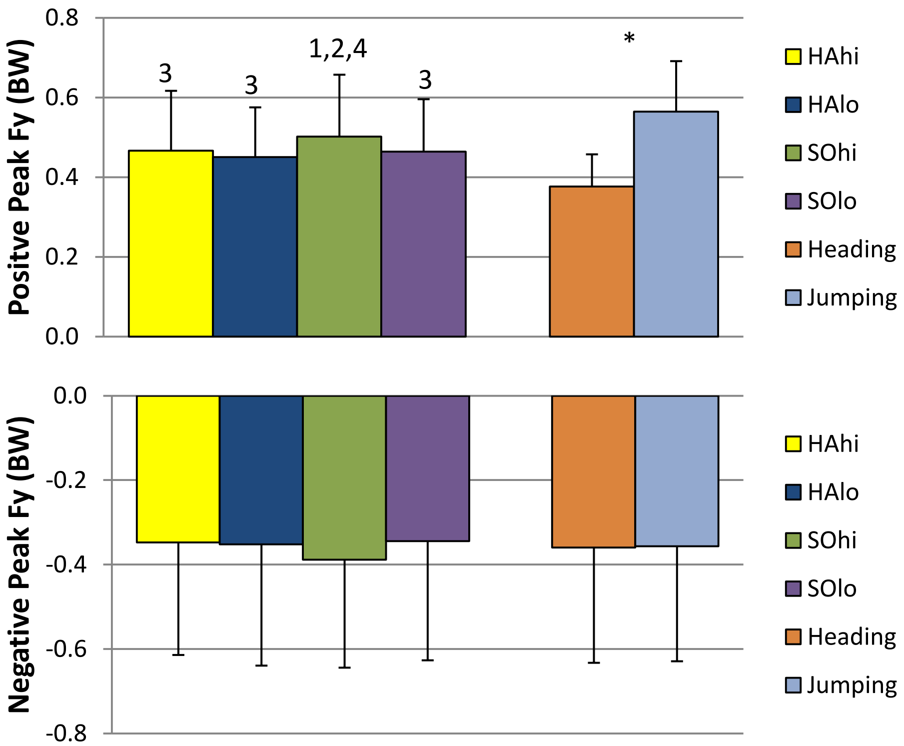


Figure 7.43. Positive and negative peak force (± standard deviation) for Fy of the JH determined over 16 subjects. Between surface conditions the positive Fy peak was significantly increased on the SOhi surface compared to all other surfaces (HAhi, p: .042; HAlo, p: .007; SOlo, p: .004). Between, the other surfaces and for the negative Fy peak no significant effects were present. Between in-game scenarios the positive Fy peak was significantly increased during the jumping condition (p: .000), the negative Fy peak showed no significant effects.

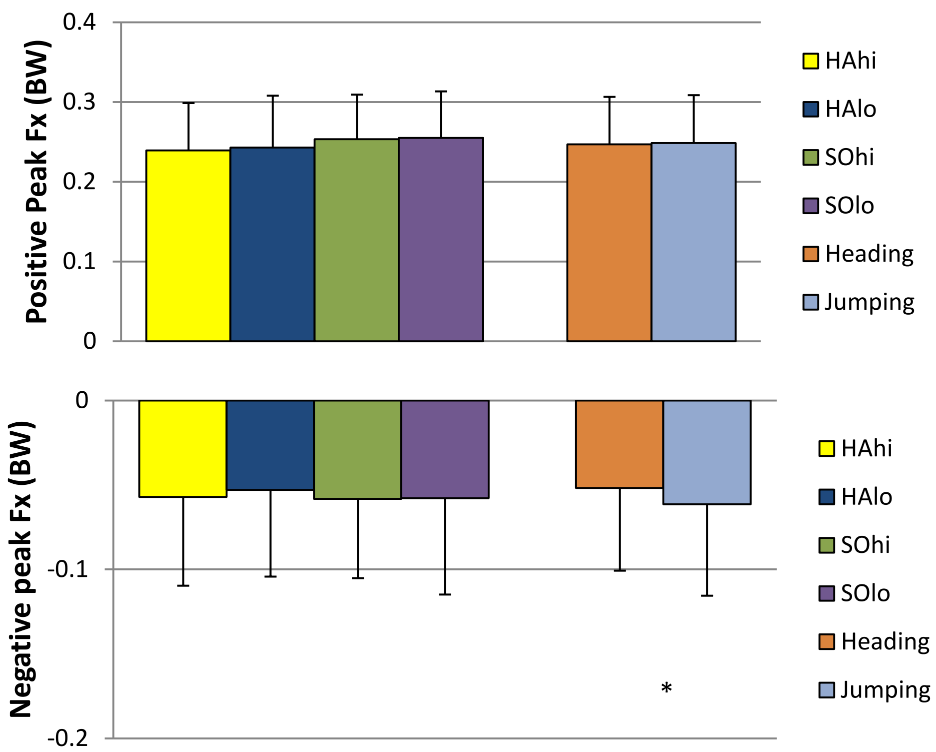


Figure 7.44. Positive and negative peak force (± standard deviation) for Fx of the JH determined over 16 subjects. Between surface conditions no significant effects were present for the peak Fx. For the in-game scenarios a significant increase was present for the negative Fx peak during the jumping condition (p: .010).

7.3.5 Loading Rates

7.3.5.1 Stop and Turn

The average loading rate varied from 42.8 to 53.7 BW/s for the different surface conditions (Figure 7.45). The average loading rate was significantly higher on both hard surfaces compared to the SOhi surface (HAhi, p: .048, HAlo, p: .042). The SOlo surface showed no significant effects with any of the other surfaces. No significant effects were present between the in-game scenarios.

The peak loading rate varied from 93.2 to 122.0 BW/s on the different surface conditions and was significantly increased on the HAhi surface compared to the SOhi surface (p: .022) (Figure 7.46). In addition to this, differences between the HAhi and SOlo (p: .075) and HAlo and SOhi (p: .084) approached significance. Similar to the average loading rates no significant effects were present between the in-game scenarios.

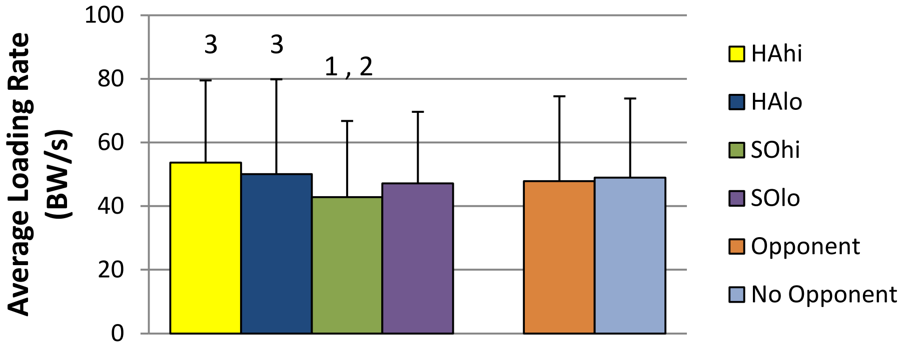


Figure 7.45. Average loading rate of the peak vertical impact force during the WA phase of the ST (± standard deviation) determined over 16 subjects. The average loading rate was significantly higher on the hard surfaces compared to SOhi surface (HAhi, p: .048, HAlo, p: .042). Between in-game scenarios no significant differences were present. (1: significant effect HAhi; 2: significant effect HAlo; 3: significant effect SOhi).

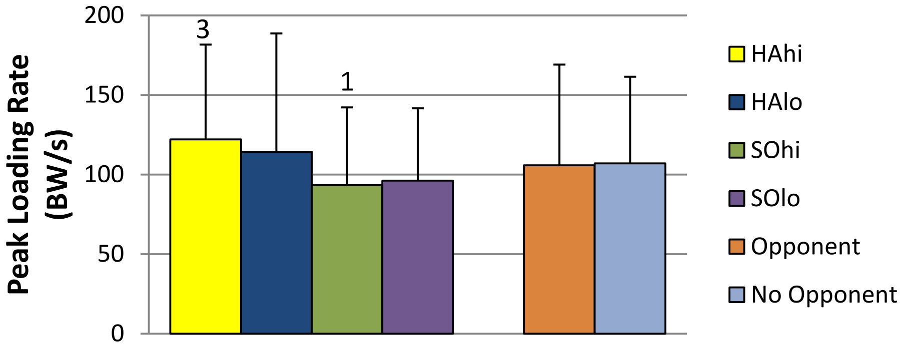


Figure 7.46. Peak loading rate of the peak vertical impact force during the WA phase of the ST (± standard deviation) determined over 16 subjects. The peak loading rate was higher on the hard surfaces compared to the soft surfaces with significant differences between the HAhi and SOhi surface (p: .022). Between in-game scenarios no significant differences were present. (1: significant effect HAhi; 2: significant effect HAlo; 3: significant effect SOhi).

7.3.5.2 Jumping / Heading

The average loading rate varied from 124.84 to 165.18 BW/s for the different surface conditions (Figure 7.47). Between the surface conditions a significant effect was present between the HAhi and SOhi surface (p: .022), with an increased average loading rate on the HAhi surface. For the in-game scenarios the average loading rate was significantly increased during the jumping condition (p: .006).

The peak loading rate varied from 350.67 to 500.52 BW/s for the different surface conditions (Figure 7.48). The peak loading rate was significantly (p: .000) increased on both hard surfaces compared to both soft surfaces. Between in-game scenarios the peak loading rate was significantly higher during the jumping condition (p: .048)

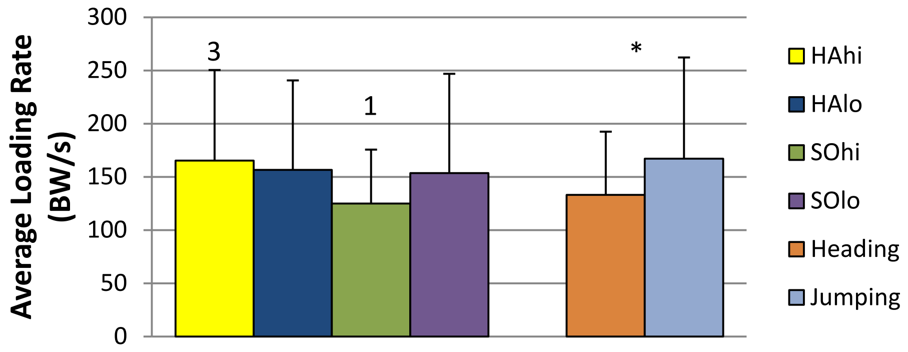


Figure 7.47. Average loading rate of the peak vertical impact force during the landing of the JH (± standard deviation) determined over 16 subjects. The average loading rate was significantly higher on the HAhi surface compared to SOhi surface (p: .022). For the in-game scenarios a significantly higher average loading rate was found for the jumping condition (p: .006). (1: significant effect HAhi; 3: significant effect SOhi; *: significant effect in-game scenarios).

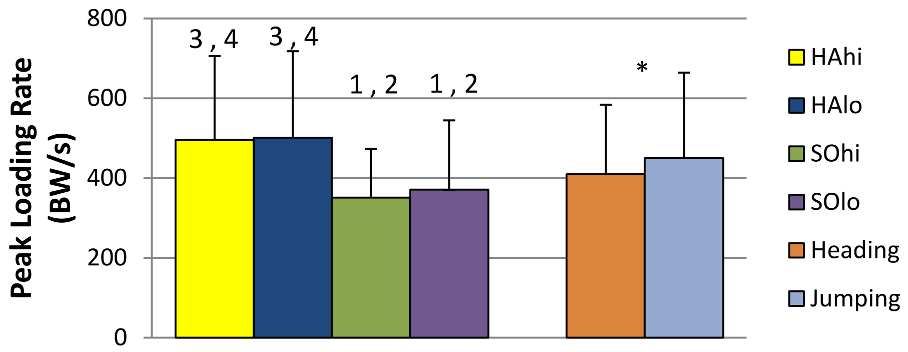
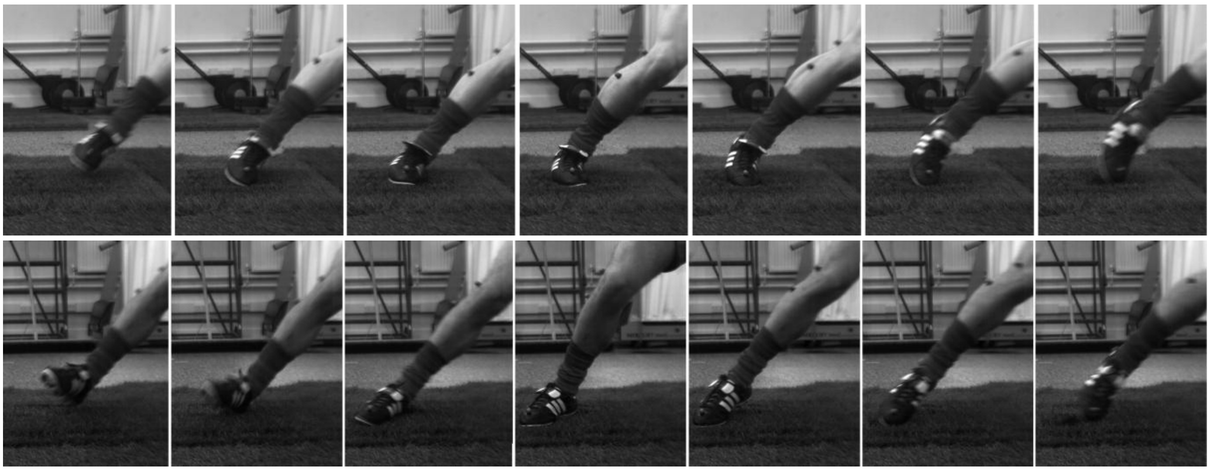


Figure 7.48. Peak loading rate of the peak vertical impact force the landing of the JH (± standard deviation) determined over 16 subjects. The peak loading rate was significantly higher on the hard surfaces (p: .000) compared to the soft surfaces. Between in-game scenarios the peak vertical impact force was significantly higher during the jumping condition (p: .048). (1: significant effect HAhi; 2: significant effect HAlo; 3: significant effect SOhi; 4: significant effect SOlo; *: significant effect in-game scenarios).

7.3.6 Lower Limb Movement (ST)

7.3.6.1 Foot Contact

All players planted their foot during the ST at a ~90° to the running direction (Figure 7.49). For the majority of the ST trials and players, the players landed on the medial part of their forefoot, for the other instances they landed on the medial part of their heel (Figure 7.49). After the initial ground contact the heel, or forefoot, was brought to the surface and the weight was shifted from the medial part of the foot towards the lateral part during mid-stance. The highspeed video footage also showed that during the medial – lateral shift the foot also twisted, suggesting the foot does not act as a single segment as used in the plug-in-gait model. During the push-off the heel was lifted off the surface and the weight was shifted towards the medial part of the forefoot after which the foot was lifted of the surface.



PRE **Touchdown** **WA** **MS** **PO** **FP** **Toe-off**

Figure 7.49. Representation of the different foot strikes found during the ST with the high speed video camera. The upper sequence shows a forefoot strike during which the foot makes initial contact with the medial front part of the foot. The lower sequence shows a heel strike during which the foot makes initial ground contact with the medial heel part of the foot. Take-off of the foot was similar with the front medial part of the foot being the last part to leave the surface.

The highspeed video footage suggested that the rotation of the foot during ground contact was minimal. Looking at the rotation of the foot segment in the global lab coordinate system in the Vicon data showed that on average the foot rotated a total of 11.6° in the turning direction (Table 7.10). Furthermore, rotation of the foot during the ST was not linear and the rotation during the MS phase was minimal. This is also confirmed by the rotation curves of the foot (Figure 7.50). These curves also showed that for some subjects / trials the foot did not continuously rotate in the direction of the turn. No significant effects were found for either surface or in-game conditions.

Table 7.10. Average foot rotation angles (± standard deviation) during the stop and turn determined over 16 subjects

	TOTAL	**WA**	**MS**	**PO**	**FP**
Foot Rotation (°)	11.6 ± 5.8	6.6 ± 3.1	1.2 ± 1.0	3.1 ± 1.7	5.4 ± 3.3

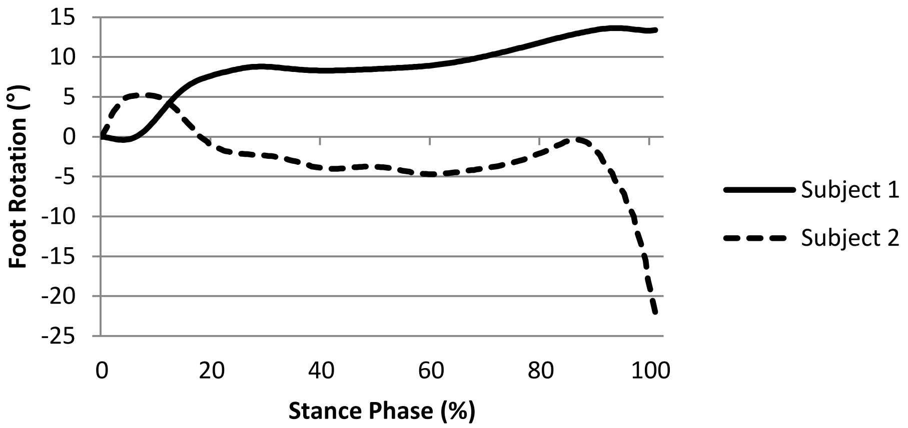


Figure 7.50. Examples of foot rotation during ground contact of the ST. The graph shows that the foot rotation was not linear and that the foot rotation during MS (40-60%). Furthermore, for some subjects / trials the foot did not rotate continuously in the direction of the turn. In this example (Subject 2), the foot rotated in the opposite direction of the turn just after ground contact and also during the final 15% of ground contact.

7.3.6.2 Ankle

During the ST the ankle joint moved from plantar flexion during the PRE phase to dorsi flexion during the WA phase and back to plantar flexion during the FP phase (Table 7.11). On average the ankle was inverted during all phases with an increase in inversion from the PRE phase to the MS phase of the ST. Furthermore the external rotation of the ankle joint increased during the same phases.

Between the surface conditions, the differences in average angle were no larger than 2.1° and no significant differences were present. Also for the in-game scenarios the angle differences were small, no larger than 0.8°. A significant difference of 0.1° (p: .041) was present for the ankle inversion during the PO phase of the ST (Figure 7.52). This small difference was also present during the other phases, but it was not significant.

Table 7.11. Average ankle angles (± standard deviation) during the stop and turn determined over 16 subjects

Angle (°)	PRE	WA	MS	PO	FP
Plantar (-) / Dorsi (+) Flexion	-5.9 ± 5.5	7.8 ± 4.9	22.7 ± 7.4	15.1 ± 5.6	-6.3 ± 4.7
Eversion (-) / Inversion (+)	1.0 ± 2.7	2.6 ± 3.0	3.7 ± 3.0	3.9 ± 3.1	3.7 ± 2.7
External (-) / Internal (+) Rotation	-5.2 ± 12.5	-12.1 ± 12.9	-17.3 ± 11.5	-18.1 ± 12.3	-17.5 ± 11.4

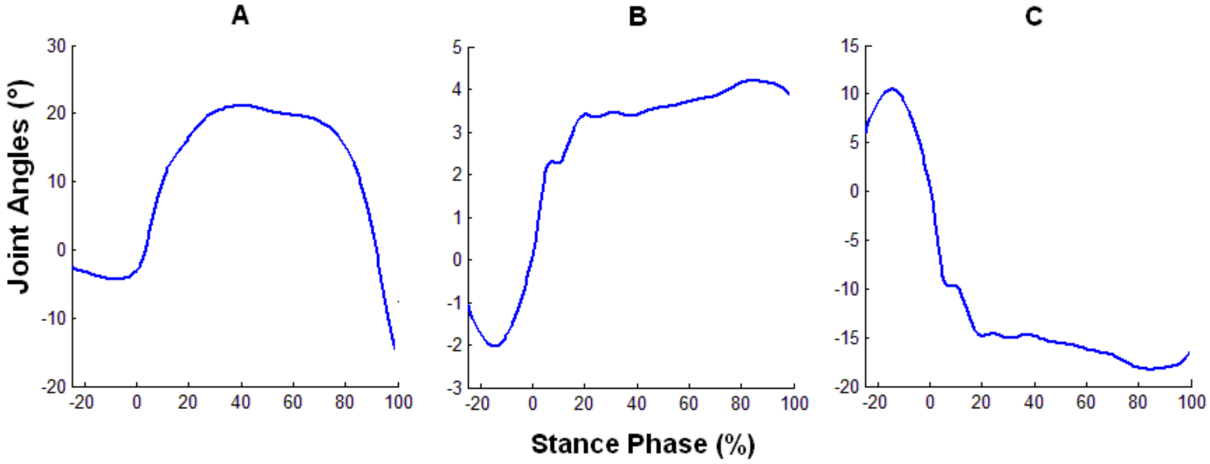


Figure 7.51. Typical movement curves of the ankle joint during the ground contact phase of the ST and PRE phase. A= plantar / dorsi flexion, B= eversion / inversion, C= external / internal rotation.

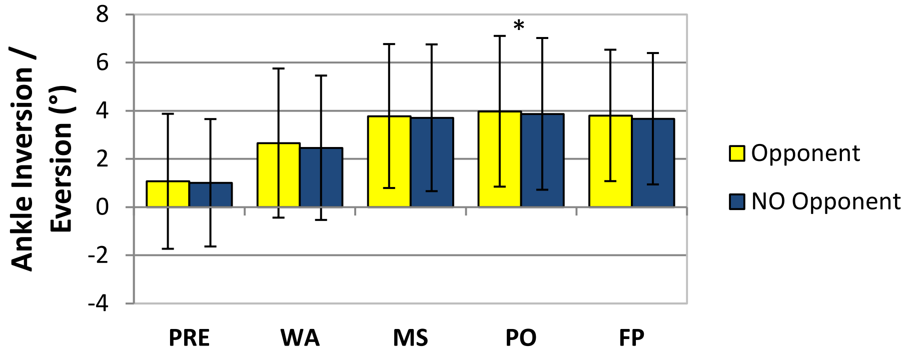


Figure 7.52. Average ankle inversion / eversion angles (± standard deviation) during all phases of the ST determined over 16 subjects. A significant difference was present between the in-game conditions during PO (0.1°, p: .041). (* significant effect)

7.3.6.3 Knee

During all phases of the ST the knee was flexed with average values varying from 26.5° during FP to 64.2° during MS (Table 7.12). On average the knee was in a varus position during all phases reaching a maximum of ~12° during the MS and PO phase. Knee rotation was limited during the PRE phase and led up to an average 8.6° internal rotation during MS and reaching an average external rotation of 7.8° during FP.

Table 7.12. Average knee angles (± standard deviation) during the stop and turn determined over 16 subjects

Angle (°)	PRE	WA	MS	PO	FP
Extension (-) / Flexion (+)	26.5 ± 7.9	37.7 ± 7.4	64.2 ± 8.3	45.7 ± 8.7	25.6 ± 6.9
Valgus (-) / Varus (+)	2.1 ± 6.1	5.4 ± 10.4	12.2 ± 13.9	12.0 ± 11.3	8.1 ± 7.3
External (-) / Internal (+) Rotation	-1.5 ± 10.7	3.1 ± 10.9	8.6 ± 10.2	3.2 ± 10.4	-7.8 ± 10.4

Between surface conditions the differences in knee angles were not significant with maximal differences of 1.7°. The in-game scenarios also showed no significant differences in knee angles, with a maximal difference of 0.8°.

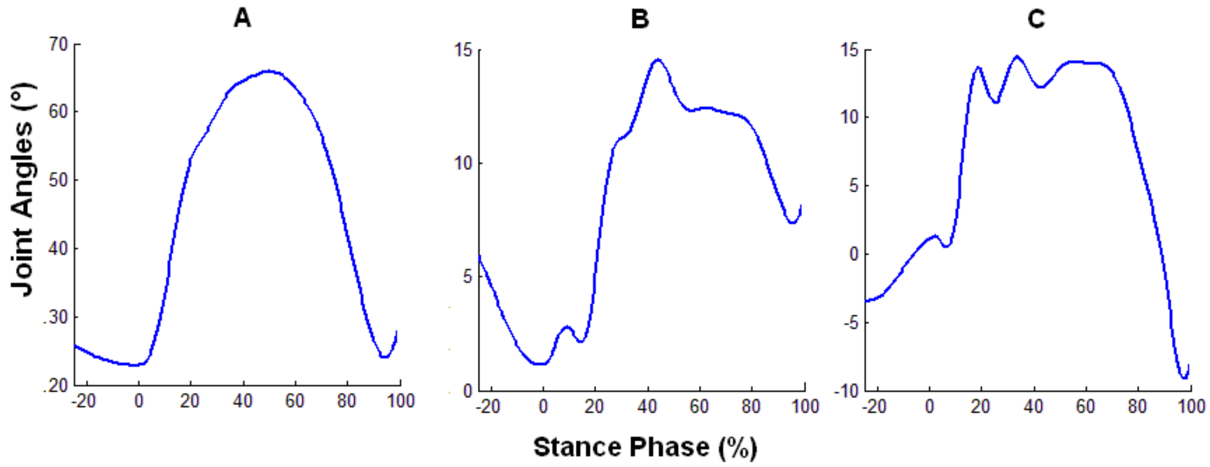


Figure 7.53. Typical movement curves of the knee joint during the ground contact phase of the ST and PRE phase. A= extension / flexion, B= valgus / varus, C= external / internal rotation.

7.3.6.4 Hip

The hip was flexed during all phases of the ST with an average maximal flexion of 54.4° during MS (Table 7.13). Furthermore the hip was adducted between 24.4° during the PRE phase to 33.5° during the PO phase. The internal rotation of the hip reached a maximum of 11.0° during the MS phase, after which the hip rotated to a 5.2° external rotation during FP. Between the different surface conditions, no significant differences were present in hip angles, with maximum differences of 2.7°. Differences between in-game conditions were also non-significant, with maximum differences of 0.3°.

Table 7.13. Average hip angles (± standard deviation) during the stop and turn determined over 16 subjects

Angle (°)	PRE	WA	MS	PO	FP
Extension (-) / Flexion (+)	37.0 ± 11.5	40.6 ± 14.2	54.4 ± 17.5	32.9 ± 15.3	14.5 ± 10.8
Abduction (-) / Adduction (+)	-24.4 ± 4.6	-26.6 ± 5.6	-30.0 ± 6.7	-33.5 ± 7.3	-27.5 ± 7.3
External (-) / Internal (+) Rotation	2.3 ± 16.0	6.8 ± 17.2	11.0 ± 17.6	-0.7 ± 18.1	-5.2 ± 16.6

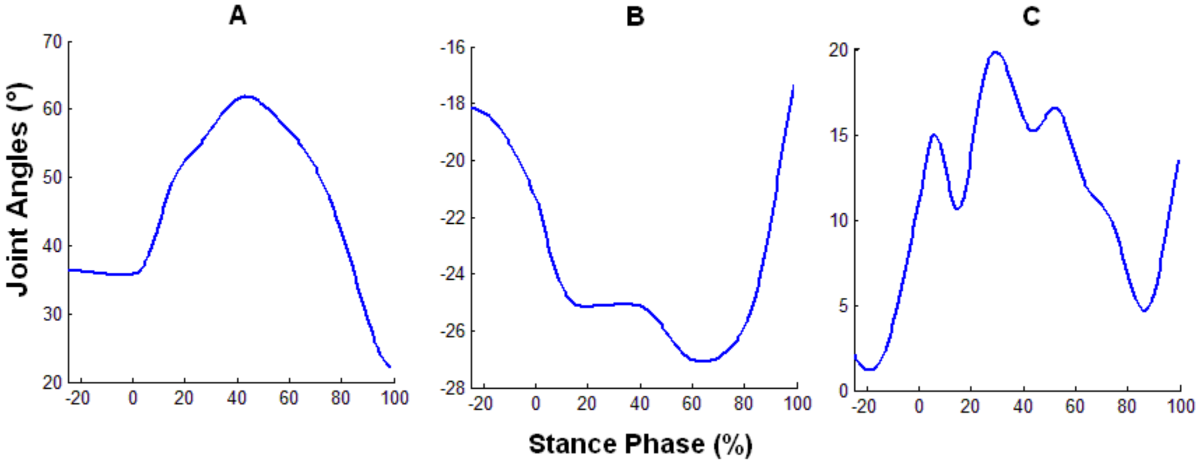


Figure 7.54. Typical movement curves of the hip joint during the ground contact phase of the ST and PRE phase. A= extension / flexion, B= abduction / adduction, C= external / internal rotation.

7.3.7 Upper Body Movement (ST)

During all phases of ST the spine was flexed and the thorax tilted forward (Table 7.14, Table 7.15). Both the spine and the thorax reached maximum flexion and forward tilt during the MS phase after which the spine extended and the thorax tilt decreased during PO and FP. In addition to the forward flexion and tilt, the players also used a lateral bend of the spine to the same side as the turning direction, in which the thorax was also tilted, reaching an average lateral bend of 6.0° and sideways tilt of 15.0° during the MS phase.

Table 7.14. Average spine rotation angles (± standard deviation) during the stop and turn determined over 16 subjects

Angle (°)	PRE	WA	MS	PO	FP
Extension (-) / Flexion (+)	18.8 ± 10.9	25.3 ± 11.2	35.3 ± 11.3	28.1 ± 12.8	20.0 ± 13.7
Lateral Bend opposite side turn (-) / same side turn (+)	3.2 ± 6.0	4.6 ± 6.3	6.0 ± 7.1	4.0 ± 7.1	2.2 ± 8.5
Rotation in opposite direction as turn (-) / same direction as turn (+)	7.1 ± 3.9	8.2 ±5.1	4.9 ± 6.8	-3.6 ± 7.6	-5.9 ± 7.3

Table 7.15. Average thorax angles (± standard deviation) during the stop and turn determined over 16 subjects

Angle (°)	PRE	WA	MS	PO	FP
Backward (-) / Forward (+) Tilt	30.6 ± 16.2	36.8 ± 17.6	49.4 ± 21.0	39.6 ± 23.1	30.5 ± 24.8
Lateral Tilt opposite side as turn (-) / same side as turn (+)	10.6 ± 12.3	11.4 ± 14.7	15.0 ± 18.8	24.7 ± 14.8	30.0 ± 12.9
Rotation in same direction as approach (-) / opposite direction as approach	-7.8 ± 27.5	-0.3 ± 26.4	10.3 ± 25.1	28.7 ± 30.6	41.3 ± 34.5

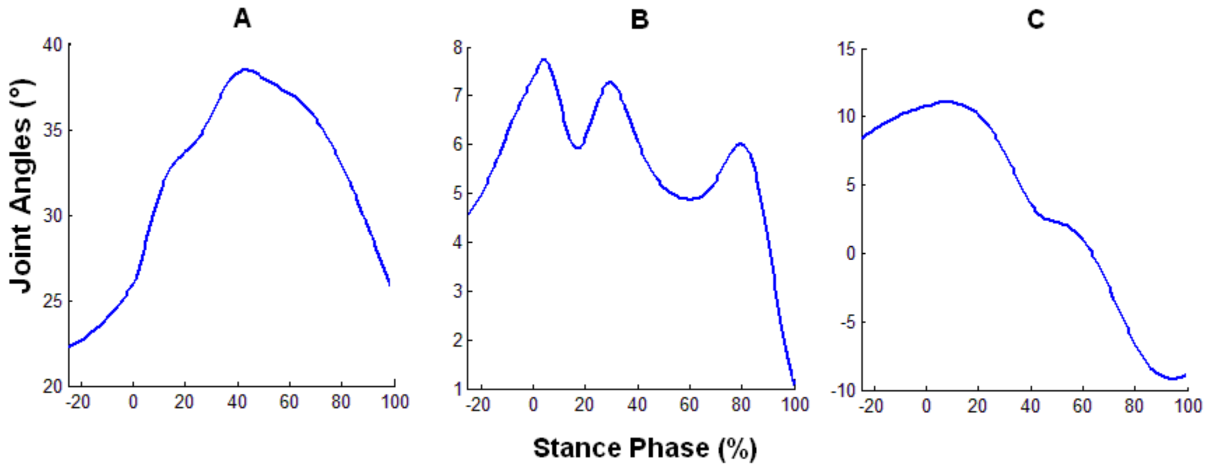


Figure 7.55. Typical movement curves of the spine joint during the ground contact phase of the ST and PRE phase. A= extension / flexion, B= lateral bend opposite side as turn / same side as turn, C= rotation in opposite direction as turn / same direction as turn.

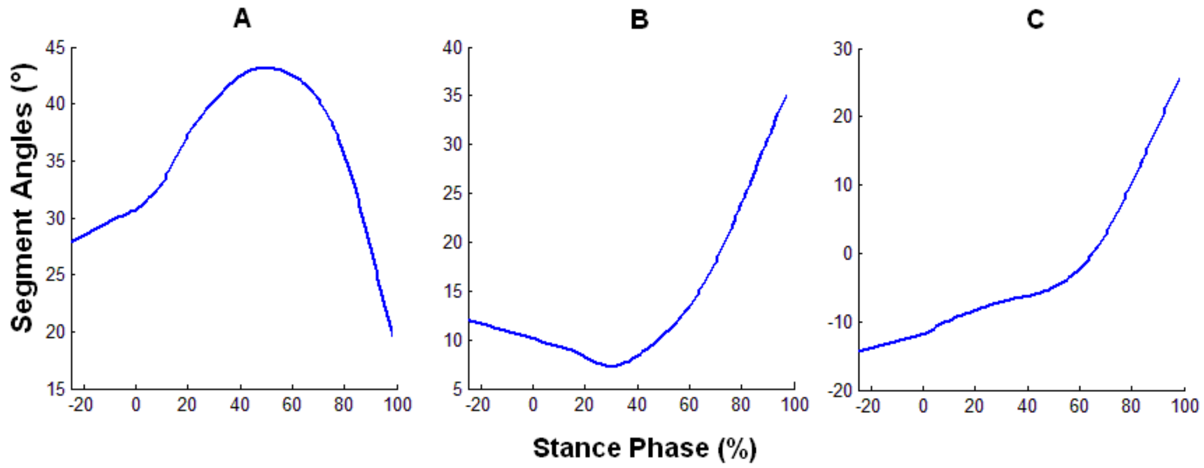


Figure 7.56. Typical movement curves of the thorax segment during the ground contact phase of the ST and PRE phase. A= backward / forward tilt, B= lateral tilt opposite side as turn / same side as turn, C= rotation in same direction as approach / opposite direction as approach.

The rotation of the spine changed from being rotated to the same direction as the turn during PRE, WA and MS to being rotated to the opposite direction during PO and FP. Suggesting that the initial rotation took place in the lower limbs while the main change in rotation of the upper body took place during the MS and PO phase which was visible for the thorax segment. The thorax was rotated slightly in the same direction as the approach during the PRE phase, whereas during MS the thorax was rotated in the opposite direction of the approach on all surfaces.

No significant differences were present between surface conditions for either the spine or thorax angles. While non-significant it appeared that on average the thorax was turned more toward the turning direction on the low traction surfaces than on the high traction surfaces during all phases, with differences of up to 8.1° (Figure 7.57). This may indicate that that the players adjusted their upper body rotation for the change in rotational traction. Between the in-game scenarios the differences for all angles were small and not significant.

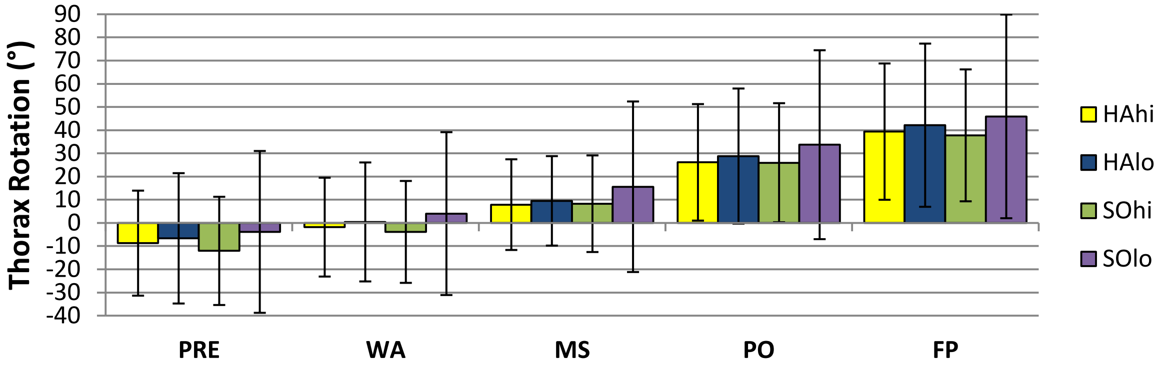


Figure 7.57. Thorax orientation angles (± standard deviation) during all phases of the ST determined over 16 subjects. While no significant differences were present the thorax was on average rotated further to the opposite direction on the low traction surfaces, with differences up to 8.1°.

7.3.8 Centre of Mass (ST)

The centre of mass (COM) gave an indication of the resultant body movement during the ST as the vertical COM of a more flexed body would be lower than a more straight posture (Table 7.16). The differences for the vertical COM were limited for the different surfaces and in-game conditions. Between surfaces the differences were no larger than 11 mm and not significant. The in-game conditions showed a lower vertical COM during all phases for the condition with a simulated opponent with significant effect during MS (3.2 mm, p: .049), PO (6.5 mm, p: .048), and FP (6.6 mm, p: .036) (Figure 7.59).

Table 7.16. Average vertical COM (± standard deviation) during the stop and turn determined over 16 subjects

	PRE	**WA**	**MS**	**PO**	**FP**
Vertical COM (mm)	836 ± 48	771 ± 51	700 ± 56	766 ± 56	811 ± 58

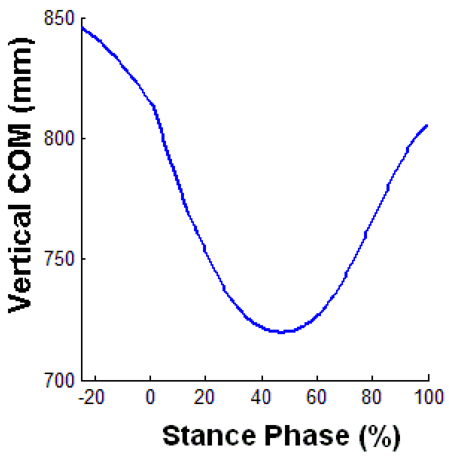


Figure 7.58. Typical curve of the vertical COM during the ground contact and PRE phase of the ST.

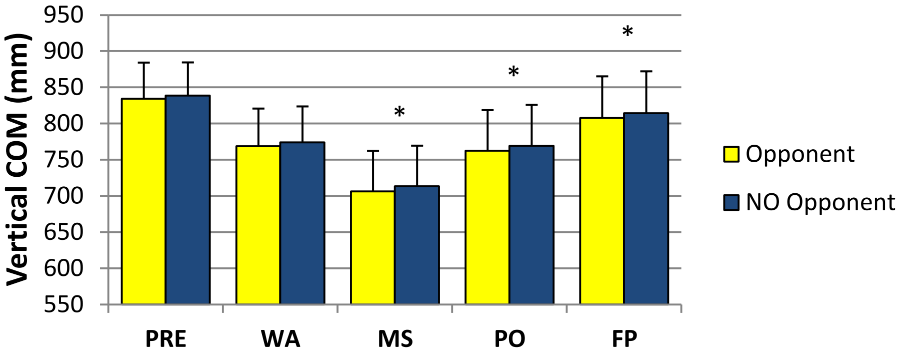


Figure 7.59. Average vertical COM location (± standard deviation) during all phases of the ST determined over 16 subjects. The COM reached its lowest point during the MS phase of the ST and was significantly lower during the Opponent condition during MS (p: .049), PO (p: .048) and FP (p: .036). (* significant effect)

7.3.9 Lower Limb Movement (JH)

7.3.9.1 Ankle

The ankle joint moved from an average 16.4° plantar flexion in the PRE phase to an average 21.1° and 23.5° dorsi flexion during KNE and FIN (Table 7.17). During the phases after impact a slight ankle inversion angle was present as well as an external rotation

Table 7.17. Average ankle angles (± standard deviation) during jumping / heading determined over 16 subjects

Angle (°)	PRE	IMP	KNF	FIN
Plantar (-) / Dorsi (+) Flexion	-16.4 ± 11.4	0.0 ± 6.0	21.1 ± 6.0	23.5 ± 7.1
Eversion (-) / Inversion (+)	-0.4 ± 2.7	0.8 ± 2.9	2.7 ± 2.5	2.6 ± 2.4
External (-) / Internal (+) Rotation	1.7 ± 12.7	-4.0 ± 13.0	-13.0 ± 10.8	-12.6 ± 10.7

Between surface conditions no significant differences were present for the any of the ankle joint movements. For the in-game conditions a significant difference was present during all phases for the plantar / dorsi flexion (Figure 7.61). During the PRE phase a higher plantar flexion was found for the heading condition (7.9°, p: .000), whereas during KNF and FIN the dorsi flexion angle was smaller, 1.8° (p: .001) and 2.5° (p: .000) for the heading condition. The differences for the inversion / eversion and rotation were significant during PRE and IMP, with a slightly higher eversion angle for the heading condition during PRE (0.5°, p: .003), and a slightly lower inversion angle during IMP (0.3°, p: .048). Whereas the internal ankle rotation was higher for the heading condition during PRE (2.6°, p: .000) and the external ankle rotation higher for the jumping condition during IMP (2.6°, p: .007).

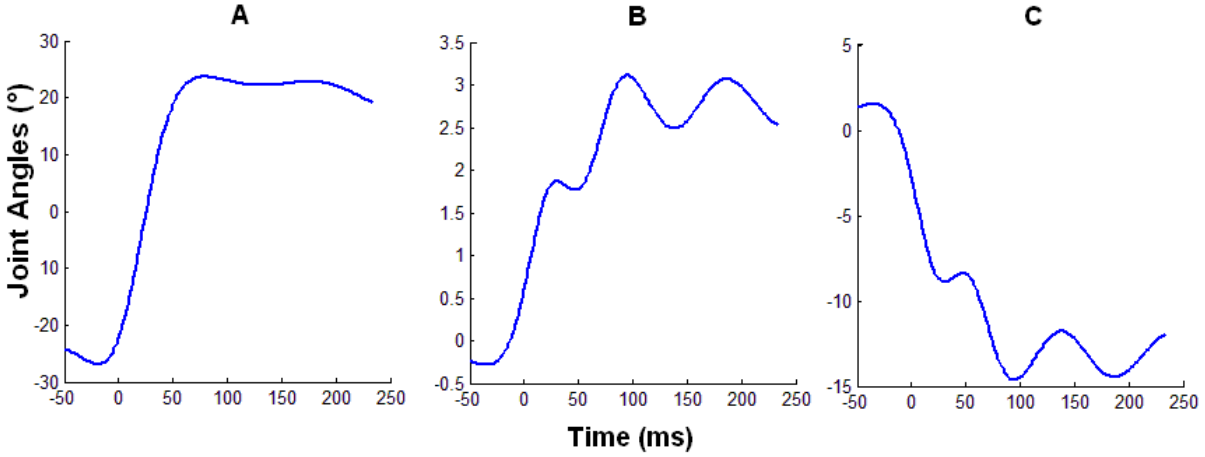


Figure 7.60. Typical movement curves of the ankle joint from the PRE phase until the end of the FIN phase of the JH. A= plantar / dorsi flexion, B= eversion / inversion, C= external / internal rotation.

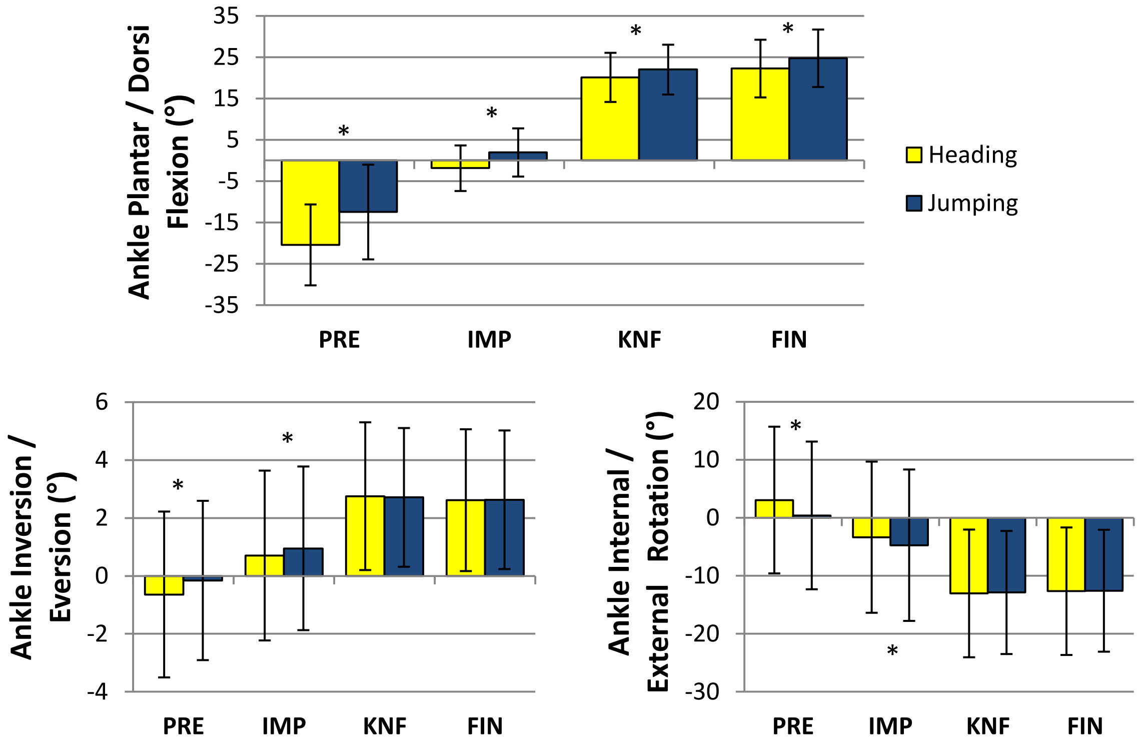


Figure 7.61. Average ankle angles (± standard deviation) during all phases of the JH determined over 16 subjects. A significant difference was present during all phases for the plantar /dorsi flexion: PRE (p: .000), IMP (p: .000), KNF (p: .001), FIN (p: .000). For the ankle inversion / eversion a significant difference was present during PRE and IMP, and for the internal / external rotation also during PRE (p: .000) and IMP (p: .007). (* significant effect)

7.3.9.2 Knee

The knee joint was flexed during all phases of the JH and increased from an average flexion of 14.5° during PRE to 71.9° during FIN (Table 7.18). As with the knee flexion the knee joint was in a varus position during all phases and increased from 7.7° during PRE to

13.5° during FIN. The rotation of the knee changed from an average 12.9° external rotation during PRE to an internal rotation of 9.5° during FIN.

Table 7.18. Average knee angles (± standard deviation) during jumping / heading determined over 16 subjects

Angle (°)	PRE	IMP	KNF	FIN
Extension (-) / Flexion (+)	14.5 ± 5.5	26.4 ± 6.0	64.9 ± 11.6	71.9 ± 15.9
Valgus (-) / Varus (+)	7.7 ± 5.2	10.1 ± 6.8	13.3 ± 11.3	13.5 ± 12.0
External (-) / Internal (+) Rotation	-12.9 ± 9.7	-5.0 ± 9.6	8.4 ± 9.0	9.5 ± 10.3

Between the surface conditions the differences were small for all knee angles and no significant differences were present. For the in-game conditions the knee flexion was significantly higher for the jumping condition during all phases, PRE (3.9°, p: .000), IMP (2.4°, p: .005), KNF (5.5°, p: .001), FIN (8.0°, p: .001) (Figure 7.63). The knee varus angle during PRE (1.4°, p: .000) and IMP (1.1°, p: .006), and knee rotation during KNF (1.1°, p: .006) and FIN (1.7°, p: .010) were significantly higher for the jumping condition.

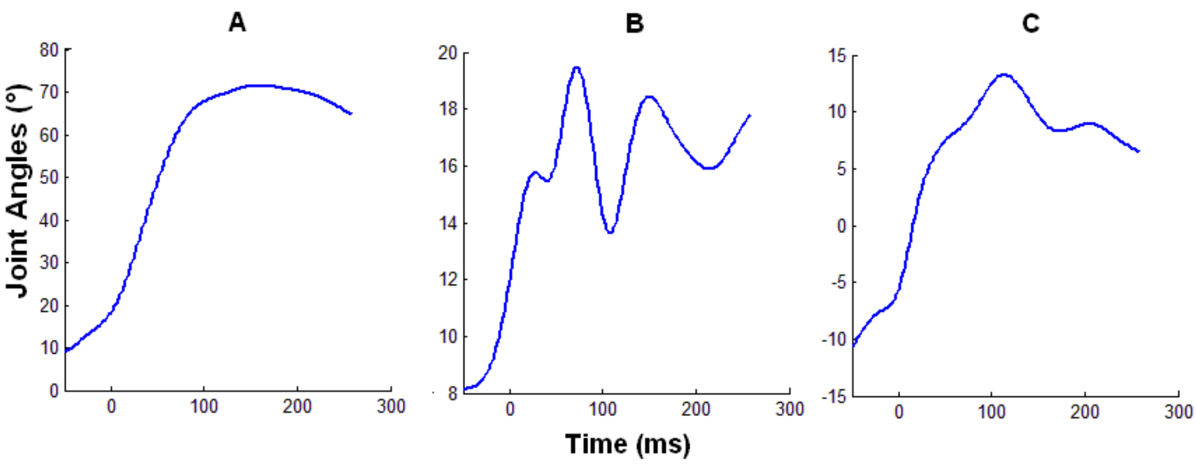


Figure 7.62. Typical movement curves of the knee joint from the PRE phase until the end of the FIN phase of the JH. A= extension /flexion, B= valgus / varus, C= external / internal rotation.

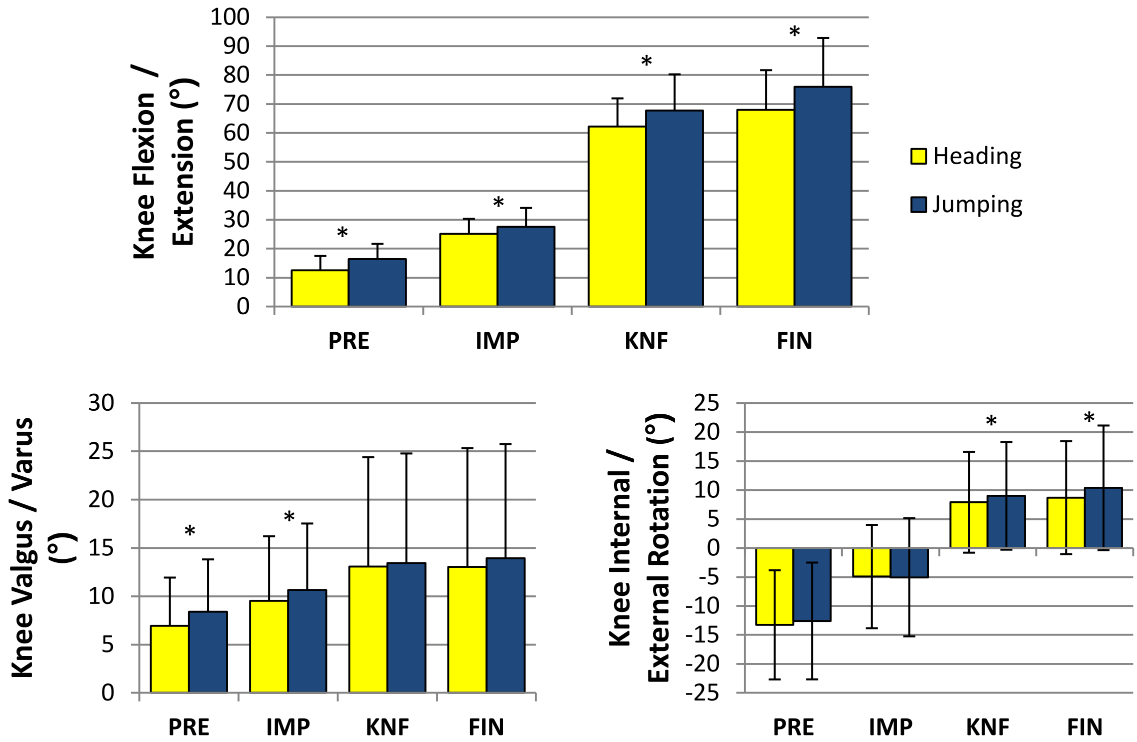


Figure 7.63. Average knee rotation angles (± standard deviation) during all phases of the JH determined over 16 subjects. The in-game scenarios had a significant effect on all movements with the heading condition leading to higher flexion angles during PRE (p: .000), IMP (p: .005), KNF (p: .001), FIN (p: .001) (upper), higher varus angles during PRE (p: .000) and IMP (p: .006) (lower left) and internal knee rotation during KNF (p: .006) and FIN (p: .017) (lower right). (* significant effect)

7.3.9.3 Hip

The hip joint was flexed during all phases of the JH and increased from an average flexion of 32.9° during PRE to an average flexion of 54.6° and 58.3° during KNF and FIN (Table 7.19). As for the flexion the hips were in an abducted position during all phases. The average abduction was consistent during all phases and changed no more than 2.5° on the different surfaces. The rotation of the hip increased from a minimal rotation during the PRE phase to an average internal rotation of 9.3° during FIN. The standard deviations for the rotation of the hip were large.

The surface conditions showed no significant effects with maximal differences of 1.3° for all movements. The in-game conditions showed a significantly higher hip flexion for the jumping condition during FIN (6.3°, p: .036) and for the rotation during PRE (1.3°, p: .004) and IMP (1.5°, p: .013) (Figure 7.64). The hip internal / external rotation values were accompanied with large standard deviations.

Table 7.19. Average hip angles (± standard deviation) during jumping / heading determined over 16 subjects

Angle (°)	PRE	IMP	KNF	FIN
Extension (-) / Flexion (+)	32.9 ± 9.0	36.5 ± 9.9	54.6 ± 14.0	58.3 ± 16.4
Abduction (-) / Adduction (+)	-12.7 ± 4.2	-13.7 ± 4.3	-15.0 ± 5.1	-15.3 ± 5.6
External (-) / Internal (+) Rotation	1.0 ± 13.2	3.2 ± 12.8	8.2 ± 13.7	9.3 ± 15.1

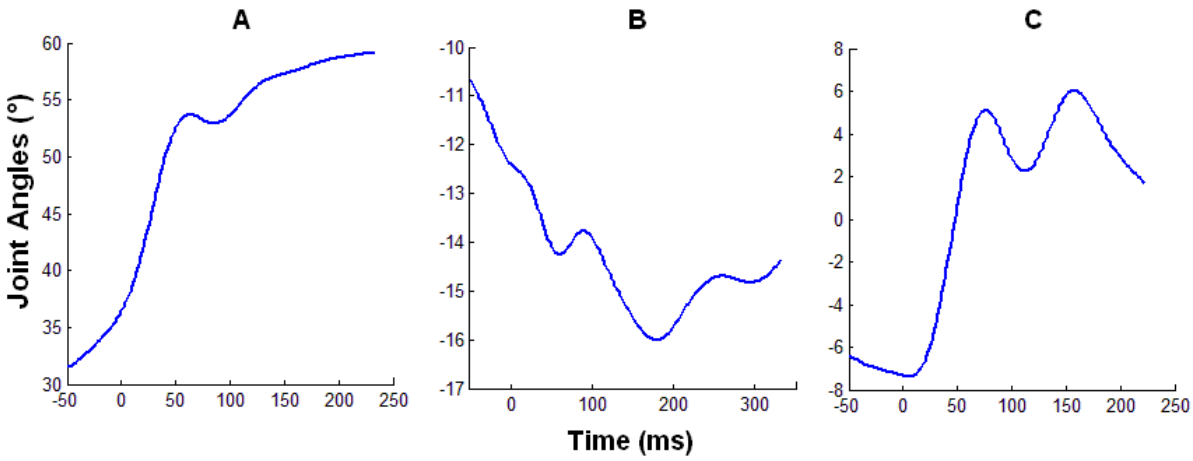


Figure 7.64. Typical movement curves of the hip joint from the PRE phase until the end of the FIN phase of the JH. A= extension /flexion, B= abduction / adduction, C= external / internal rotation.

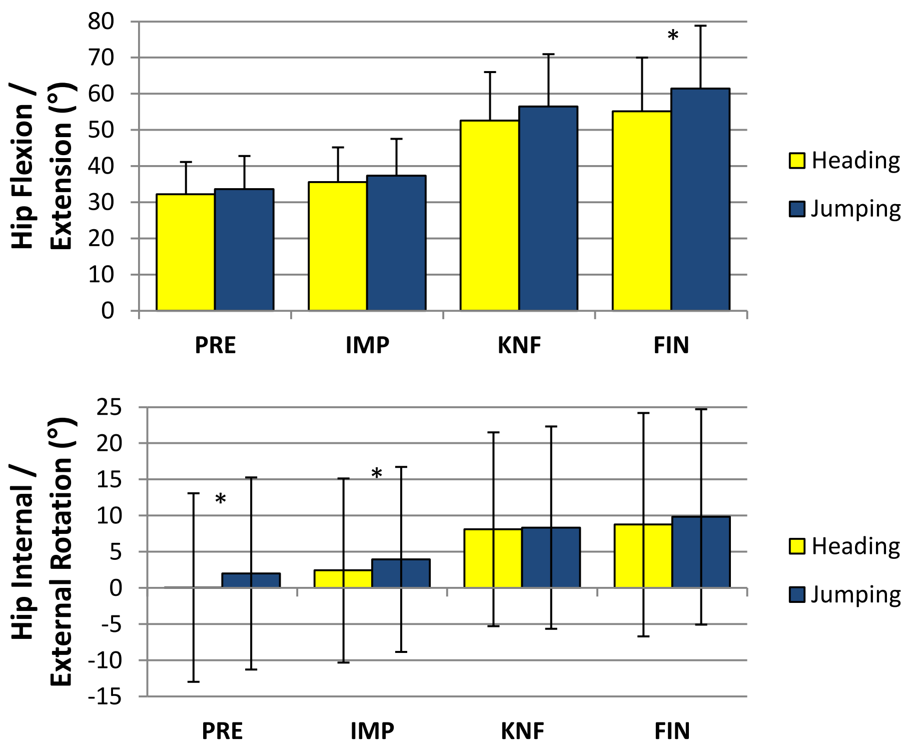


Figure 7.65. Average hip rotation angles (± standard deviation) during all phases of the JH determined over 16 subjects. The hip flexion was higher for the jumping condition during all phases with a significant difference during FIN (p: .036). The internal hip rotation was significantly higher during PRE (p: .004) and IMP (p: .013) for the jumping condition. (* significant effect)

7.3.10 Upper Body Movement (JH)

The movement of the upper body during the JH manoeuvres was limited. On average the spine was slightly extended during PRE and IMP with a slight forward tilt of the thorax (Table 7.20, Table 7.21). Whereas during KNF and FIN the spine was slightly flexed with an increased forward tilt of the thorax. The lateral bend and rotation of the spine was no larger than 1.6°, whereas the lateral tilt and rotation of the thorax reached values of up to 5.1° and 9.6°.

On the different surface conditions the differences in spine and thorax movement were not significant and no larger than 1.9°. The in-game scenarios showed a significant increased spine flexion during KNF (2.7°, p: .023) and FIN (2.7°, p: .046) (Figure 7.68).

Table 7.20. Average spine angles (± standard deviation) during jumping / heading determined over 16 subjects

Angle (°)	PRE	IMP	KNF	FIN
Extension (-) / Flexion (+)	-5.2 ± 7.4	-5.0 ± 7.8	3.3 ± 9.6	8.1 ± 12.0
Lateral Bend Left (-) / Right (+)	1.6 ± 3.2	1.5 ± 3.2	1.1 ± 3.2	0.9 ± 4.6
Rotation Left (-) / Right (+)	1.6 ± 4.6	2.1 ± 4.4	1.5 ± 4.0	1.7 ± 3.2

Table 7.21. Average thorax angles (± standard deviation) during jumping / heading determined over 16 subjects

Angle (°)	PRE	IMP	KNF	FIN
Backward (-) / Forward (+) Tilt	10.2 ± 8.2	10.2 ± 8.8	16.7 ± 11.4	23.0 ± 15.4
Lateral Tilt Left (-) / Right (+)	3.1 ± 3.2	3.3 ± 3.3	4.2 ± 4.1	5.1 ± 4.8
Rotation Left (-) / Right (+)	9.3 ± 9.2	9.6 ± 9.3	9.0 ± 9.0	7.4 ± 9.0

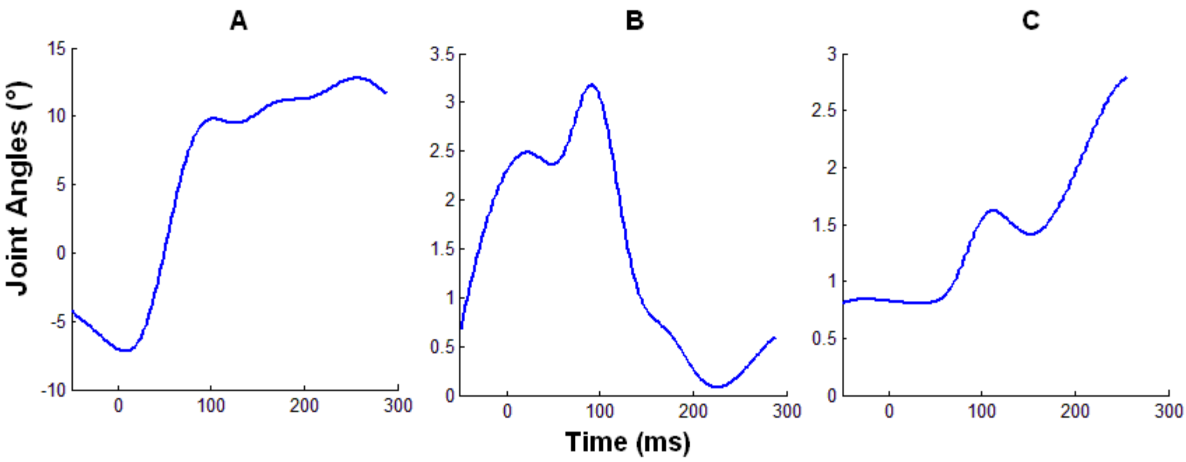


Figure 7.66. Typical movement curves of the spine joint from the PRE phase until the end of the FIN phase of the JH. A= extension /flexion, B= lateral bend left / right, C= rotation left / right

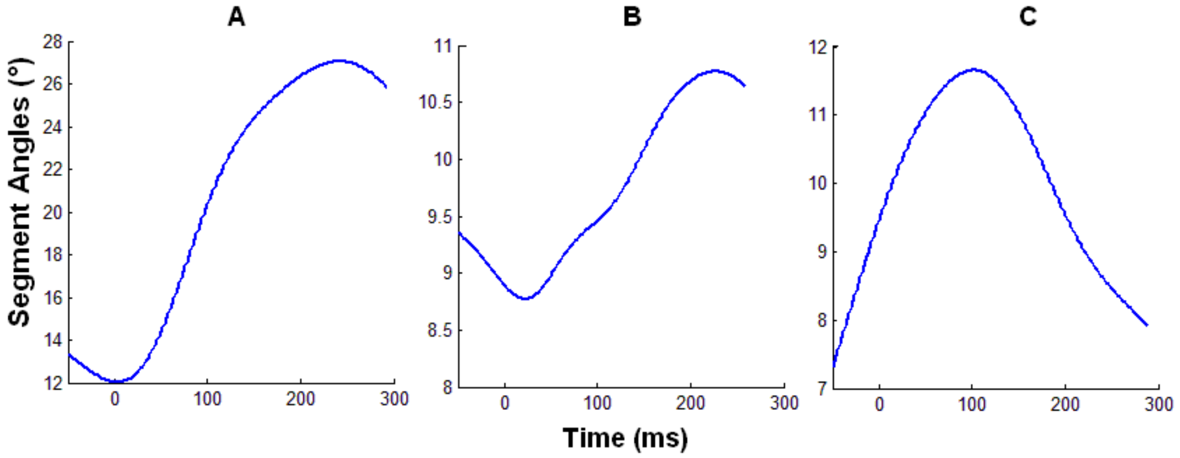


Figure 7.67. Typical movement curves of the thorax segment from the PRE phase until the end of the FIN phase of the JH. A= backward / forward tilt, B= lateral tilt left / right, C= rotation left / right.

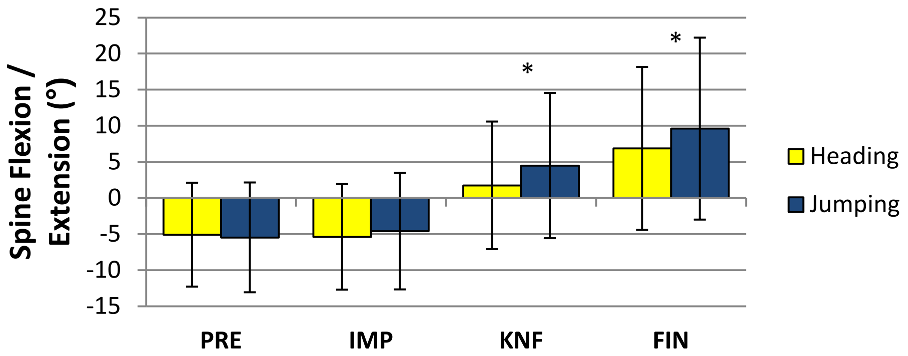


Figure 7.68. Average spine flexion / extension angles (± standard deviation) during all phases of the JH determined over 16 subjects. The spine was on average significantly more flexed during the jumping conditions during KNF (p: .023) and FIN (p: .046). (* significant effect)

7.3.11 Centre of Mass (JH)

The COM location gave an indication of the resultant body movement during the JH as the vertical COM of a more flexed body would be lower than a more straight posture (Table 7.22). The vertical COM was significantly higher for the heading condition during PRE (20.1 mm, p: .000), IMP (15.0 mm, p: .000), KNF (31.5 mm, p: .001), FIN (25.8 mm, p: .024) (Figure 7.70). This suggests that the posture of the players was straighter during the landing after a heading manoeuvre than after a vertical stop-jump without heading a ball.

Table 7.22. Average vertical COM location (± standard deviation) during jumping / heading determined over 16 subjects

	PRE	IMP	KNF	FIN
Vertical COM (mm)	1171 ± 53	1047 ± 49	905 ± 82	856 ± 113

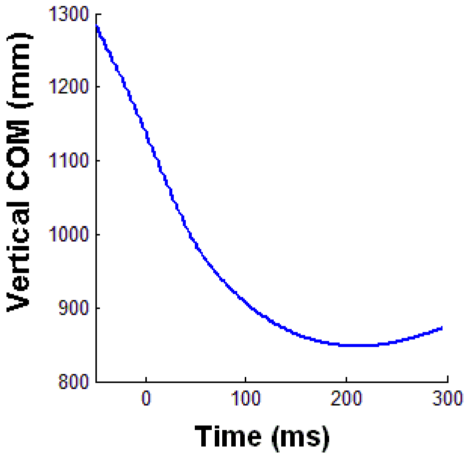


Figure 7.69. Typical the vertical COM curve during the landing after a JH manoeuvre.

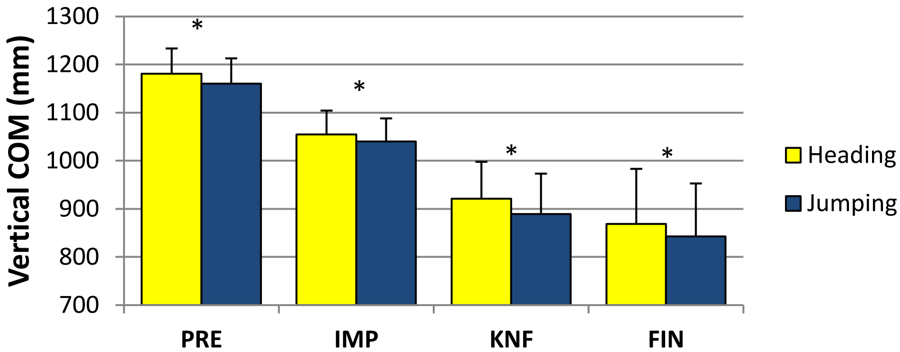


Figure 7.70. Average vertical COM location (± standard deviation). The vertical COM was significantly higher for the heading condition during PRE (p: .000), IMP (p: .000), KNF (p: .001), FIN (p: .024), indicating a more straight posture during the landing. (* significant effect)

7.3.12 Joint Moments (ST)

7.3.12.1 Ankle

During the ST the average plantar flexion moment of the ankle reached its highest level during the MS and PO phase (Table 7.23). The average eversion moment was consistent during the WA, MS and PO phase and dropped during the FP phase, whereas the external rotation moment reached its highest level during the PO phase of the ST.

Between surface conditions significant effects were found for the plantar flexion moment and eversion moment of the ankle (Figure 7.72). The plantar flexion moment was significantly higher on the HAhi surface than on the SOhi surface during PO (0.12Nm/kg, p: .007). On the other surfaces and during the other phases the differences were not significant, but during WA, MS and PO the plantar flexion moments were 0.03 – 0.14 Nm/kg higher on the hard surfaces than on the soft surfaces, which suggests that a harder surface leads to increased plantar flexion moments.

Table 7.23. Average ankle joint moments (± standard deviation) during the stop and turn determined over 16 subjects

Moment (Nm/kg)	WA	MS	PO	FP
Dorsi (-) / Plantar (+) Flexion	0.64 ± 0.46	1.33 ± 0.56	1.28 ± 0.52	0.37 ± 0.23
Eversion (-) / Inversion (+)	-0.47 ± 0.13	-0.54 ± 0.14	-0.47 ± 0.15	-0.14 ± 0.07
External (-) / Internal (+) Rotation	-0.89 ± 0.42	-0.97 ± 0.48	-1.12 ± 0.52	-0.38 ± 0.13

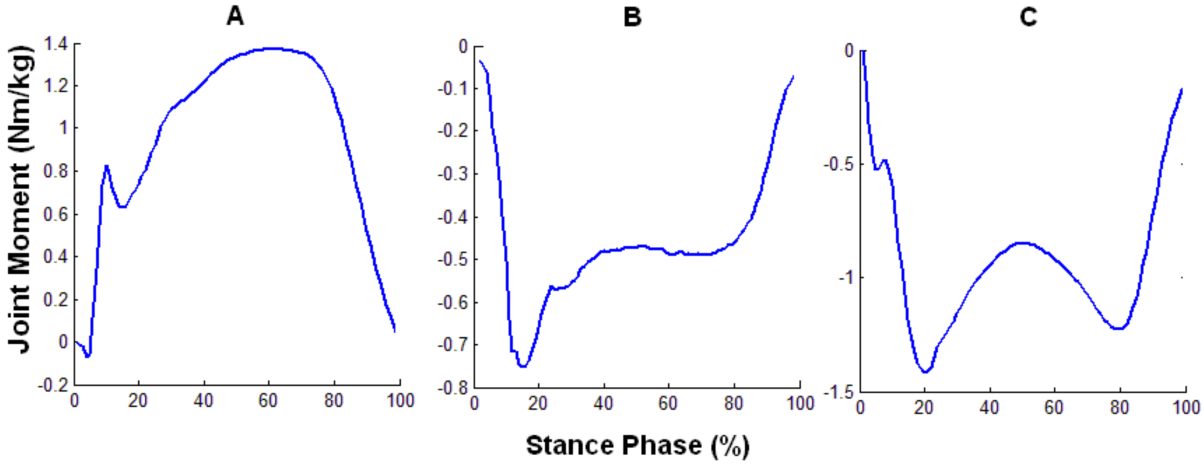


Figure 7.71. Typical ankle joint moment curves during the stance phase of the ST. A= dorsi / plantar flexion, B= eversion / inversion, C= external / internal rotation.

The eversion moment was significantly lower on the HAlo surface than on all other surfaces during MS (HAhi: 0.05 Nm/kg, p: .005; SOhi: 0.09 Nm/kg, p: .042; SOlo: 0.06 Nm/kg, p: .008) (Figure 7.72) Between both high traction and between both low traction surfaces a trend appeared visible for the eversion moments during MS, which were lower on the hard surfaces than on the soft surfaces, 0.05 and 0.06 Nm/kg. Furthermore a trend also appeared visible during the same phase between both hard surfaces and between both soft, for which the eversion moment was 0.03 and 0.04 Nm/kg higher on the high traction surfaces than on the low traction surfaces. It has to be noted that the differences regarding hardness were only present between the HAlo surface and both soft surfaces, and regarding the traction only between the HAlo and HAhi surface.

No significant differences were present between the in-game conditions for any of the ankle joint moments and differences were no larger than 0.02 Nm/kg.

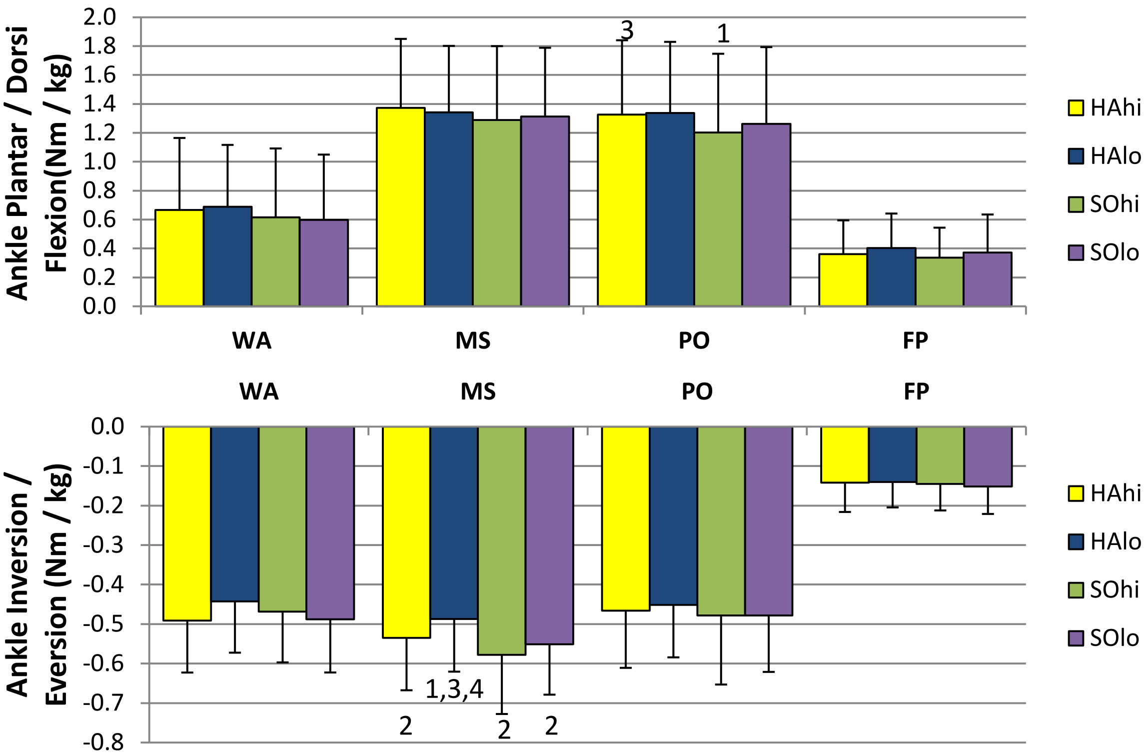


Figure 7.72. Average ankle plantar / dorsi flexion (upper) and inversion / eversion (lower) moments (± standard deviation) determined over 16 subjects during ST. The plantar flexion moment was significantly higher on the HAhi surface than on the SOlo surface during PO (p: .007). While not significant during WA, MS, and PO the plantar flexion moment was higher on the hard surfaces relative to the traction. The ankle eversion moment was significantly different between the HAlo surface and all other surfaces during MS (HAhi: p: .005; SOhi: p: .042; SOlo: p: .008). Between both hard and between both soft surfaces the eversion moment was higher on the high traction surface and between both high traction surfaces and between both low traction surfaces higher the soft surfaces during MS. (1: significant effect HAhi; 2: significant effect HAlo; 3: significant effect SOhi; 4: significant effect SOlo)

7.3.12.2 Knee

The average knee extension moment reached the maximum during the MS phase of the ST (Table 7.24). During all phases a large standard deviation was present. The valgus moment of the knee was highest during the WA phase after which it dropped during MS and increased again during the PO phase. With regards to the knee rotation moments the highest values were reached during MS and PO.

Table 7.24. Average knee joint moments (± standard deviation) during the stop and turn determined over 16 subjects

Moment (Nm/kg)	WA	MS	PO	FP
Flexion (-) / Extension (+)	0.83 ± 0.66	1.51 ± 0.95	1.11 ± 0.71	0.06 ± 0.26
Valgus (-) / Varus (+)	-2.06 ± 0.43	-1.52 ± 0.57	-1.70 ± 0.57	-0.94 ± 0.26
External (-) / Internal (+) Rotation	-0.95 ± 0.40	-1.16 ± 0.54	-1.22 ± 0.50	-0.34 ± 0.12

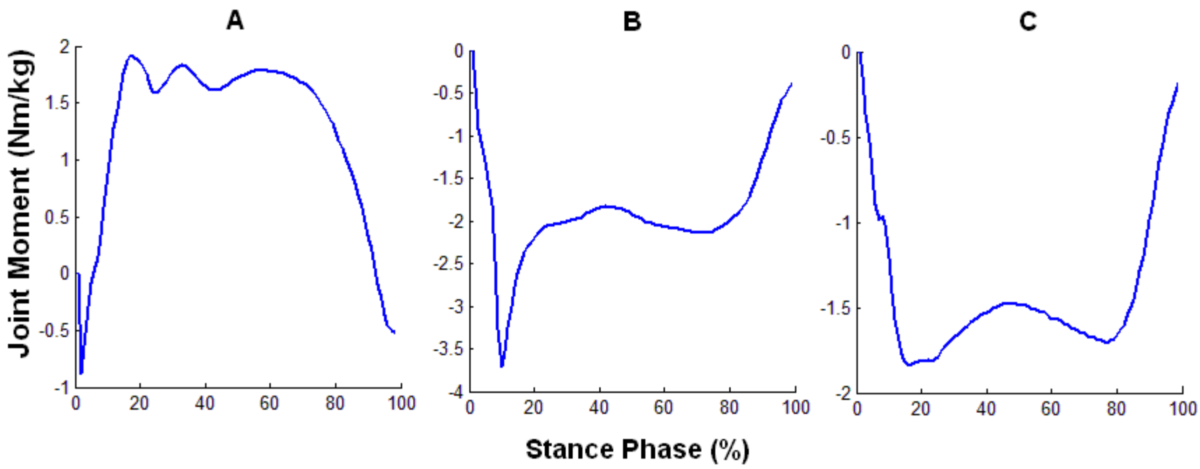


Figure 7.73. Typical knee joint moment curves during the stance phase of the ST. A= flexion / extension, B= valgus / varus, C= external / internal rotation.

For the surface conditions significant effects were present for valgus moments (Figure 7.74). During the WA and MS phase the valgus moment was significantly higher on the HAhi surface than on the HAlo surface, 0.19 Nm/kg (p: .032) and 0.15 Nm/kg (p: .025). This seems to suggest that a surface with a higher traction leads to an increased valgus moment. However, on the soft surfaces the valgus moment was higher on the low traction surface during WA, 0.11 Nm/kg. While this difference was not significant it contradicts the findings on the hard surfaces.

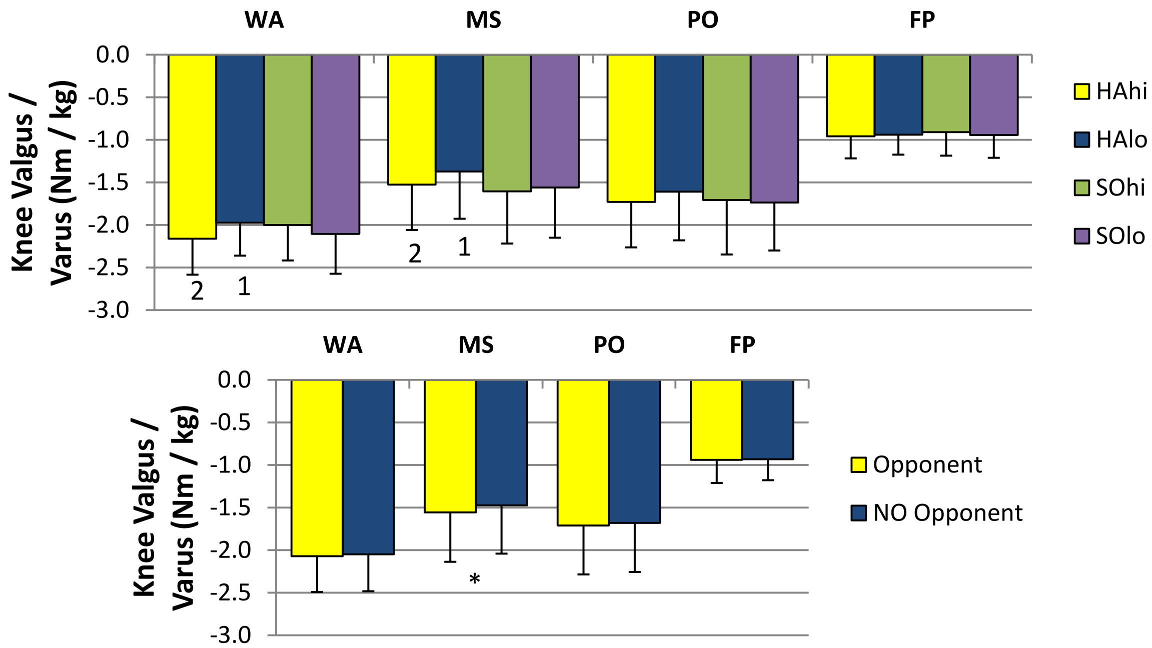


Figure 7.74. Average knee valgus / varus moments (± standard deviation) for different surface and in-game conditions determined over 16 subjects during ST. The valgus moment was significantly higher on the HAhi surface than on the HAlo surface during WA (p: .032) and MS (p: .025). No significant difference was present between the soft surfaces and the valgus moment during WA contradicts the findings on the hard surfaces. Between the in-game conditions the valgus moment was significantly higher during the condition with a simulated opponent during MS (p: .005). (1: significant effect HAhi; 2: significant effect HAlo; * significant effect in-game condition)

When comparing in-game conditions no significant differences were present for the knee extension and rotation moments. For the valgus moment the condition with an opponent led to a significantly higher moment during the MS phase (0.08 Nm/kg, p: .005) (Figure 7.74). Differences during other phases were small and not significant.

7.3.12.3 Hip

The hip flexion / extension moments on average changed from an extension moment during WA and MS to a flexion moment during the FP phase of the ST (Table 7.25). The average abduction moments of the hip reached the highest levels during the WA and PO phase. For the internal rotation moment of the hip the highest levels were reached during the MS phase.

Table 7.25. Average hip joint moments (± standard deviation) during the stop and turn determined over 16 subjects

Moment (Nm/kg)	WA	MS	PO	FP
Flexion (-) / Extension (+)	0.12 ± 1.33	0.81 ± 1.53	-0.25 ± 1.37	-1.13 ± 0.69
Abduction (-) / Adduction (+)	-3.94 ± 0.72	-3.65 ± 0.61	-3.90 ± 0.78	-1.46 ± 0.52
External (-) / Internal (+) Rotation	0.73 ± 0.57	1.20 ± 0.56	0.66 ± 0.60	0.17 ± 0.20

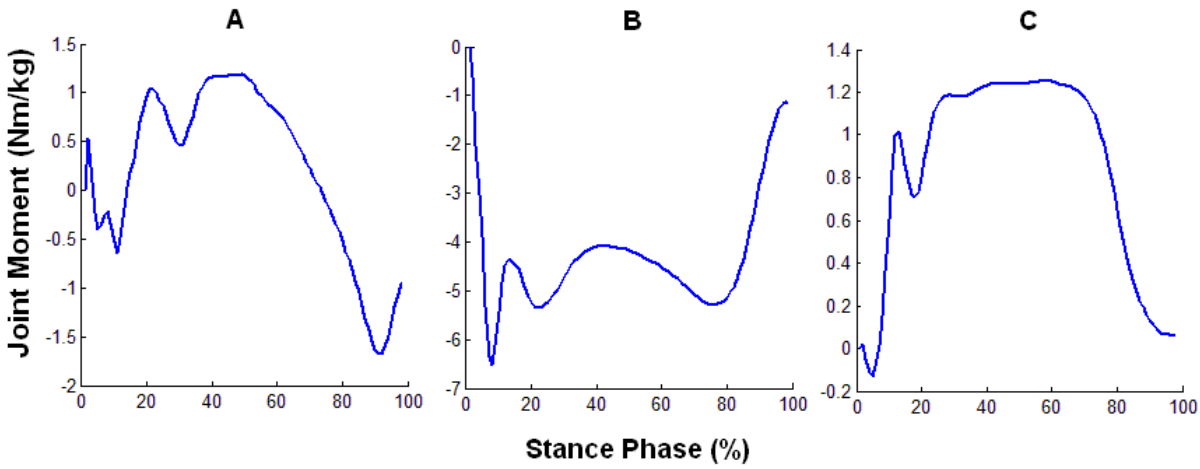


Figure 7.75. Typical hip joint moment curves during the stance phase of the ST. A= flexion / extension, B= abduction / adduction, C= external / internal rotation.

Between surface conditions significant differences were present for all directions (Figure 7.76). The flexion / extension showed a significantly increased extension moment on the SOhi surface compared to the HAhi surface during PO (0.38Nm/kg, p: .037), the magnitude of the hip extension moment was small during this phase. In the other phases these differences were also present between these surfaces, but they were not significant. For the high traction surfaces this suggests an effect for the surface hardness, but for the low traction surfaces no effect was present.

The hip abduction moment showed a significant difference between the HAhi and HAlo surface during MS (0.42Nm/kg, p: .001). Not only during this phase but also during WA and OP the abduction moment was higher (0.34 – 0.41Nm/kg) on the HAhi surface. During MS the abduction moment was also increased on the soft and high traction surfaces, but these differences were not significant.

The internal rotation moment was higher on the HAhi surface than the HAlo surface during all phases (0.05 – 0.16Nm/kg) with a significant difference during the WA phase (0.16Nm/kg, p: .016). As with the abduction moment no difference was present between the SOhi and SOlo surface.

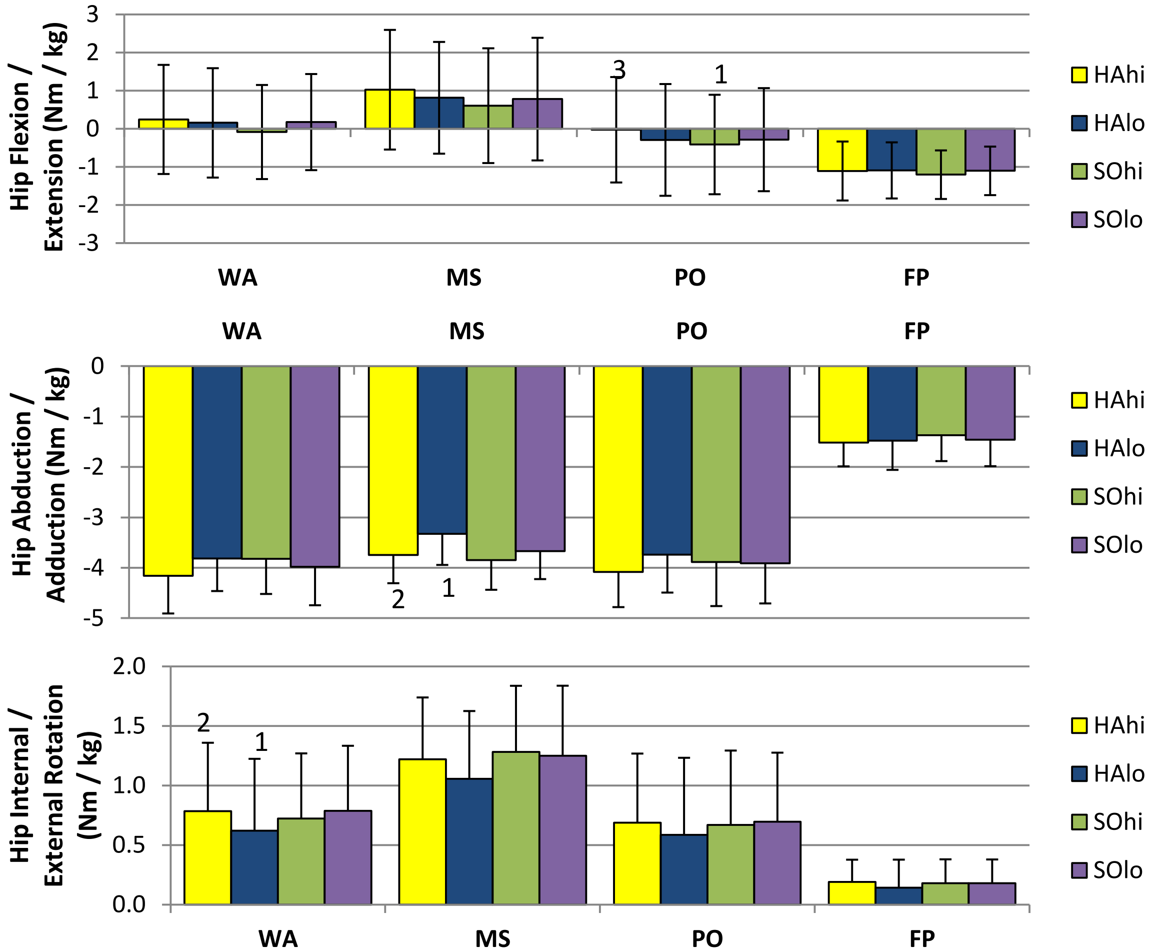


Figure 7.76. Average hip joint moments (± standard deviation) for different surface conditions determined over 16 subjects during ST. The flexion / extension moment showed a significant difference between the HAhi and SOhi surfaces (p: .037). The hip abduction moment was significantly higher on the HAhi surface than on the HAlo surface during MS (p: .001), during other phases this difference was also present but not significant. During MS the abduction moment was also increased on the soft and high traction surfaces, but these differences were not significant. A similar effect was present for the hip rotation moment with a significant effect during WA (p: .016). (1: significant effect HAhi; 2: significant effect HAlo; 3 significant effect SOhi).

Between in-game conditions a significant effect was present for the abduction moment and the internal rotation moment (Figure 7.77). The abduction moment was significantly higher for the condition with a simulated opponent during MS phase (0.13Nm/kg, p: .014). The internal rotation moment was also higher during the condition with the simulated opponent, with significant differences during MS (0.08Nm/kg, p: .002), PO (0.05Nm/kg, p: .028) and FP (0.03Nm/kg, p: .002).

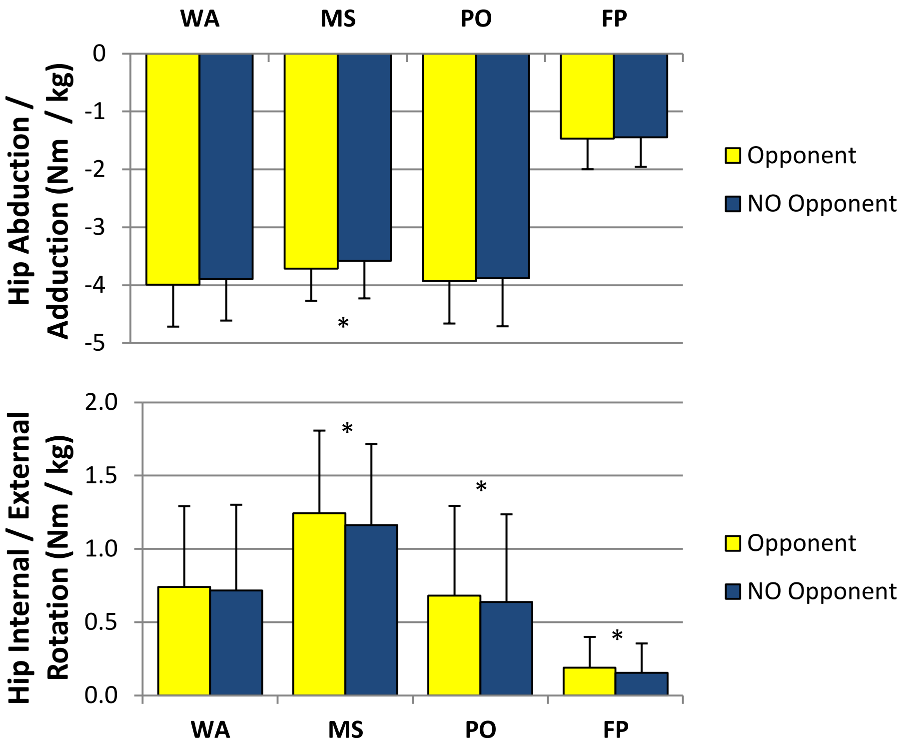


Figure 7.77. Average hip abduction / adduction (upper) and internal / external rotation moments (± standard deviation) for different in-game conditions determined over 16 subjects during ST. The hip abduction moment was higher during the opponent condition during all phases with a significant difference during MS (p: .014). The internal hip rotation moment was also higher during the opponent condition during all phases with significant differences during MS (p: .002), PO (p: .028) and FP (p: .002). (* significant effect)

7.3.13 Joint Moments (JH)

7.3.13.1 Ankle

During the landing after the JH the highest ankle plantar flexion moment was reached during the KNF phase (Table 7.26). As well as a plantar flexion moment the ankle experienced an eversion moment, which was highest during the IMP phase, and an external rotation moment which was highest during the KNF phase of the landing.

Between surface conditions significant differences were present for the eversion moment during all phases for which the moment on the SOlo surface was higher than on the high traction surfaces, IMP (HAhi: 0.02Nm/kg, p: .017; SOhi: 0.02Nm/kg, p: .003), KNF (HAhi: 0.02Nm/kg, p: .006; SOhi: 0.02Nm/kg, p: .010), FIN (HAhi: 0.02Nm/kg, p: .011; SOhi: 0.02Nm/kg, p: .003) (Figure 7.79). In addition to this the eversion moment was increased on the low traction surfaces, but the difference between the HAlo and high traction surfaces were not significant. For the other moments no significant differences were present.

Table 7.26. Average ankle joint moments (± standard deviation) during jumping / heading determined over 16 subjects

Moment (Nm/kg)	IMP	KNF	FIN
Dorsi (-) / Plantar (+) Flexion	1.12 ± 0.45	1.57 ± 0.47	1.07 ± 0.29
Eversion (-) / Inversion (+)	-0.17 ± 0.09	-0.12 ± 0.10	-0.08 ± 0.07
External (-) / Internal (+) Rotation	0.26 ± 0.24	0.32 ± 0.30	0.18 ± 0.18

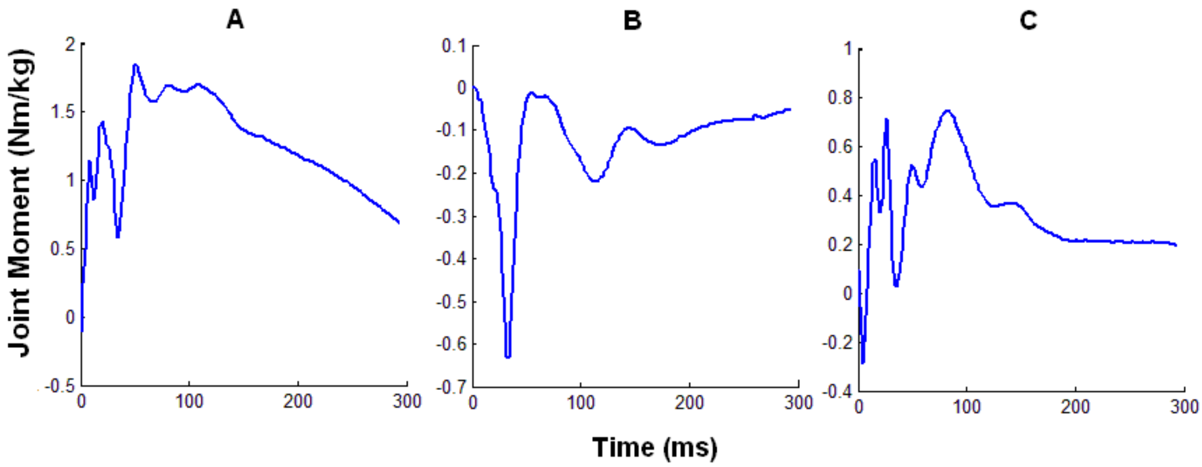


Figure 7.78. Typical ankle joint moment curves from the initial impact to the end of the FIN phase. A= dorsi / plantar flexion, B= eversion / inversion, C= external / internal rotation.

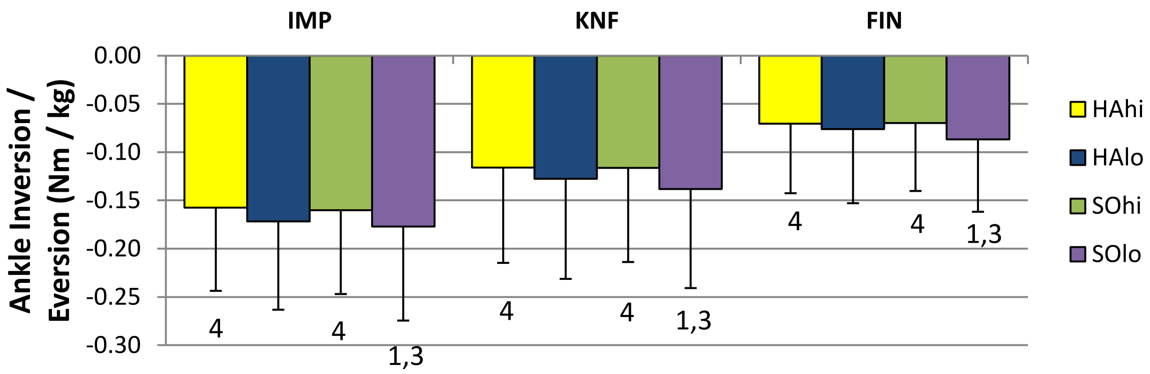


Figure 7.79. Average ankle inversion / eversion moments (± standard deviation) for different surface conditions determined over 16 subjects during JH. The ankle eversion moment was significantly higher on the SOlo surface than on the high traction surfaces during IMP (HAhi: p: .017; SOhi: p: .003), KNF (HAhi: p: .006; SOhi: p: .010) and FIN (HAhi: p: .011; p: .003). The eversion moment of the HAlo surface was also higher than the high traction surfaces but not significant. (1: significant effect HAhi; 3: significant effect SOhi; 4: significant effect SOlo)

When comparing the in-game conditions a significant effect was present for the plantar flexion and eversion moment of the ankle (Figure 7.80). During both the IMP and KNF phase the moments were higher for the heading condition than for the vertical stop-jump without heading a ball for the plantar flexion (IMP: 0.19Nm/kg, p: .003; KNF: 0.19Nm/kg, p: .003) and the eversion moment (IMP: 0.01Nm/kg, p: .044; KNF: 0.01Nm/kg, p: .003).

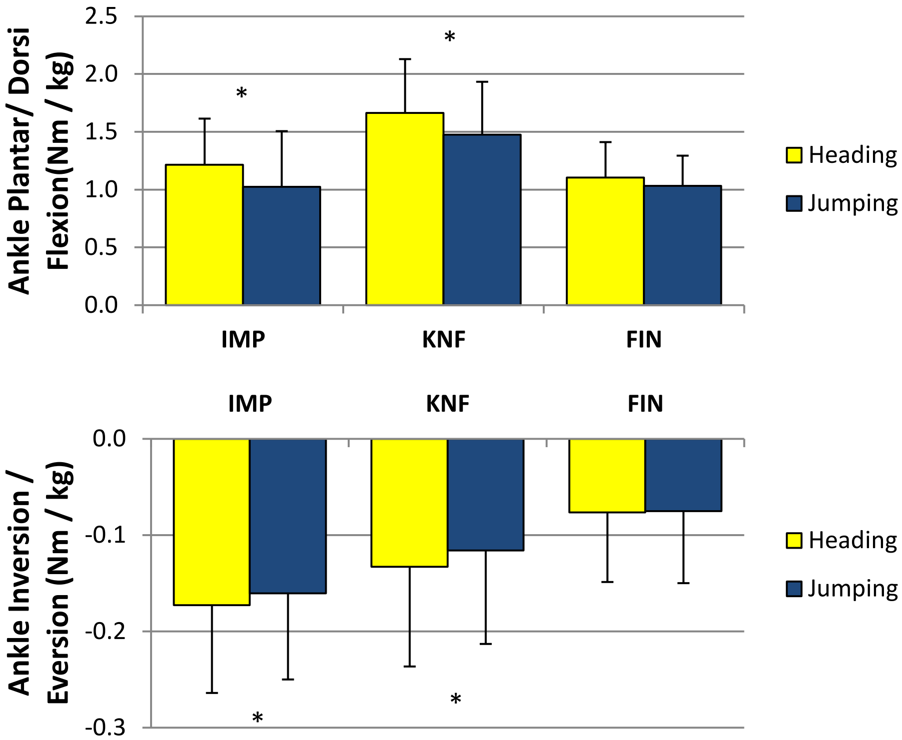


Figure 7.80. Average ankle plantar / dorsi flexion (upper) and inversion / eversion (lower) moments (± standard deviation) for different in-game conditions determined over 16 subjects during JH. The ankle plantar flexion moment was higher during the landing after the heading condition with significant differences during the IMP (p: .003) and KNF (p: .003) phase. The eversion moment was also higher during the landing after the heading condition with significant differences during IMP (p: .044) and KNF (p: .002). (* significant effect)

7.3.13.2 Knee

The knee extension moment reached its highest average value during the KNF phase of the landing (Table 7.27). The valgus and internal rotation moment was highest during the IMP phase after which it gradually decreased during the other phases. The knee extension moment was significantly higher for the jumping condition during IMP (0.16Nm/kg, p: .000) and FIN (0.11Nm/kg, p: .000). The knee valgus moment was significantly higher for the heading condition during KNF (0.06Nm/kg, p: .012) and FIN (0.03Nm/kg, p: .023) (Figure 7.82).

Table 7.27. Average knee joint moments (± standard deviation) during jumping / heading determined over 16 subjects

Moment (Nm/kg)	IMP	KNF	FIN
Flexion (-) / Extension (+)	0.12 ± 0.49	1.25 ± 0.49	0.79 ± 0.32
Valgus (-) / Varus (+)	-0.23 ± 0.31	-0.14 ± 0.35	-0.10 ± 0.22
External (-) / Internal (+) Rotation	0.25 ± 0.22	0.19 ± 0.30	0.08 ± 0.18

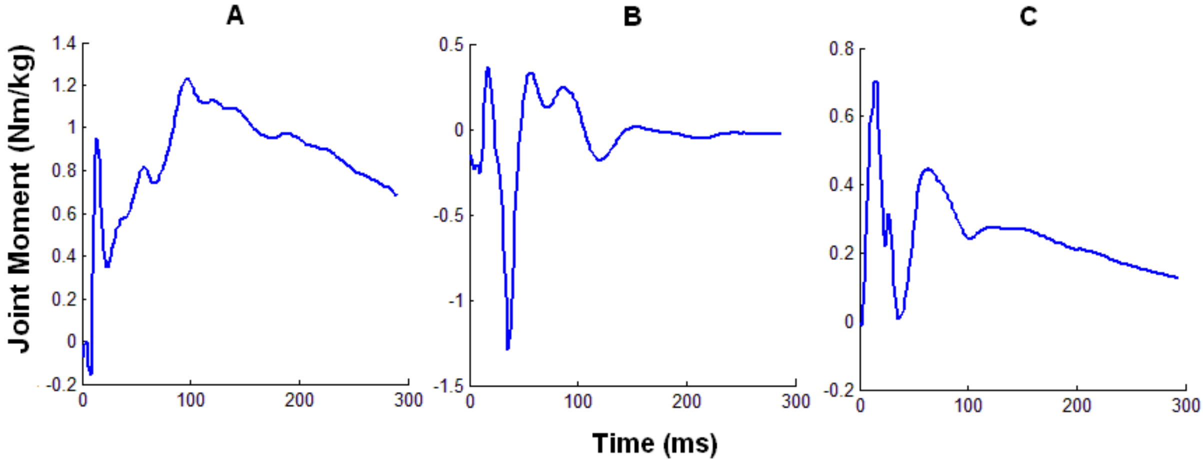


Figure 7.81. Typical knee joint moment curves from the initial impact to the end of the FIN phase. A= flexion / extension, B= valgus / varus, C= external / internal rotation.

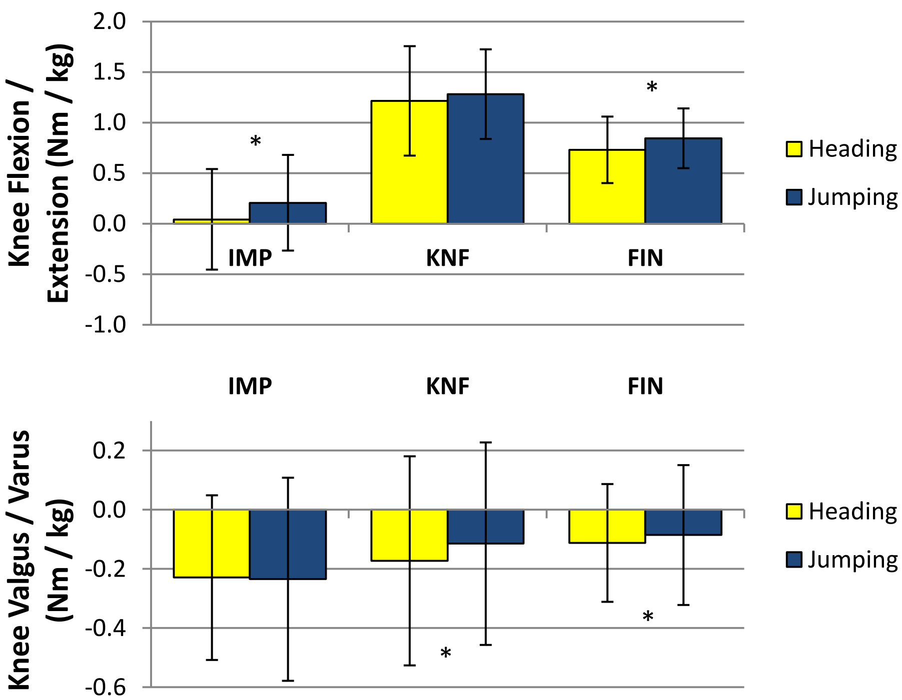


Figure 7.82. Average knee flexion / extension (upper) and valgus / varus (lower) moments (± standard deviation) for different in-game conditions determined over 16 subjects during JH. The knee extension moment was higher during the landing after the jumping condition with significant differences during IMP (p: .000) and FIN (p: .000). The valgus moment was significantly higher during the landing after the heading condition during KNF (p: .012) and FIN (p: .023). (* significant effect)

7.3.13.3 Hip

The maximum average hip extension moment was reached during KNF, whereas during IMP on average a hip flexion moment was present (Table 7.28). As for the hip extension the highest average moments for the hip abduction and internal rotation were present during KNF.

For the surface conditions no significant differences were present for any of the hip moments. Between in-game conditions a significant effect was found for the hip abduction during KNF, with the hip abduction moment being higher (0.07 Nm/kg, p: .009) for the heading condition (Figure 7.84). During IMP (0.06 Nm/kg) and FIN (0.02 Nm/kg) these differences were also present, but not statistically significant.

Table 7.28. Average hip joint moments (± standard deviation) during jumping / heading determined over 16 subjects

Moment (Nm/kg)	IMP	KNF	FIN
Flexion (-) / Extension (+)	-0.36 ± 0.99	1.77 ± 0.90	1.11 ± 0.61
Abduction (-) / Adduction (+)	-0.37 ± 0.45	-0.62 ± 0.58	-0.39 ± 0.36
External (-) / Internal (+) Rotation	0.37 ± 0.21	0.48 ± 0.22	0.30 ± 0.15

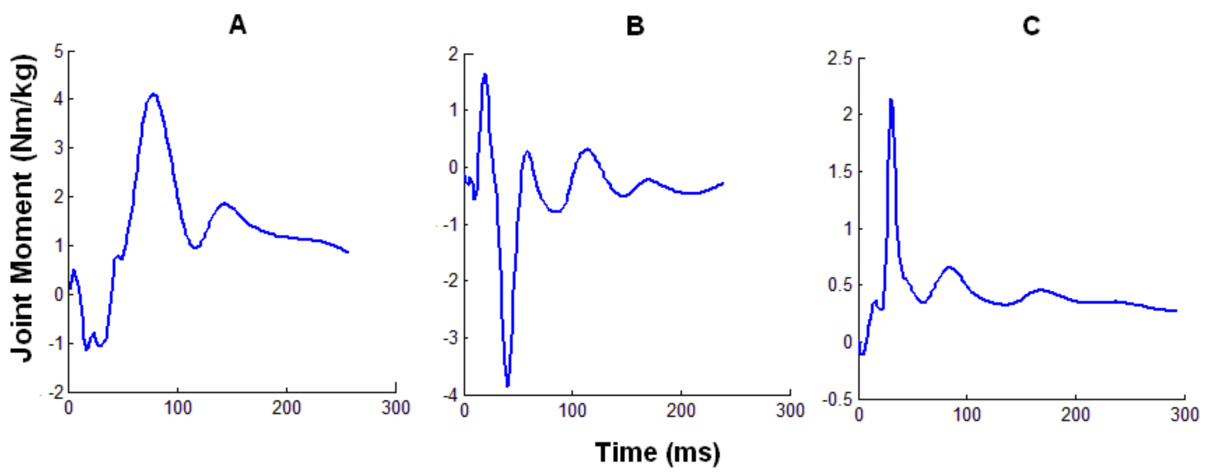


Figure 7.83. Typical hip joint moment curves from the initial impact to the end of the FIN phase. A= flexion / extension, B= abduction / adduction, C= external / internal rotation.

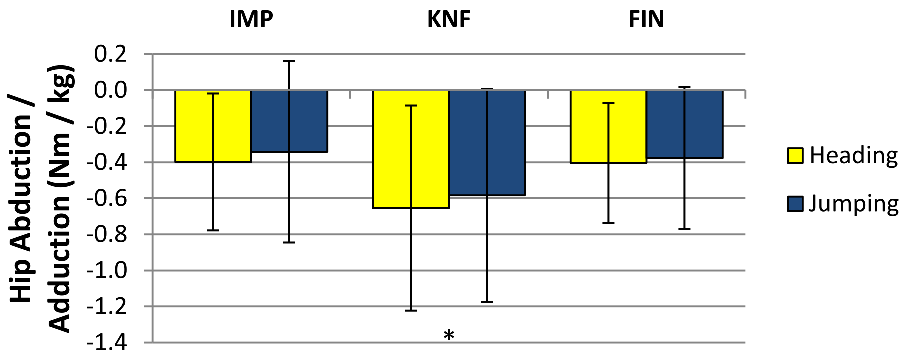


Figure 7.84. Average hip abduction / adduction moments (± standard deviation) for different in-game conditions determined over 16 subjects during JH. The hip abduction moment was higher during the landing after the heading manoeuvre with a significant difference during the KNF (p: .009) phase. (* significant effect)

7.3.14 Player Perception and Preferences of Surface Conditions

Regarding the four surfaces used in the study the majority of the players indicated that they preferred one of the high traction surfaces, both during the ST (75%) and the JH (87.5%) (Figure 7.85). The low traction surfaces were disliked by most players, with the HAlo surface being disliked by more players than the SOlo surface. Considering the high traction surfaces, the SOhi surface was disliked by more players than the HAhi surface.

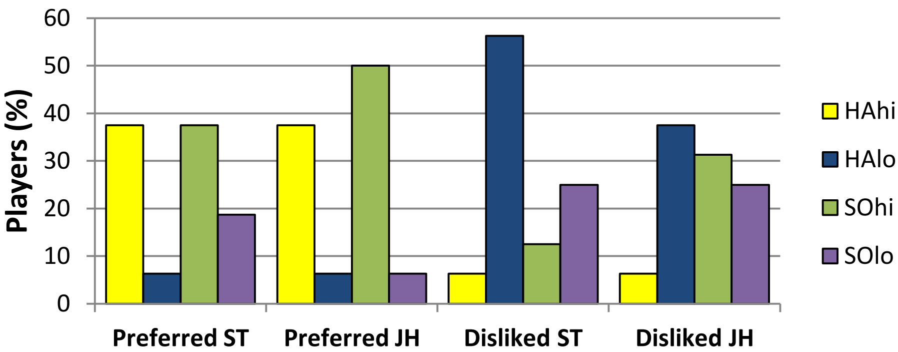


Figure 7.85. Overview of the surfaces the players preferred and disliked the most during the ST and JH. The surfaces with a high traction were preferred the most during both movements with the HAlo surface being preferred the least. During the ST the HAlo surface was disliked by most of the players. This was also the case for the JH, but during the JH difference with the SOhi and SOlo surface was smaller.

The individual ratings of the surfaces showed that the player perception of the surfaces during the ST and JH did not agree with the mechanical test results (Figure 7.86). Up to 50% of the players rated one of the soft surfaces as being the hardest of the four, while up to 37.5% of the players rated one of the hard surfaces as being the softest. Similar findings were present for the traction properties for which up to 56.1% of the players rated one of the high traction surfaces as having the lowest traction and up to 50% of the players rated one of the low traction surfaces as having highest traction. This seems to suggest that players are not always able to identify the surface properties correctly.

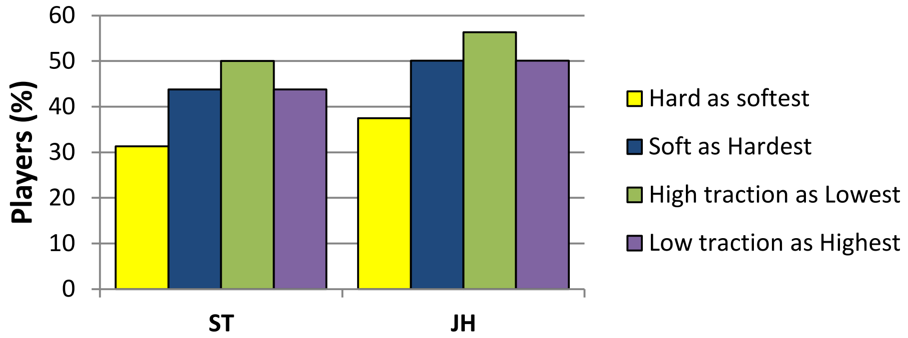


Figure 7.86. Percentage of players that wrongly rated a surface as being the hardest / softest or having the highest / lowest traction, while the mechanical measurements indicated the opposite, e.g. rated the hardest by the players but quantified as being the softest with the AAA.

While the perception on the surface conditions did not agree with the mechanical test results, a pattern was present between the hardness and traction ratings of the surface, and the surface the players rated to like or dislike the most. In the 75 – 81% of the cases the players disliked a surface which they rated as being the hardest / softest, or as having the highest / lowest traction. For the surfaces the players preferred the ratings indicated that for the ST 81% preferred a surface rated as having an intermediate hardness, whereas during the JH no clear preference was found. The traction was preferred as high by 56% of the players during the ST and 50% during the JH. During both movements 31% preferred a surface with an intermediate traction.

7.3.15 Summary: Effects of Surface Properties

The surface conditions showed effects for the ground contact time, average GRF, peak vertical impact force, average and peak loading rate, joint kinematics and joint moments for the ST (Table 7.29). For the JH a significant effect for the surface conditions was present for the peak vertical impact force and loading rate, peak positive Fy, as well as for the ankle eversion moment. Significant effects for all four surfaces were only present or the peak loading rate for the JH. However, in addition to this some parameters showed effects across the hardness and / or rotational traction properties of the surface, albeit not significant on all surfaces (Table 7.29).

Table 7.29. Summary of the effects the different surface conditions had on the study parameters

Parameter			Surfaces	Effect
ST	Ground Contact Time		HAhi - HAlo	+ on HAlo
			Hard - Soft surfaces*	+ on Hard surfaces
			High - Low traction *	+ on Low traction surfaces
	Average GRF	Fz	HAlo - SOhi	+ on SOhi MS
				+ on HAlo PO, FP
			Hard - Soft surfaces*	+ on Soft surfaces MS + on Hard surfaces PO
			High - Low traction*	+ on High traction surfaces MS
		Fy	HAhi - HAlo	+ on HAlo FP
			Hard - Soft surfaces*	+ on Soft surfaces MS
			High - Low traction*	+ on High traction surfaces MS
	Peak GRF	Fz	HAhi - Soft surfaces	+ on HAhi
	Loading Rate	Average	Hard surfaces - SOhi	+ on Hard surfaces
		Peak	HAhi - SOhi	+ on HAhi surface
			Hard -Soft surfaces*	+ on Hard surfaces
	Joint Angles	Thorax Rotation	High - Low traction*	+ rotation in opposite direction on Low traction surfaces All phases
	Joint Moments	Ankle Plantar Flexion	HAhi - SOhi	+ on HAhi PO
			Hard - Soft surfaces*	+ on Hard surfaces WA, MS, PO
		Ankle Eversion	HAlo - All other	- on HAlo MS
			Hard - Soft surfaces*	+ on Soft surfaces MS
			High - Low traction*	+ on High traction surfaces MS
		Knee Valgus	HAhi - HAlo	+ on HAhi WA, MS
			Hard - Soft surfaces*	+ on Soft surfaces MS
			High - Low traction*	+ on High traction surfaces MS
		Hip Extension	HAhi - SOhi	+ on SOhi PO
		Hip Abduction	HAhi - SOhi	+ on HAhi MS
			Hard - Soft surfaces*	+ on Soft surfaces MS
			High - Low traction*	+ on High traction surfaces MS
		Hip Int. Rot.	HAhi - HAlo	+ on HAhi WA
JH	Peak GRF	Fz	Hard surfaces - SOhi	+ on Hard surfaces
			HAlo - SOlo	+ on HAlo
			Hard - Soft surfaces*	+ on Hard surfaces
		Fy +	SOhi - All surfaces	+ on SOhi surface
	Loading Rate	Average	HAhi - SOhi	+ on HAhi
		Peak	Hard - Soft	+ on Hard surfaces
	Joint Moments	Ankle Eversion	HAhi and SOhi - SOlo	+ on SOlo All phases
			High - Low Traction*	+ on Low traction surfaces All phases

+: increase -: decrease *: difference not significant on all surfaces

7.3.16 Summary: Effects of In-game Conditions

The in-game conditions had a significant effect on the COM, joint kinematics and joint moments both for the ST and JH, and on the GRF for the JH (Table 7.30). For the ST the simulated opponent led to an increase of the affected parameters, whereas for the JH the heading condition led to an increase of the vertical COM, average GRF, affected joint moments as well as the ankle plantar flexion and inversion angle. The average and peak loading rate of the vertical impact force, peak positive Fy and negative Fx, ankle plantar /

dorsi flexion and eversion, knee flexion, eversion and internal rotation, hip flexion and internal rotation, and spine flexion angle were all decreased during the heading condition.

Table 7.30. Summary of the effects of the in-game conditions on the study parameters

Parameter			Effect
ST	**COM**		- Simulated opponent MS, PO, FP
	Joint Angles	Ankle Inversion	+ Simulated opponent PO
	Joint Moments	Knee Valgus	+ Simulated opponent MS
		Hip Abduction	+ Simulated opponent MS
		Hip Int. Rot.	+ Simulated opponent MS, PO, FP
JH	**COM**		+ Heading All phases
	Average GRF	Fz	+ Heading KNF
		Fy	+ Heading KNF
		Fx	+ Heading KNF
	Peak GRF	Fy +	- Heading
		Fx -	- Heading
	Loading Rate	Average	- Heading
		Peak	- Heading
	Joint Angles	Ankle Plantar Flexion	+ Heading PRE
		Ankle Dorsi Flexion	- Heading KNF, FIN
		Ankle Inversion	+ Heading IMP
		Ankle Eversion	- Heading PRE
		Ankle Int. Rot.	+ Heading PRE
		Ankle Ext. Rot	- Heading IMP
		Knee Flexion	- Heading All phases
		Knee Varus	- Heading PRE, IMP
		Knee Int. Rot	- Heading KNF, FIN
		Hip Flexion	- Heading FIN
		Hip Int. Rot.	- Heading PRE, IMP
		Spine Flexion	- Heading KNF, FIN
	Joint Moments	Ankle Plantar Flexion	+ Heading IMP, KNF
		Ankle Eversion	+ Heading IMP, KNF
		Knee Extension	- Heading IMP, FIN
		Knee Valgus	+ Heading KNF, FIN
		Hip Abduction	+ Heading KNF

+: increase -: decrease

7.4 Discussion

The previous sections presented the methodology and results of the player movement study in which biomechanical data was collected to investigate the effects artificial turf hardness and rotational traction properties have on the human dynamics during a stop and turn (ST) and jumping / heading (JH) manoeuvre. In addition to this, the movements were manipulated by adding in-game scenarios, which included a simulated opponent for the ST and heading a ball at maximal stop-jump height for the JH.

This section aims to evaluate the results of the player movement study with respect to the effects of surface properties on player movement and loading, and the relevance of in-game scenarios under lab testing conditions (objective 6 (Chapter 1)). To address the different aspects of the player movement study this chapter has been divided into three sections. In each of these sections the results of the player movement study are used to test the hypotheses set in Chapter 3. The first sub-section discusses the effects of the different surface conditions on the player movement dynamics during the ST and JH, as well as the perception of the players on each surface. The second sub-section discusses the effects of in-game scenarios, while the third gives an overall summary of the found results.

7.4.1 Surface Effects

Previous studies on running, hopping and cutting manoeuvres have shown that the properties of the surface and the shoe-surface interface can affect the musculoskeletal loading (D. Ferris et al., 1999; Kerdok et al., 2002; Meijer et al., 2007; Wannop et al., 2010; Stefanyshyn et al., 2010). However, the literature review has shown several gaps in knowledge with regards to the previous studies. Based on this four different surfaces were designed (Chapter 6) with different hardness and rotational traction values of which the hardness values were close to the limits of the FIFA one star qualification and the rotational traction values covered a large range of the FIFA two star qualification (Table 7.31). The goal of this was to gain insight into how the hardness and rotational traction properties, as set in the FIFA criteria, affect the human movement dynamics during a ST and JH manoeuvre, which were selected with the help of a player focus group and questionnaire (Chapter 4) (FIFA, 2012a). Furthermore, the surfaces were designed so the surfaces with different hardness had equal rotational traction properties and vice versa. This allowed for the results of the player movement study to be investigated in terms of hardness effects, rotational traction effects, and if the two properties had an interaction effect. During both the ST and JH test sessions the surface properties were maintained to ensure that these would be equal for all participants.

Table 7.31. Design characteristics of the surfaces used in player movement study, including mechanical properties determined in Chapter 6. For all surfaces a Tiger Turf Soccer Real 50 MS carpet was used and all surfaces contained 10 kg of sand per m^2.

Surface	Rubber per m^2	Shockpad	Force Reduction (%)	Rotational traction (Nm)
Hard / High (HAhi)	10 kg, 1 – 3 mm	No	52.3 ± 1.8	38.0 ± 1.9
Hard / Low (HAlo)	7 kg, 2 – 8 mm	No	51.5 ± 1.6	29.3 ± 1.2
Soft / High (SOhi)	10 kg, 1 – 3 mm	Yes	68.7 ± 0.6	38.0 ± 1.9
Soft / Low (SOlo)	7 kg, 2 – 8 mm	Yes	68.0 ± 0.9	29.3 ± 1.2

The following hypotheses were formulated in §3.5.1 regarding the effects the surface properties have on the human dynamics:

Harder surfaces will lead to:	**High traction surfaces will lead to:**
Increased ground reaction forces *Increased flexion angles lower limbs* *Increased flexion / extension moments lower limbs*	*Increased ground reaction forces, mainly horizontally* *Increased joint moments, both medial / lateral and rotational moments* *Similar ground contact times as on low traction surfaces.*

7.4.1.1 Stop and Turn

During the ST the different surface conditions had significant effects on the ground contact time, average vertical and posterior ground reaction force (GRF), peak vertical impact force, average and peak loading rate of the vertical impact force, ankle plantar flexion and eversion moments, knee valgus, and hip extension, abduction and internal rotation moments (Table 7.29). While significant, these effects were only present between two of the four surfaces, which means that the effects cannot be generalised for the surface hardness or rotational traction. However, for some parameters trends were visible across all four surfaces. For these parameters the effects can be attributed to the surface hardness and / or rotational traction. These involved the: average vertical (hardness / rotational traction) and posterior (hardness / rotational traction) GRF, peak loading rate (hardness), ankle plantar flexion moment (hardness), frontal plane moments of ankle, knee and hip joint (hardness / rotational traction), thorax rotation angle (rotational traction), and ground contact time (hardness / rotational traction).

With regards to the hypotheses the effects of surface hardness on the average vertical GRF was dependent on the ground contact phase. The average vertical GRF was increased on the soft surfaces during the mid-stance phase (MS) and increased on the hard surfaces during peak push off (PO). The average posterior GRF was also increased on the soft surfaces during MS, which was in contrast to the hypotheses. The average GRF showed no effects during the weight acceptance (WA) phase. However, the peak loading rate of the peak vertical impact force showed an increase on the hard surfaces, as hypothesised. Regarding the rotational traction, the average vertical and posterior GRF was, as hypothesised, increased on the high traction surfaces during MS. For the joint moments an increase in ankle plantar flexion moment was present on the hard surfaces as hypothesised, but in contrast to the hypotheses no effects were present for the knee extension moment. The effect of surface hardness on the hip extension moment was only present between the HAhi and SOhi surface. The effects of the rotational traction on the frontal plane moments was as hypothesised, while in contrast to the hypotheses no effects were visible for the external knee and ankle rotation moments. Also in contrast to the hypotheses the ground contact time was affected by the rotational traction (and hardness) of the surfaces. Finally, in contrast to the hypotheses, no significant surface effects were present for any of the joint angles.

As mentioned above, the frontal plane moments for the lower limbs showed an effect for the hardness and rotational traction properties on all surfaces. For all of these an effect was present for both properties during the MS phase. The clearest effect was present for the ankle eversion moment which was increased on the soft (7.5 – 12.7%) and on the high traction (4.8 – 9.8%) surfaces, with a significant effect between the HAlo surface and all other surfaces. The effects for knee valgus and hip abduction moment were less clear and a significant effect was only present between the HAhi and HAlo surface. Both moments were increased on the soft (knee: 4.8 – 11.9%; hip: 2.6 – 9.3%) and high traction (knee: 2.8 – 11.1%; hip: 4.8 – 12.5%) surfaces.

There were no significant effects for either the kinematics or ground reaction forces that can directly be linked to these changes. However, looking at the average GRF in the posterior and vertical direction shows that the posterior GRF was slightly higher on the high traction (4.7 – 4.9%) and soft (7.3 – 7.5%) surfaces during the MS phase. This was also the case for the average vertical GRF both for the rotational traction (2.8 – 4.3%) and surface hardness (1.9 – 3.5%), which was significant between the HAlo and SOhi surface. Furthermore, the ground contact times were slightly lower on high traction (3.5 – 4.7%) and soft (3.9 – 4.3%) surfaces, which was significant between the HAhi and HAlo surface. This suggests that an increased rotational traction allowed the players to decelerate / accelerate faster during the ST leading to increased frontal plane moments in the lower limbs. That these effects took place during the MS phase may be related to the observation that the high speed video footage showed that during mid-stance the entire foot was in contact with the ground. This may have allowed the players to make use of the increased surface traction. As little rotation took place during this phase (1.2° ± 1.0) it may be that players made use of the linear translational traction. While the linear translational traction was not measured Wannop et al. (2010) suggested that this is correlated to peak rotational traction. The increase in average GRF on the soft surfaces during MS may have been caused by an increased need for stability as a result of the deformation of the added shockpad as the GRF during this phase hardly changed (Figure 7.34) and the players came to a complete stop during this phase.

Of the parameters that showed a trend for the hardness on all four surfaces the ankle plantar flexion moment was the only one in the sagittal plane. On the hard surfaces the ankle plantar flexion moment was increased (5.6 – 9.3%) during PO, with a significant difference between the HAhi and SOhi. This effect was also visible during the WA and MS phase, but these differences were not significant. The average vertical GRF was also increased (3.7 – 4.6%) during the PO phase on the hard surfaces, with a significant difference between the HAlo and SOhi surface. The effect for the average vertical GRF is opposite to that found during the MS phase. A possible explanation for this is that the hard surface deform less during the push off and therefore allow for a larger force generation during the PO phase, leading to a higher ankle plantar flexion moment.

While some parameters showed effects for the hardness and / or rotational traction on all four surfaces, others such as the peak vertical impact force (HAhi – Soft surfaces), average loading rate of the peak vertical impact force (Hard surfaces – SOhi), knee valgus (HAhi – HAlo, WA), hip extension (HAhi – SOhi, PO) and hip internal rotation (HAhi – HAlo, WA) moment showed only an effect between two or three of the four surfaces (Table 7.29). This suggests that different combinations of properties can have different effects on the human loading. Especially considering the knee valgus moment, this was increased (9.6%) on the HAhi surface during WA compared to the HAlo surface, but at the same time a 5% decrease was found on the SOhi surface compared to the SOlo surface during the same phase. Therefore, on their own the hard and soft surfaces would show an opposite effect for the rotational traction regarding the knee valgus moment. A similar effect was visible for the hip internal rotation moment for the rotational traction, and for the hip extension moment for the surface hardness. This suggests that the effects of the rotational traction on human loading can be dependent on the surface hardness, and vice versa the effects of the hardness dependent on the rotational traction.

Looking at previous studies, very few have measured the rotational traction properties of the shoe-surface interface in combination with biomechanical. A study by Wannop et al. (2010) involved a 45° cutting manoeuvre, whereas a study by Stefanyshyn et al. (2010) involved both a 45° cutting manoeuvre and a 180° turning movement, which has the most resemblance to the ST used in this study. The main difference is that the rotational traction in the previous studies was modified by using different shoes, the study by Wannop et al. (2010) used indoor shoes on a track surface, whereas the study by Stefanyshyn et al. (2010) used a combination of soccer boots with different cleat design and a running shoe on a sand and rubber filled artificial turf surface. Both studies found, similar to this study, that an increased rotational traction leads to an increased knee valgus moment, and Stefanyshyn et al. (2010) also found a trend for the ankle eversion moment similar to this study during the 180° turn. The hip joint was not included in both studies. However, as the frontal plane knee and ankle joint moments were both increased during the 180° turn it may be that the traction had a similar effect on the hip abduction moment, as was found in this study.

In contrast with the hypotheses and previous studies, no significant effects were found for the external rotation moments in the knee and ankle joint. It is unclear why this effect was not present in this study as the range in this study (~ 10 Nm) was similar to that in previous studies (8 – 9.5 Nm) (Wannop et al., 2010; Stefanyshyn et al., 2010). It may be that differences in technique had an effect on this as the peak knee valgus moment during the 180° turn used by Stefanyshyn et al. (2010) was substantially lower than the averages found in this study, ~37 Nm versus ~154 Nm, while the body mass was similar. The exact landing of the foot before the turn was not defined by Stefanyshyn et al. (2010). However, the description of the manoeuvre described that the foot was first planted followed by a 180° turn. Therefore it may have been that the subjects in the study by Stefanyshyn et al. (2010) had to rotate their lower limbs more than the players in this study, and made less of a lateral movement, causing differences in joint moments compared to this study. In this study the high speed footage showed that the players planted their foot already rotated ~90° towards the turning direction and also rotated a substantial part of the 180° rotation just after take-off, meaning that most of rotation took place in the air. This is also confirmed by the foot rotation data during ground contact which showed that on average the total foot rotation was no more than 11.6 ± 5.8°. As the players in this study did not receive instructions on how to place and turn their foot, or were asked why they used this technique, it is not known on what basis they used this technique. However, as all players in this study used the same technique a possible explanation may be that this technique was the most natural for the players, either because they were trained to perform the ST like this, as all players were part of Loughborough University teams, or because it is the easiest to perform the ST like this and reduces the loading on the body. Either way the finding suggests that giving subjects specific instructions on how to perform a manoeuvre may cause them to perform the manoeuvre in an unnatural manner and therefore may influence the outcomes and relevance of a study. However, more research is needed to determine if the technique used by all the players in this study generally is a more natural way to perform a ST compared to that used by Stefanyshyn et al. (2010), or was only the most natural technique for the players in this study as a result of training. Another explanation that Stefanyshyn et al. (2010) did find effects may be that the marker set used by them allowed them to track changes for the internal / external rotation of the knee and ankle more accurately. Finally, it may be that the different mechanical measurement method for the rotational traction used by Wannop et al. (2010) and Stefanyshyn et al. (2010) was more representative of the rotational traction players experience during a ST, which is further discussed in §7.4.1.3.2.

The players may also have adjusted for the differences in rotational traction by adjusting their thorax rotation. While the results were not significant and large standard deviations were present, a trend was visible in the data that the thorax of the players was rotated slightly more towards the turning direction on the low traction surfaces. As a study on cutting manoeuvres showed that the thorax rotation can affect the peak internal rotation moment of the knee during a sidestep cut it may well be that the players adjusted for the change in rotational traction by adjusting the thorax rotation (Dempsey et al., 2007). However, more research will be needed before a definite conclusion can be made.

With regards to injuries, previous studies have shown that an increased knee loading, especially varus / valgus loading, can lead to ACL injuries. Previous studies on cadavers suggested that ligament damage in the knee occurs at valgus moments ranging from 125 – 210 Nm (Piziali et al., 1980). Furthermore, a study by Senter and Hame (2006) suggested that the risk on ACL injuries increased as the knee flexion angle decreased from 45° to 0°. The results from this study show that the average knee flexion was smaller than 45° during WA (37.7 ± 7.4°) and final push off (FP) (25.6 ± 6.9°) and only just above it during PO (45.7 ± 8.9°), whereas the valgus moments were within or close to the mentioned range for the average weight of the players (75 kg) during WA (~154.5 Nm), MS (~113.7 Nm) and PO (~127.2 Nm). The joint moments found in the cadaver study are likely to be an underestimation as previous studies reported moments exceeding the cadaveric injury limits without reporting any injuries (Besier et al., 2001; Kaila, 2007; Wannop et al., 2010). However, in combination with the knee flexion angles it seems that the rotational traction properties can affect the risk of ACL injuries during a ST, especially during WA where the knee valgus moment was highest, and the average knee flexion angle was less than 45°. Notably, the valgus moment was significantly increased by 9.6% on the HAhi surface compared to the HAlo surface. However, the results also show that more research is needed in this field as the effect was not conclusive for all four surfaces.

Regarding the ankle eversion moment, previous studies on injuries have often speculated that high traction surfaces were a risk factor for ankle injuries (Torg et al., 1974; Lambson et al., 1996; Orchard & J. Powell, 2003; Orchard et al., 2005; Villwock et al., 2009; Livesay et al., 2006). The results of this study seem to support this as the ankle eversion moment was increased on the high traction surfaces and may contribute to the high ankle injury incidence in soccer identified in §2.3.3. As previous studies mainly focused on the ankle and knee loading during turning manoeuvres no information is available on how the hip is affected by the rotational traction. However, the results from this study indicate that rotational traction may also contribute to the hip injury incidence in soccer identified in §2.3.3 due to the increased loading on the hip.

While the rotational traction may be a risk factor for injuries, the decrease in ground contact time on high traction surfaces also suggests it may increase athlete performance. With regards to this, the question can be asked if it is better to have a lower risk of injury or a better performance during a match. A previous study on player perception on hockey fields showed that the players did not mind any soreness on the ankles and knees if the game performance was increased, suggesting that players preferred a good performance over a lower musculoskeletal loading (Fleming et al., 2005). On the other hand, the players that participated in the player focus group (Chapter 4) all agreed that they did not mind if their own performance on the pitch decreased if it would lead to fewer injuries. The main argument for this was that the performance effects would also affect their opponents, therefore it would not lead to any (dis)advantage during a match.

No previous studies have investigated the effects of the surface hardness on musculoskeletal loading during cutting / turning manoeuvres. However, it is relevant to compare the ST results to those found in previous studies on running and hopping on surfaces with differing hardness. Based on these previous studies it was hypothesised that the extension moments would increase on the hard surfaces (Meijer et al., 2007; Moritz & Farley, 2005). Especially as the hardness range in this study was similar (FR: 52 – 70%) to that used by Meijer et al. (2007) (FR: 56 – 74%). An effect for all surfaces for the flexion / extension was only present for the ankle plantar flexion moment, which was increased on the hard surfaces, whereas the average vertical GRF showed some effect but this was not consistent during the different phases. At the same time, the hip extension moment was increased on the HAhi surface relative to the SOhi surface during PO, but no effects were present between the low traction surfaces. The limited effects for the extension moments may be explained by the fact that the vertical GRF during the ST was smaller than those reported in previous studies on running or hopping, which is likely to be caused by the deceleration of the players in the final few steps before the turn (Meijer et al., 2007; Moritz & Farley, 2003; Farley & Morgenroth, 1999). It may therefore be that during these final few steps the surface hardness plays a more important role than during the actual turn itself. However, as the choice was made to collect the data during the turn only further research is necessary to investigate the braking steps prior to the turn. The limited effects for the flexion / extension may also be caused by limitations in the mechanical measurement of the hardness, which is discussed further in §7.4.1.3.1.

7.4.1.2 Jumping / Heading

During the landing of the JH manoeuvre the peak vertical impact force, peak posterior GRF, average and peak loading rate of the vertical impact force, and ankle eversion moment were affected by the different surface conditions. The peak vertical impact force and peak loading rate were increased on the hard surfaces which is in line with the hypotheses, whereas the average loading rate only showed a significant effect between the HAhi and SOhi surface. The peak posterior GRF was increased on the SOhi surface compared to all other surfaces. However, this increase was minimal with a maximal difference of 0.05 BW.

The ankle eversion showed a trend during all phases that low traction surfaces increased the eversion moment compared to the high traction surfaces, with a significant difference between the SOlo surface and both high traction surfaces during all phases (impact (IMP), peak impact to peak knee flexion (KNF), peak knee flexion to peak knee flexion + 100 ms (FIN)). While the effects were statistically significant the differences between the surface conditions were no larger than 0.022 Nm/kg. It is not expected that these differences have any substantial effect on the musculoskeletal loading, moreover as the ankle eversion moment was up to three times as high during the ST.

While the hypotheses of increased peak vertical impact force and loading rates on the hard surfaces were confirmed, the other hypotheses, in example, an increase in sagittal joint angles and moments were not. A possible explanation for this may be found in the specific movement used. A previous study on drop jumps suggested that the adjustment of humans to surfaces with different hardness, is not only dependent on the hardness but also on the demands of the activity (Arampatzis et al., 2004). The study by Arampatzis et al. (2004) did not find any significant effects for GRF or joint moments or angles for a drop jump, which is in line with the findings in this study. In contrast to the present study, previous studies found that the surface hardness can affect the drop jumping performance, whereas no differences in maximal jump height were found in this study (Arampatzis et al., 2004; L. Johnson & Forrester, 2011). However, the previous studies do not concur as Arampatzis et al. (2004) found an increased jump height on the soft surface, whereas Johnson and Forrester (2011) found an increase in jump height with an increased hardness.

7.4.1.3 Influence of Surface Measurement Methods

The previous sections showed that not all hypotheses were confirmed with regards to the surface properties. For example, for the hardness it was hypothesised that the harder surfaces would lead to increased GRF and sagittal plane angles and moments, whereas for the rotational traction it was hypothesised that the higher traction surfaces would lead to increased transverse plane moments during the ST. However, the only parameter that showed significant differences between both soft and both hard surfaces was the peak loading rate of the vertical impact force of the JH manoeuvre. Other parameters such as the peak loading rate of the ST showed a trend between both hard and soft surfaces, but significant differences were only present between some of the surfaces. Finally effects in the sagittal plane joint angles and moments were limited to an increased ankle plantar flexion moment on the hard surfaces. With regards to the rotational traction, no effects were found for transverse plane moments of the knee and ankle joint, which were present in previous studies (Wannop et al., 2010; Stefanyshyn et al., 2010). As previously noted, that the hypotheses were not confirmed in this study may be related to the mechanical measurement methods used to quantify the surface properties.

7.4.1.3.1 Hardness

The hardness of the surfaces in this study was measured using an Advanced Artificial Athlete (AAA), which is also used by FIFA (FIFA, 2012b). With regards to the impact conditions of the ST and JH there are several aspects that may explain why not all hypotheses were confirmed. First of all it may be that the difference in force reduction values between the surfaces simply was not large enough to affect the human movement dynamics. However, a previous study on running on 3G artificial turf surfaces did find significant effects for the ankle plantar flexion moments between surfaces with force reduction values ranging from 56.6 – 74.2% (Meijer et al., 2007), which is similar to the maximal range in this study (18.8%). Furthermore, as effects were present for the ankle plantar flexion moment during the ST one would expect that the surface hardness would have an effect on a movement with a larger vertical GRF and larger range of motion in sagittal plane of the lower limb joints. In addition to this, due to the predominantly vertical nature of the landing after the JH, it was expected that the hardness would play a larger role during the JH than during the ST.

Looking at other parameters it becomes clear that the decrease in force reduction mainly was visible in the impact force parameters of the ST and JH, which are the parameters that the AAA resembles the most. However, even amongst these parameters the differences between the hard and soft surfaces were not always significant despite the substantial differences in force reduction values. This may be related to the difference in peak vertical impact force values of the ST and JH manoeuvre and those measured with the AAA. For the ST and JH manoeuvre the differences between the hard and soft surfaces in peak vertical impact force were no larger than 0.15 BW for the ST (Figure 7.33) and 0.49 BW for the JH (Figure 7.34). The difference in measured peak force with the AAA between the hard and soft surfaces on the other hand was much higher at 1.8 BW, based on the average body mass (75 kg) of the players in the study. Furthermore, the peak force measured with the AAA (FR 50%: 4.5 BW, FR 70%: 2.7 BW) was substantially different to the typical peak vertical GRF during the ST (1.7 – 1.9 BW), suggesting the AAA measurement overestimates the impact for the ST on both hard and soft surfaces (Figure 7.87). Regarding the JH the peak force of the AAA and landing (3.9 – 4.4 BW, per leg) were closer. However, depending on the surface (hard / soft) and landing a difference of up to 1.3 BW is possible between the peak impact force of the AAA and the force experienced by the players.

A similar pattern is visible for the average loading rate. The difference in loading rate measured with the AAA between a hard surface (FR 50%: 240 BW/s) and a soft surface (FR 70%: 128 BW/s) was much larger than that present during the ST (3 – 11 BW/s) and JH (3 – 41 BW/s) manoeuvre. The average loading rate on the soft surfaces during the JH (124 – 153 BW/s) were close to those measured with the AAA (128 BW/s), yet on the hard surfaces the average loading rate measured with the AAA (240 BW/s) was substantially higher than those found during the JH (156 – 165 BW/s). Furthermore, the average loading rates measured with the AAA were up to almost six times as high as those found during the ST (43 – 54 BW/s) and higher than the average loading rates reported in previous studies on running (S. Dixon et al., 2000; Gottschall & Kram, 2005; Milner et al., 2006). In that light it seems that the FIFA test method, using a single impact condition with the AAA, does not resemble a range of human movements on different surfaces and overestimates the difference in peak impact force and average loading rate. As a result the FR values of the AAA seem to only provide some indication on the differences in peak vertical impact force and loading rates between surfaces during various manoeuvres, but as the results of the ST and JH showed these differences are not always significant.

The variation in impact force and average loading rate, as visible in Figure 7.87, may also create the possibility that the hardness experienced by the players was different to that measured with the AAA. Especially when considering that third generation surfaces have visco-elastic properties and that the surface response is not linear, this means that depending on the force applied, the hardness of the same surface can vary (McMahon & Greene, 1979; Oyen & Cook, 2003). However, more research is necessary to determine how different loading conditions affect the surface hardness.

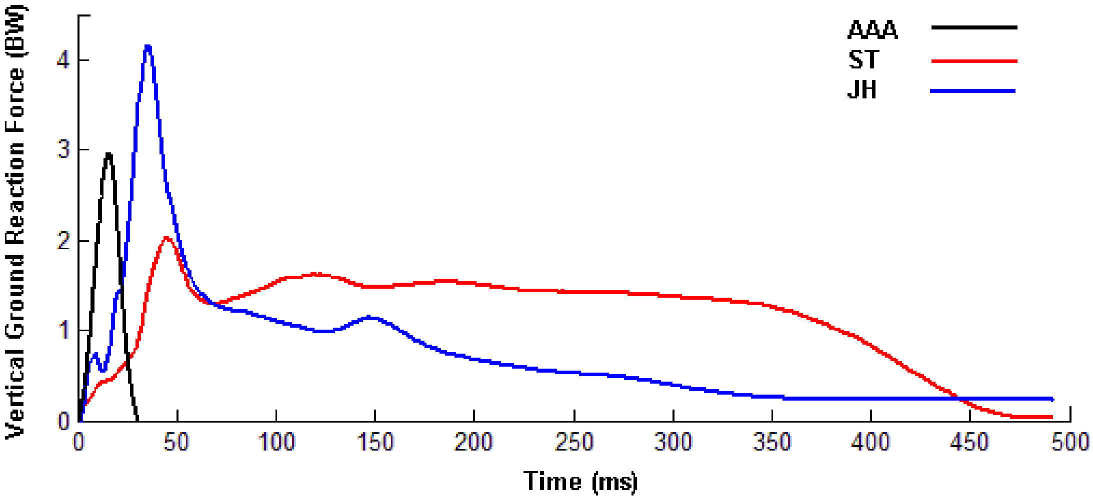


Figure 7.87. Examples of the typical vertical ground reaction forces (BW) during the ST and JH of a player with a body mass of 75 kg and the vertical force measured with the AAA based on a body mass of 75 kg.

7.4.1.3.2 Rotational Traction

The rotational traction properties of the surfaces in this study were measured using the standard test device as used by FIFA (FIFA, 2012b). Looking at the foot rotation angles it appears that the standard FIFA test may not give the best representation of the rotational traction experienced during a turning manoeuvre. As mentioned, on average the foot rotated by 11.6 ± 5.8°, but the data also showed that the foot did not always rotate continuously in the direction of the turn and that during MS hardly any foot rotation took place. This is quite different to the FIFA protocol for the rotational traction measurements which requires a minimum 45° rotation at a constant speed of 12 rev/min (FIFA, 2012b). Furthermore, the high speed video footage showed that during ground contact the proportion of the foot in contact with the surface varied greatly. During the initial landing and take-off only part of the foot was in contact with the surface, whereas during mid-stance the entire foot was in contact with the surface. Previous studies that looked at the development of the rotational traction during the rotation have shown that the rotational traction of a surface is not linear and that peak traction can be reached at different parts in the rotation (Livesay et al., 2006; Villwock et al., 2009). This means that with the limited rotation of the foot the players may not have reached the peak traction as measured with the rotational traction device. In addition to this, Livesay et al. (2006) also showed that the magnitude of the peak rotational traction is dependent on the normal load applied. Comparing this, the average vertical GRF during the ST (~931 N) for the average player was substantially higher than the 451 N (46 kg) applied with the rotational traction device (FIFA, 2012b). As a result, the experienced rotational traction and the differences between the surfaces may have been different to those quantified with the mechanical test. It is also thought that the changes in rotation speed and the variation in ground contact during the ST may have had an effect on this. There is, however, no scientific data available to support this and therefore more research is needed before any conclusions can be drawn.

Compared to previous biomechanical studies that found changes in the transverse knee and ankle moments, the mechanical measurement method used in the present study was different as those studies used a custom made robot (Wannop et al., 2010; Stefanyshyn et al., 2010). The main differences between these devices is that in the studies by Wannop et al. (2010) and Stefanyshyn et al. (2010) a complete shoe was used at an plantar flexion angle of 20° and that the surface was rotated, rather than the test foot, during which the rotational traction was determined with a tri-axial load cell at a normal load of 400 N (Figure 7.88). Compared to the test results in Chapter 6 it appears that this method gives different rotational traction values as the standard rotational traction device. The rotational traction measured by Stefanyshyn et al. (2010) using a boot with similar studs as used in the present study was more than 10 Nm lower than any of the sand and rubber filled samples used in Chapter 6. As the studies that used this method did find significant differences for the transverse plane moments it may be that this method gives a better representation of the rotational traction experienced by a player during a turning manoeuvre than the standard FIFA test. Finally, for part of the ST it may be that the translational traction properties of the shoe-surface interface provide a better measure of the traction players experience. This is especially relevant during the ground contact phases during which the foot rotation was minimal, such as MS.

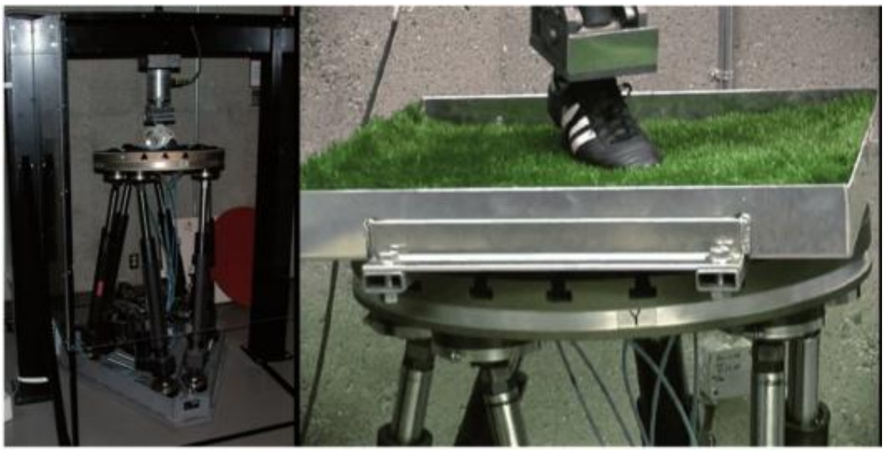


Figure 7.88. Test device used in studies by Wannop et al. (2010) and Stefanyshyn et al. (2010) to measure the rotational resistance of the shoe surface interface.

7.4.1.4 Player Perception

After each surface condition during the ST and JH test the players were asked to rate how they perceived the hardness, from very soft to very hard, and rotational traction, from very low to very high traction, of each surface on a visual analogue scale. The aim of this was to gain insight into whether players were able to identify the mechanically measured differences between the four surfaces. At the end of the test the players were asked to indicate which of the four surfaces they preferred and disliked the most to see if there was a common preference amongst players and if this was related to their perception of the surfaces, or the biomechanical results.

As a clear difference was present in the mechanically measured hardness (12.3 – 18.8%) and rotational traction (9.5 – 10.1 Nm), and previous studies showed a good correlation between the AAA and rotational traction measurements and the perception of athletes (Young, 2006; Hopper et al., 2010), it was hypothesised that the players would be able to notice differences in hardness and rotational traction between the four surfaces. However, contrary to this the player perception questionnaires showed that the players were not able to do this as up to 50% of the players falsely identified one of the soft surfaces as being the hardest of the four, and vice versa indentified one of the hard surfaces as being the softest, despite the significant differences being present for the peak impact forces and loading rates of both manoeuvres. The same pattern was visible for the rotational traction properties for which up to 56% of the players rated a high traction surface as being the surface with the lowest traction and vice versa. To add to this, in only four of the 32 questionnaires were all four surfaces rated correctly, suggesting the players were not able to identify the differences in mechanical properties between surfaces.

That the players were not able to identify the differences between surfaces may have been caused by several factors. As described in §7.4.1.3 it may have been that differences in actual experienced hardness and rotational traction were different to the mechanically measured values due to differences in surface response during different loading conditions. On the other hand, for the hardness effects were present for the peak vertical impact forces and loading rates, suggesting the difference in measured hardness may have been noticeable to the players. Furthermore, previous studies have shown a good correlation between the mechanically measured values and the perception of athletes on surfaces with similar differences as the surfaces used in the present study (Young, 2006; Hopper et al., 2010). Compared to these studies, the players spent little time on the surfaces, as effectively they performed no more than 15 trials on each surface each lasting only a few seconds. This may have been too short for the players to get a good idea of what the surface properties were like, thus affecting their ratings of the surfaces. This effect may have been increased by the fact that the players did not have any familiarisation time on each surface to get used to the different properties of the surfaces. Another aspect is the observation that for none of the biomechanical parameters a significant difference was present between all four surfaces. This may have increased the difficulty for the players to correctly identify the mechanically measured differences between surfaces.

Regarding the surfaces the players preferred and disliked, the majority (75 – 87.5%) indicated to prefer one of the high traction surfaces during both manoeuvres and it was clear that the HAlo surface was the surface that was disliked the most. From how the players rated the surfaces it appears that the majority rated the surface they disliked the most as being perceived as either the hardest or softest, or as having the highest or lowest traction. With regards to the surfaces they preferred the most, 81% of the players chose a surface they rated as having an intermediate hardness (neither the hardest or softest), whereas for the rotational traction 50 – 56% preferred a surface with a perceived high traction. These findings seem to agree with the results of Chapter 4, in which players indicated a preference for a surface with higher than intermediate traction and an intermediate hardness. However, these findings cannot be linked to specific values as players were not able to identify the mechanically measured differences.

Looking back at the biomechanical findings, the high traction surfaces were related to decreased ground contact times and increased average vertical GRF, posterior GRF, and frontal plane moments in the lower limbs. It may be that these effects were considered beneficial for their performance. However, as the players were unable to identify the surfaces it is questionable that the players made their decision based on this.

7.4.2 In-game Scenarios

One of the limitations identified in previous biomechanical studies was the use of isolated movements in a lab environment. As a result, they lack realism as in actual match situations other factors such as opponents, use of a ball, fatigue and many more, can influence the execution of the movements. This is especially relevant as previous studies have shown that simulated opponents, fatigue, and the use of a ball can affect the human movement dynamics (Reilly, 1997; McLean et al., 2004; Ford et al., 2005; Chan, Huang, Chang & Kernozek, 2009b). Therefore, to investigate if more realistic manoeuvres affect the human movement dynamics an in-game scenario was added to the ST and JH.

The in-game scenario for the ST involved a simulated opponent who was instructed to stand 5 – 10 cm behind the force platform, allowing comparison of the ST with and without a simulated opponent. For the JH, a ball was suspended from the ceiling at the maximal vertical jump height for that player to compare a maximal vertical stop jump with a maximal vertical stop jump during which the players had to head a ball. More detailed information on the in-game scenarios is available in Chapter 7.

The following hypotheses were formulated in §3.5.2 regarding the effects the surface properties have on the human movement dynamics:

Simulated opponent will lead to:	**Heading a ball will lead to:**
Increased ground reaction forces *Increased flexion and medial / lateral joint angles in lower limbs* *Increased flexion / extension and medial / lateral joint moments in lower limbs*	*Increased anterior / posterior ground reaction forces* *Decreased flexion lower limbs during initial impact, increased flexion after impact* *Increased upper body flexion* *Increased flexion / extension joint moments in lower limbs*

7.4.2.1 Simulated Opponent (ST)

The simulated opponent scenario used for the ST was similar to that used in a study by McLean et al. (2004) on a sidestep cutting manoeuvre with the main difference that the simulated opponent was represented by a human rather than a skeleton to increase the reality of the scenario. The players were instructed to start at the beginning of the runway and accelerate to a speed of 12.5 – 14 km/h (Figure 7.1). At 1.5m from the force platform they were required to decelerate and make a 180° stop and turn on top of the force platform and accelerate back towards the first timing gates as if they had to chase a ball or opponent, or were chased by an opponent. The same instructions were used for the in-game scenario with the simulated opponent standing 5 – 10 cm behind the force platform. The simulated opponent was instructed to only stand behind the force platform

With regards to the hypotheses the simulated opponent had no effects on the GRF, whereas the ankle inversion angle was significantly increased as were the knee valgus, hip abduction and hip internal rotation moments. In contrast to the hypotheses, the sagittal plane angles and moments did not show any effects. However, the opponent condition did have a significantly lower vertical centre of mass (COM), suggesting an overall more flexed posture of the players during the ST.

A closer look at the effects for the simulated opponent showed that the difference for the ankle inversion angle was minimal, only 0.1°, and this also had no effect on the ankle inversion / eversion moment. The effects found for the knee valgus, hip abduction and hip internal rotation moments all took place during MS during which all investigated joints reached their peak flexion and the hip joint reached its peak rotation angle. During this phase the knee valgus moment was increased by 5.6%, the hip abduction moment by 3.6% and the hip internal rotation moment by 7.1%. The effects for the internal hip rotation moment were also visible during the PO and FP phase of the ST.

While a direct comparison cannot be made with the study by McLean et al. (2004) due to the different movements used, some discussion is warranted. The kinematics and GRF did not show a similar mechanism of dealing with the simulated opponent as in the study by McLean et al. (2004), which found a significant increase for the knee and hip flexion angle, knee valgus and hip abduction angle, and medial GRF during peak stance phase. However, while the present study found no significant effects for the kinematics or GRF, the knee valgus and hip abduction moment were increased for the simulated opponent condition. This shows similarities with the study by McLean et al. (2004) assuming that the increase in GRF and joint angles also led to an increase in joint moments. Furthermore, the lower vertical COM in this study suggests a more flexed posture which seems to be in conjunction with the increased flexion in the study by McLean et al. (2004), albeit less profound.

That the effects found in the study by McLean et al. (2004) were not all present in this study may be caused by the different nature of the movements used and subsequently the proximity of the simulated opponent. During the ST the players had to come to a complete stop to turn in the opposite direction, whereas during a sidestep cutting manoeuvre the players maintain their speed while changing direction. The study by McLean et al. (2004) suggested that the increased flexion of the knee and hip reflected a need to come to a quicker deceleration on initial contact due to imposed spatial changes. However, as the players had to come to a complete stop during the ST it may have been that the players increased the deceleration during the braking steps prior to the turn. Furthermore, it is possible that during the turn the players relied more on the increased knee valgus and hip adduction moments for the deceleration / acceleration as the high speed video footage showed that body and foot of the players was turned at ~90° to the running direction throughout the ST.

Other factors that may have affected the results in relation to the previous study by McLean et al. (2004) are that a larger force platform was used in this study, and that the players did not have to get past the simulated opponent. As a result, the necessity of an increased deceleration may not have been as profound as in the study by McLean et al. (2004) as the risk of hitting the opponent will have been smaller, despite the simulated opponent being closer to the force platform. However, even though no effects were present for the GRF and kinematics in this study, the increased knee and hip moments do show that the loading on both joints was affected by the simulated opponent.

With regards to the risk of injuries, it has already been discussed in §7.4.1 that the increase in knee valgus moment may be a risk factor for ACL injuries. However, during the MS, for which the effect was significant, the knee flexion angle was larger than the 0 – 45° range mentioned in previous studies to be the risk area for ACL injuries (Senter & Hame, 2006). As mentioned, the distance between the simulated opponent and the players in this study was relatively large and the simulated opponent was also static. It may be that the effect of the simulated opponent will be larger when they are in closer proximity and also if there is a real need to move away from the opponent. However, more research with more complex in-game scenarios is needed to investigate this.

7.4.2.2 Heading a Ball (JH)

Comparing a vertical stop-jump with a vertical stop-jump including a heading manoeuvre has not been done in previous studies. Therefore no direct comparisons can be made with previous research. For the jumping trials the players were instructed to perform a maximal vertical stop-jump, whereas for the heading condition the instructions were similar with the addition of heading a ball suspended from the ceiling at maximal jump height (determined without the ball). The ball for the heading condition meant that the players would have a point to aim for during their jump which could potentially have led to a difference in jump height as previously found in a study by Ford et al. (2005). However, the maximal COM data showed no significant differences between both in-game conditions suggesting that addition of the ball did not affect the jump height.

It was hypothesised that the heading condition would lead to increased horizontal breaking forces and an increased flexion of the upper body during landing. Furthermore it was hypothesised that the sagittal plane joint moments of the lower limbs would be increased, especially for the ankle and knee joint and that the flexion of the lower limbs would be decreased before and during the initial impact and increased after. No changes were expected in the frontal and transverse planes of the joints due to the predominantly vertical nature of the manoeuvre.

The main significant differences were present for the average vertical GRF, peak posterior and lateral GRF, average and peak loading rate of the vertical impact force, and flexion / extension joint angles and moments. The average vertical GRF was increased during the heading condition (KNF), as was the ankle plantar flexion (IMP, KNF) moment. Contrary to the average vertical GRF the average and peak loading rate of the vertical impact force were decreased during the heading condition. This was also case for the knee extension moments (IMP, FIN), which was in contrast to the ankle plantar flexion moments (IMP, KNF). The flexion angles of the ankle (all phases), knee (all phases), hip (FIN) and spine (KNF, FIN) were all decreased and the vertical COM location was significantly higher for the heading condition suggesting a more upright posture.

Looking in more detail at what happened during the different phases it appears that the players used a different landing strategy after heading a ball than when they performed a maximal stop jump. During PRE the ankle plantar flexion angle was significantly larger for the heading condition, allowing a larger angular change from the PRE to KNF phase during the landing after the heading condition (40.5° versus 34.5°), while the angular changes in knee (51.2° versus 49.7°) and hip flexion (22.9° versus 20.4°) were smaller for the heading condition. In addition to this, the ankle plantar flexion moment was significantly increased (0.19 Nm/kg, IMP) during the heading condition, whereas the knee flexion moment was decreased (0.16 Nm/kg, IMP). The increase of the ankle plantar flexion moment and decrease in knee extension moment was also visible in the other phases with significant differences during KNF for the ankle and FIN for the knee moment. This all indicates that after heading a ball the players changed their landing strategy to absorb a greater proportion of the landing impact through of the ankle joint. This may also explain the differences found for the average vertical GRF and loading rates of the vertical impact force as the jump height was similar in both conditions.

A comparison with previous studies shows similarities to the different landing strategies found in a gender comparison for a drop landing in a study by Decker et al. (2003). In this study it was found that females land with a more erect posture compared to men, with decreased knee flexion angles and increased plantar flexion angles. This is similar to the effects found for the heading condition. It was suggested that the more erect posture allowed the females to fully utilise the capacity of the ankle plantar flexor muscles to absorb the shock (Decker et al., 2003). Similar findings were found for the knee joint in a study by Chappell et al. (2005) that looked at the effect of fatigue on the landing after a stop-jump task, which also showed that the knee flexion of the subjects decreased when fatigued.

While the change in strategy is similar to that found in previous studies, the cause differs, as both the gender (only male players were used), and fatigue (the trials were randomised and players were allowed sufficient rest) were not factors in this study (Decker et al., 2003; Chappell et al., 2005). A plausible option is that the change in strategy was caused by a shift in attention. During the maximal vertical stop jump the players can pay all their attention to landing after the jump and absorbing the energy of the landing, whereas for the heading manoeuvre part of their attention has to go to the actual heading of the ball. Therefore they may have less time to prepare for the impact which they compensate for with a more erect posture and absorb the impact more with their ankles than with their knees. This may be related to previous findings in hopping studies, that showed the ankle plays the largest role in adjusting leg stiffness, and may allow the players better control of their movement dynamics during landing when their attention is shifted (Farley et al., 1998; Farley & Morgenroth, 1999; Moritz & Farley, 2006).

The change in landing strategy after the heading condition may also explain the changes found in the frontal plane. The ankle inversion and knee varus angle were both decreased during the landing after the heading condition, while the ankle eversion, knee valgus, and hip abduction moment were increased. In addition to this, the internal rotation angle of the knee was also decreased during the heading condition. Looking at these differences it can be said that the differences in joint angles were small as they were no larger than 1.9°. The effects on the joint moments were significant, but the magnitude of the joint moments was small. Especially compared to the frontal plane joint moments the players experienced during the ST.

For the average GRF a significant increase was present in the posterior direction (12.5%), but also in the medial direction (11.9%) during KNF. The increase in the medial direction was not expected. However, this again may be part of the change in landing strategy especially since the peak posterior and lateral forces were decreased for the heading condition. Therefore, it may be that the players, due to their more erect posture during landing, are less able to absorb of the impact in the horizontal directions during the initial phase of the landing and have to compensate for this during the KNF phase. Another possibility is that the forward momentum of the players was higher due to the heading manoeuvre, which seems to be supported by the increased average GRF in the posterior direction. As the players were required to stand still after the landing they may have absorbed part of the energy by a medial / lateral movement of the limbs, instead of making a step forward.

The extra forward momentum during the heading manoeuvre was expected as previous research showed a forward motion of both the torso and head when heading the ball in stance including a short rapid acceleration (Shewchenko et al., 2005). Based on this it was hypothesised that an increase in upper body flexion would be present during the heading condition. However, this was not the case and during KNF and FIN the spine flexion was even reduced. This may have been caused by players already adjusting the position of their upper body prior to the PRE phase, but from personal observation it appeared that the players also used the forward motion of the jump to head the ball. Therefore it may be that they did not have much need for an increased upper body movement in order to head the ball, as was the case in the study by Shewchenko et al. (2005). The fact that the ball was hanging still in the air may have contributed to this.

Previous studies have suggested that a more erect posture during the landing as well as an increased knee valgus moment are risk factors for ACL injuries (Decker et al., 2003; Cochrane et al., 2007; Senter & Hame, 2006). Therefore the strategy used for the landing after the heading manoeuvre may be a risk factor for injury. Particularly since the knee valgus angles and moments were increased and the knee flexion angle during the IMP phase was less than 45°, while previous research has shown that ACL injuries often occur with knee flexion angles <45° (Senter & Hame, 2006). On the other hand the frontal plane joint moments during the ST were three to nine times higher than during JH, which suggests that the joints are well able to deal with the moments experienced during the JH.

As previous studies showed that fatigue and gender can have similar effects on the landing strategy it may be possible that the risk increases when players are fatigued or when female players perform a heading manoeuvre (Chappell et al., 2005; Decker et al., 2003). The results also showed an increased ankle eversion moment during the landing after the heading condition. This may not be a direct risk factor, but during the player focus group (Chapter 4) the players mentioned that if the studs did not penetrate the surface properly it was easier to twist their ankle. The increased ankle eversion moment may add to this when the landing is unstable, also in combination with the observation that for the surface conditions a significant effect was found for ankle eversion moment during the landing after the JH, albeit small. This is especially relevant as a previous study on injuries in soccer showed that landing was responsible for the most non-contact ankle injuries in soccer (Kofotolis et al., 2007).

7.4.3 Summary

7.4.3.1 Surface Effects

The different surface conditions had significant effects on both the ST and JH manoeuvre. Regarding the ST the surface conditions had significant effects on the joint moments, average GRF, peak loading rate of the vertical impact force and ground contact time. On the soft surfaces increases in ankle eversion, knee valgus, and hip abduction moments were present, together with an increased average vertical and posterior GRF during MS. In addition to this the soft surfaces also led to a decreased average vertical GRF during PO and a decreased ankle plantar flexion moment. For the rotational traction it was found that an increase in rotational traction leads to increased frontal plane moments, as well as increased average vertical and posterior GRF during MS and a decreased ground contact time.

The increased average vertical and posterior GRF during MS, and decreased ground contact time on the soft and high traction surfaces suggested that the increased rotational traction allowed the players to decelerate / accelerate faster, leading to increased frontal plane joint moments. The addition of the shockpad on the soft surfaces may have required a larger force generation during MS to come to a complete stop as a result of the lower peak impact force and loading rates during that were present during WA. At the same time, the increased average GRF on the hard surfaces during PO suggested that during this phase the hard surfaces allow for a larger force generation, as they deform less, leading to an increase in ankle plantar flexion moment.

In addition to the effects found for the surface hardness and rotational traction, the knee valgus and hip internal rotation moment during WA, and hip extension moment during

PO showed that the effects of the surface hardness and rotational traction can be dependent of each other. For example, the knee valgus moment was increased on the HAhi surface compared to the HAlo surface during WA, but decreased on the SOhi surface, compared to the SOlo surface. Therefore, on their own the hard and soft surfaces would show a completely opposite effect for the rotational traction. This is especially relevant as previous studies only modified one property of the shoe-surface interface.

Contrary to previous studies and the hypotheses, the present study did not find any effects for the ankle and knee external rotation moment as a result of the change in rotational traction (Wannop et al., 2010; Stefanyshyn et al., 2010). Possible explanations for this are that the technique used for the ST in this study was different compared to that used by Stefanyshyn et al. (2010), the data collection methods were more sensitive for changes in internal / external rotation of the knee and ankle joints, or the different mechanical measurement techniques to quantify for the surface properties used in previous studies may have been more representative of the rotational traction properties the players experience during a turning manoeuvre.

The effects of the surface hardness were limited in this study and in contrast to the hypotheses no effects were found for the flexion angles or for the knee extension moment. It has been suggested that the hardness may have a larger effect on the human movement dynamics during the braking steps prior to the turn than during the actual turn itself. Furthermore, it may be that the experienced hardness during the ST may be different to that measured with the AAA, as §7.4.1.3.1 discussed that the magnitude and average loading rate of the impact force of the AAA appears to be an overestimation of the vertical GRF exhibited by the players during the ST. Therefore, since previous research showed that the surface response of visco-elastic surfaces is not linear, it may be that the surface response under the loading conditions of the ST was different to that quantified with the AAA (McMahon & Greene, 1979).

The effects of the surface properties on the JH manoeuvre were limited an increased peak vertical impact force and peak loading rate of this force on the hard surfaces, and to an increased ankle eversion moment on the low traction surfaces. This was in contrast with the hypotheses, which expected effects for the sagittal plane joint angles and moments. That the other parameters were not affected may have been caused by the high demands of the manoeuvre, as suggested in a previous study by Arampatzis et al. (2004). It may also have been caused by limitations in the surface measurement test methods as it was shown in §7.4.1.3.1 that the measured difference in peak force and average loading rate between the hard and soft surfaces measured with the AAA was much larger than those found in this study. Therefore the AAA may give some indication of the difference in hardness, but may not represent the difference in as hardness experienced by the players.

With regards to the player perception it appeared players were not able to identify the different surface conditions. At the same time they had a clear preference for the high traction surfaces, whereas the HAlo was the most disliked surface. The high traction surfaces were related to decreased ground contact times and increased average vertical GRF, average posterior GRF, and frontal plane moments in the lower limbs, but the question remains if this is what the players based their choice on, or other factors.

7.4.3.2 In-game Scenario Effects

In addition to the different surface conditions the results of the player movement study showed that the inclusion of an in-game scenario can significantly affect the human movement dynamics during a ST and JH. The inclusion of a simulated opponent during the ST did not lead to changes in GRF or joint angles, as found in previous research (McLean et al., 2004). However, it did lead to increases in knee valgus, hip abduction and hip internal rotation moments, as well as a lower COM, which suggest a more flexed posture. That not all hypotheses were confirmed may have been caused by the different nature of the ST compared to the sidestep cut used by McLean et al. (2004). Furthermore, due to the large force platform used in this study and the fact that the players did not have to get past the opponent the necessity of an increased deceleration may not have been as profound as in the study by McLean et al. (2004).

When heading a ball during a maximal vertical stop jump it appears players use a different landing strategy compared to a normal vertical stop jump by landing in a more upright position to absorb the impact of the landing. For absorbing the energy from the landing after heading a ball the players relied more on their ankle by increasing the ankle plantar flexion during PRE to allow for a larger angular change in plantar / dorsi flexion angle from the PRE to KNF phase. At the same time angular changes in knee and hip flexion were decreased. Regarding the joint moments the ankle plantar flexion moment was increased after heading a ball, whereas the knee extension moment decreased. The change in landing strategy is similar to that found in previous studies on the effects of gender and fatigue on jump landings in which women and fatigued subjects landed in a more upright position (Decker et al., 2003; Chappell et al., 2005). The change in landing strategy also led to increased frontal plane moments of the lower limbs. This may be related to the extra forward momentum generated by the players to head the ball. However, it has to be noted that this also may have been caused by the players being instructed to stand still after the landing. Furthermore, the heading condition led to higher average GRF in all directions during KNF as well as a higher COM, and decreased peak posterior and lateral GRF, and average and peak loading rates of the peak vertical impact force.

7.5 References

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8. CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

8.1 Introduction

This chapter presents the main conclusions of this thesis which investigated the effects of surface properties and in-game scenarios on the stop and turn (ST) and jumping / heading (JH) manoeuvre. The aim of these conclusions is to answer the following research questions that were set in Chapter 1:

A: How do varying surface properties of artificial turf in soccer affect the movement dynamics of players during soccer relevant movements?

B: How do in-game scenarios affect the movement dynamics of players during soccer relevant movements?

In addition to this the main limitations of the study are presented; these involve the data collection, both regarding the surface properties as well as biomechanical data collection, and the in-game scenarios used. This is followed by recommendations for future studies are presented based on the findings and limitations of this thesis regarding the surfaces, in-game scenarios, and the biomechanical data collection. The final section includes implications for future research and industry that can be drawn from the findings presented in this thesis.

8.2 Main Conclusions

8.2.1 Contribution to Knowledge

This PhD contributed to the current knowledge in several ways regarding the surfaces, movements and in-game scenarios used. First of all this research combined the rotational traction and hardness properties of artificial turf surfaces, whereas previous research focussed on only one of the surface properties. This provided insight into how different the rotational traction and surface hardness properties affect the movement dynamics how they influence each other. Furthermore, this research provided detailed information on both surface design and behaviour as quantified with the FIFA standard mechanical measurement methods, whereas previous research often lacks this information. This is important as this information is crucial to gain insight into how the surface design and properties affect the human dynamics during various movements.

Regarding the movements used in this research, few previous studies have used a stop and turn, and to the author's knowledge no previous studies have used a ST or JH manoeuvre in combination with surfaces that were designed around the limits of the FIFA standards. This provided insight into how the surface design and standards set by FIFA affect the movement dynamics of a ST and JH movement.

Finally, this PhD also contributed to the current knowledge by including in-game scenarios. These scenarios provided insight into how the movement dynamics of soccer players are affected during actual match situations. The simulated opponent used for the ST increased the reality of the in-game scenario as used by McLean et al. (2004) as a real person was used instead of a skeleton. The comparison between a maximal stop-jump and a maximal stop-jump including a heading manoeuvre for the JH has, to the author's knowledge, not been done in previous research.

8.2.2 Surface Properties

The results of the player movement study showed that different surface conditions mainly affected the movement dynamics during the ST. As hypothesised an increase in rotational traction led to increased ankle eversion, knee valgus and hip abduction moments during the mid-stance phase, as well as an increase in average vertical and posterior ground reaction forces. In addition to this the same moments and forces were increased on the soft surfaces, of which the increase in average ground reaction force was in contrast with the hypotheses. This in combination with the decreased ground contact times suggested that the players are able to perform the ST faster on surfaces that are soft and have a high rotational traction.

In addition to this the study showed that for some parameters the effects of the surface hardness can be influenced by the rotational traction properties, and vice versa. This was mainly apparent for the knee valgus (weight acceptance), hip extension (peak push off), and hip internal rotation (weight acceptance) moment. For these parameters a significant effect was present between two of the four surfaces, whereas at the same time the other surfaces showed either no effect or the opposite effect.

In contrast to the hypotheses and previous studies, the player movement study showed no effects for the rotational traction on the external rotation moments of the knee and ankle joint during the ST (Wannop et al. 2010; Stefanyshyn et al. 2010). A comparison between the techniques used in the previous studies and the player movement study suggested that this was caused by the fact that the players in the player movement study hardly rotated their foot while in contact with the surface. However, it may also have been that the mechanical measurement method used in the previous studies gives a better representation of the rotational traction experienced by the players during a turning manoeuvre as discussed in §7.4.1.3.2.

For the jumping / heading manoeuvre the only hypotheses that were confirmed were the increase in peak vertical ground reaction force and the peak loading rate of this force on the hard surfaces. In addition to these the ankle eversion moment was increased on the low traction surface. That not all hypotheses were confirmed may have been related to the high demands of the manoeuvres as suggested in previous research (Arampatzis et al. 2004). This may however also have been caused by limitations of the mechanical test methods as discussed in §7.4.1.3.1.

8.2.3 In-game Scenarios

The player movement study showed that in-game scenarios can significantly affect biomechanical parameters during a stop and turn and jumping / heading manoeuvre. The simulated opponent during the stop and turn mainly had an effect on the frontal plane joint moments, whereas the joint angles and ground reaction forces were not affected. The simulated opponent increased the knee valgus, hip abduction, and hip internal rotation moments and led to a lower centre of mass, which was in line with the hypotheses. However, as no effects were present for the ground reaction forces and joint angles, which were present in a previous study on cutting manoeuvres, the increased joint moments could not be related to any changes in movement strategy (McLean et al. 2004).

The in-game scenario for the jumping / heading manoeuvre showed that when heading a ball the players adjusted their movement strategy by landing in a more upright position. The movement strategy was primarily changed by increasing the plantar flexion angle of the ankle just before landing. This allowed a larger change in the ankle plantar / dorsi flexion angle to absorb the impact of the landing. At the same time, heading a ball led to an increased ankle plantar flexion moment, whereas the knee extension moment was decreased. The change in movement strategy also decreased the average and peak loading rate of the peak vertical ground reaction force whereas the average vertical ground reaction forces was increased during the knee flexion phase. While not hypothesised, the heading manoeuvre also affected the frontal plane joint angles and increased the ankle eversion, knee valgus and hip abduction moment.

8.3 Study Limitations

In the present study several limitations were identified regarding the data collection methods and test set-up. As discussed in §7.4.1.3 the mechanical surface measurement methods may have had an influence on the outcomes of the study as questions arose on how representative the mechanical measurements were for the human ST and JH movements. The mechanical surface measurement methods were chosen as they are the standard equipment used by sports governing bodies. However, there were substantial differences between the impact conditions of the ST and JH and that of the Advanced Artificial Athlete (Figure 7.1). Therefore it may be that the actual surface hardness experienced by the players on each surface was different to that mechanically measured considering previous research showed that the surface response depends on the load applied (McMahon & Greene 1979).

Also between the rotational traction device and the ST movement differences were present. The foot rotation angle (11.6° ± 5.8°) was substantially smaller than the minimum 45° required by FIFA (FIFA 2012). Furthermore, the rotation curve showed that the rotation of the foot during the ST was not linear and for some trials the foot did not continuously rotate in the direction of the turn (Figure 7.37). As previous research showed that development of the rotational traction is not linear and peak rotational traction can be reached at different parts of the rotations the players may not have reached the peak rotational traction measured with the standard test device (Villwock et al. 2009; Livesay et al. 2006). Furthermore, a study by Livesay et al. (2006) showed that the magnitude of the rotational traction is dependent of the normal load applied, which for during the ST was approximately twice as high as that of the rotational traction device. Therefore, as with the surface hardness, it may be that the actual rotational traction experienced by the players was different than that mechanically measured. However, for both the surface hardness and rotational traction more research is needed to make a definite conclusion on this.

With regards to the hardness effects during the ST it was also mentioned in §7.4.1.1 that the hardness may have a larger effect during the braking steps prior to the turn than during the turn itself as it is expected that the main deceleration takes place during these few steps. Due to limitations in the lab set-up only one force platform could be used, and therefore the choice was made to only collect ground reaction force data during the turn. More research is needed to investigate the effects the surface hardness has during the deceleration immediately prior to turning.

Another limitation of the present study was that only the surface hardness and rotational traction properties of the surfaces were quantified. As the results showed that surface hardness and rotational traction can influence each other regarding the effects they have on the human movement dynamics, it may be that other properties such as the surface damping or linear translational traction also have an effect on this. However, more research is required as they were not quantified in the current study.

A final limitation regarding the surface properties was that during player movement study the players were given a few familiarisation trials to get used to the manoeuvre at the start of the session, but they were not given any familiarisation trials to get used to a new surface condition. As a result it may have been that the movement dynamics changed when the players got more used to the surface conditions after a few trials and may have influenced the outcomes of the player movement study.

That the players were not given any familiarisation trials on a new surface condition also meant that the players effectively had no more than 15 trials per surface condition to base their perception on the surface properties on. This number of trials may have been too limited and may therefore have affected the ratings of the players and therefore the outcomes of the player perception part of the player movement study.

Regarding the biomechanical data collection the used marker set may also have influenced the outcomes of the player movement study. In contrast to the hypotheses and previous studies, the rotational traction had no effect on the external ankle and knee rotation moment (Wannop et al. 2010; Stefanyshyn et al. 2010). As mentioned in §7.4.1.1, this may have been caused by the marker sets that was used in these previous studies, as previous research showed that the marker set used can affect the results in the sagittal and transverse plane (Schulz & Kimmel 2010). Therefore, the marker sets used in previous research may have allowed them to track the internal / external rotation of the lower limb joints more accurately.

For the ST the use of the ground contact time as a measure of performance can be identified as a limitation. While studies on running and accelerating have used the ground contact time as a measure of performance the different nature of the ST, during which the players had to come to a complete stop, limits the relevance of the ground contact time (Kerdok et al. 2002; Murphy et al. 2003). Also considering that the reported ground contact times were more than two times as long as those reported in previous studies on running and accelerating. Considering this other parameters like the deceleration/acceleration speed may be better indicators of a change in performance as an increase in these parameters means a player can perform the ST faster. Therefore measuring the performance directly with the help of other parameters may have provided a better insight into changes in performance during the ST.

Looking back at the in-game scenarios used in this study, the primary limitation was that the simulated opponent and ball were static. While both in-game scenarios proved to have significant effects on the movement and joint moments it is expected that the effects will be larger during even more realistic in-game scenarios where there is a real need for the players to turn and run away from the opponent, or have to anticipate on the movement of the ball when jumping and heading.

In addition to this it was discussed in §7.4.2 that the test set-up may also have influenced the effects of the in-game scenarios. For the ST it was thought that the effects of the simulated opponent may have been larger if the ST was performed at closer proximity to the opponent, whereas for the JH the instructions for the players to stand still after the landing may have affected the execution of their movement. Regarding the JH it was thought that normally players may have set another step forward to deal with an increase in forward momentum, whereas in the present study they were required to stand still. As previous research showed that the instructions given can affect the movement dynamics it may be that the effects of the heading manoeuvre may have been different if the players were allowed to deal with the landing as they normally would do (Dempsey et al. 2007; Cortes et al. 2007; Pollard et al. 2010).

8.4 Future Research

8.4.1 Surface Properties

With regards to the surfaces several recommendations can be made for future studies based on the findings and limitations in the present study, as well as the limitations identified in previous studies (Chapter 2). Based on the findings in the present study it is recommended that future studies use a combination of surface properties, such as the hardness and rotational traction properties used in this study. In §7.4.1.1 it has been discussed that the level of surface hardness can influence the effect a change in rotational traction has on joint moments and vice versa. Therefore, using combinations of surface properties in future studies can increase the insight into how different surface properties affect each other with regards to human dynamics. Properties that could be combined are the surface hardness and traction (rotational and linear translational) when looking at the sports governing body standards, but other properties such as the damping could also be included as these may also affect the effects other surface properties have on human movement dynamics.

The second recommendation for future studies involves including detailed information on the surface design and surface properties. The literature review showed that many previous studies fail to provide sufficient information on the surface design and / or properties, making it difficult to relate any findings in the study to any of these parameters. This is also highlighted in §7.4.1.3.2, regarding the observation that the highest rotational traction value found in the study by Stefanyshyn et al. (2010) was more than 10 Nm lower than any of the rubber and sand filled samples in Chapter 6. It appeared that this difference was caused by the different measurement technique, but as Stefanyshyn et al. (2010) failed to provide more detailed information on the design (e.g. type and grade of rubber, and infill quantities) it was not possible to compare the values to the surfaces in Chapter 6. Therefore, it is recommended for future studies that detailed information on the surface design, such as the type of carpet, pile height, infill quantities and rubber type and grade, and properties is included to increase the insight into how the surface design and properties affect each other as well as biomechanical parameters.

Regarding quantifying the surface properties, the main limitation in the present study was the question of how relevant the AAA and rotational traction measurements were for the players performing the ST and JH movements. Therefore it is recommended for future studies that the surface properties are not only quantified using the recognised standards by sports governing bodies, but also using conditions closer to those expected within the study. For the surface hardness this means using similar impact conditions, such as the peak force, to the movements that are used in the study.

A possible solution for quantifying the surface hardness closer to the conditions expected within the study may be by determining the surface stiffness as identified in §2.2.4.1. With this method a force – deflection curve is generated which shows the surface response during an increasing load. This has the advantage that the surface stiffness can be determined at different force levels on the force – deflection curve and the curve can be generated for different loading rates. It may also be possible to create different impact conditions with a device such as the AAA. This could either be done by adjusting the drop height of the weight, or change the mass of the drop weight. Leading on from this, the AAA may be used in combination with a force platform to compare the measured impact with the AAA on top of a surface with that of the force platform underneath the surface. This should provide insight into how the two relate and could provide feedback on if the impact with the AAA is close to that of a movement like the ST or JH, which generally is measured with a force platform underneath the surface.

With regards to the rotational traction, it seems that a more complex device than the standard one as used by FIFA will be needed for quantifying the surface properties under conditions to those of the players. For this custom devices such as the ones presented in §2.2.4.2 may provide a solution as for these the rotation angle can be controlled and / or the rotational traction can be measured throughout the rotation. As mentioned in §7.4.1.3 it may also be useful to include changes in rotation speed and ground contact, as the rotation speed of the foot and the proportion of the foot in contact with the surface varied throughout the stance phase of the ST. Furthermore, a normal load close to the vertical GRF generated by the players may be used as previous research showed this can influence the magnitude of the rotational traction (Livesay et al. 2006). The combination of these factors should provide increased insight into the rotational traction players experience throughout a movement such as the ST.

8.4.2 In-game Scenarios

During the player movement study significant effects were found for both in-game scenarios used during the ST and JH. Therefore, it is recommended that future studies incorporate in-game scenarios in order to gain more insight into the effects of interventions that simulate actual match situations. Limitations for the in-game scenarios mainly involved the realism of the used scenarios. Therefore, it recommended that future studies try to include more realistic in-game scenarios to gain more insight into how the body of the players are loaded during actual match situations.

Options for increasing the realism of the in-game scenarios are by using dynamic opponents or balls. As discussed in Chapter 3, for the creation of more complex in-game scenario, other factors such as lab space and data collection methods, have to be suitable. For example, when using a dynamic opponent to chase a player the lab space has to be sufficient, and ideally the movement would not be restricted by the data collection such as a force platform as during such a scenario it may be more difficult to land on a force platform. This is also relevant when using a dynamic ball. While ball canon or kicking robot could be used to standardize the ball speed and ball location, anticipation of the players on the ball may lead to differences in where the accompanying manoeuvre, such as heading the ball, is performed. In addition to these factors, the variability of the movement and / or scenario has to be considered. If the variability increases more subjects and / or trials will be needed in order to compare the effects of interventions, such as surface properties or the in-game scenarios themselves.

Other methods to create in-game scenarios may also be explored in the future. This could include using virtual reality rather than an actual opponent, which would have the advantage that a response of the opponent can be regulated better. Currently the virtual reality used in studies often involves subjects interacting with a screen using a game console or custom software (Miles et al. 2012; Gordon et al. 2012). However, some studies also use head mounted displays giving subjects a more realistic feel, but have the disadvantage that they are cumbersome to wear and therefore may influence the movement of the subjects (Miles et al. 2012). With technological advances however this may be solved and subjects may be able to move around freely in a virtual world, giving limitless options regarding the creation of repeatable in-game scenario. Regarding this, it may be that the use of virtual reality influences the player response to in-game scenarios as there is no consequence for not performing a movement, such as a cutting manoeuvre, in time.

8.4.3 Biomechanical Data Collection

Regarding the biomechanical data collection several recommendations can be made based on the findings and limitations of the present study. In §7.4.1.1 it was discussed that differences between the current study and a study by Stefanyshyn et al. (2010) that used a 180° turn may have been caused by differences in technique. More specifically, from the movement description by Stefanyshyn et al. (2010) ("The turning movement was performed by running straight ahead, planting on the right foot, rotating 180° and returning running in the opposite direction"), it appears that the subjects in that study were instructed to first plant their foot and before rotating 180°. While in the study by Stefanyshyn et al. (2010) it is not entirely clear for what part of the 180° turn the foot was in contact with the surface, in another study on a 180° turning movement by Gehring et al. (2007) the subjects were clearly instructed to plant their foot in the running direction and then rotate it in the opposite direction ("the foot was placed in the running direction before the subject rotated the foot as much as possible and turned towards the reverse direction") (Gehring et al. 2007). This was quite different to the technique the subjects used in this study as in the vast majority of turns the rotation of the foot mainly took place in the air. While the study by Gehring et al. (2007) also instructed the subjects to perform the movement as natural as possible it may well be that the instructions for the foot placement caused the opposite effect. Therefore, it is recommended that all future studies do not put too many restrictions on how a movement is performed, while still controlling the movements, as has been done in the present study. This way, the effects of interventions, such as different surface properties, can be related to how a movement is naturally performed by athletes. On a side note, this may lead to a greater variation in how a movement is performed and is only possible when subjects are accustomed to the movements they have to perform.

Regarding the biomechanical data collection on different surface properties the fact that the players in the player movement study did not get any familiarisation trials to get used to a new surface condition. This may have influenced the results of the player movement study as a result of players adjusting to the new surfaces throughout the trials. Therefore it is recommended that future studies using multiple surface conditions allow the subjects a number of familiarisation trials to get used to the new surface conditions. How many trials the subjects need to get used to a new surface condition can be determined with a pilot study.

The lack of familiarisation was also identified as a limitation regarding the player perception part of the player movement study. Due to this the players may not have had enough trials on each surface condition to get a good idea on what the surface properties were like. Therefore it is recommended that future studies on player perception that include surfaces with different properties allow the subjects sufficient time to get familiar with the surface conditions. A possible solution for this in a study with a set number of trials is to, if required, allow the subjects to spend additional time on a surface to get a better perception of the surface properties.

The marker set used was also identified as a limitation regarding the data collection. This was relevant as it was believed that marker sets used in previous studies may have been more sensitive to changes in internal / external rotation angles of the lower limbs (McLean et al. 2004; Dempsey et al. 2007; Wannop et al. 2010; Stefanyshyn et al. 2010). Furthermore, during the ST the observation was made that the foot twisted while in full contact with the ground. This could not be detected with the current marker set as the entire foot was represented as a single segment. Therefore, it is recommended that future studies on changes in direction such as a ST make use of marker sets that prove more sensitive to changes in the joint angles in the lower limbs, especially regarding the sagittal and transverse plane, as well as using more than one segment for the foot.

Using the ground contact time as a measure of performance during the ST was identified as a limitation compared to running the relevance of the ground contact time with regards to changes in performance may be limited. Therefore it is recommended that future studies measure the performance directly to gain a better insight into changes in performance as a result of an intervention, like different surface conditions. One way of measuring the performance directly is by determining the movement speed with the help of one of the markers on the body of the subject. This has been done in a study by Dempsey et al. (2007) on cutting manoeuvres in which they determined average linear velocity of the marker on the left superior iliac spine across the final approach stride. This method therefore provides the opportunity to determine the movement speed during different parts of the movement and could therefore provide information on the deceleration and acceleration of the subject just before and after the turn, which are indicators of performance as an increased deceleration and acceleration mean that subjects can perform the ST faster. Information on the acceleration and after the ST can also be obtained from the stride length and frequency. These have been used in previous studies on running and accelerating and an increase in stride length and/or frequency are generally associated with an increase in performance (Keller et al. 1996; Murphy et al. 2003; Hunter et al. 2004; Meijer et al. 2007).

The final limitation regarding to the biomechanical data collection was related to the force platforms used. During the ST the lab set-up did not allow ground reaction force data to be collected during the braking steps prior to the turn, while it is thought that the surface hardness may have had a larger effect during these steps than during the turn itself. Therefore it is recommended that future studies also collect data during the braking steps prior to the turn. Regarding this, some factors regarding the data collection have to be taken into consideration. For example, due to the cameras of the 3D video analysis system being aimed at the force platform in the present study, the kinematic data only covered the final step prior to the turn. This means that the cameras would have to be aimed to cover a larger area of the runway. Furthermore, in the present study the final 2.1 m of the approach had the same properties as the area covering the force platform to allow the players to adjust to the surface properties when reaching the force platform. Therefore, to allow the players to adjust to the properties before the braking steps would require that a larger part of the runway has similar properties.

The force platforms may also have had an effect on the execution of the manoeuvres and in-game scenarios. For the simulated opponent it was believed that the effects may have been larger if the ST was performed at a closer proximity, which would have been possible when using a smaller force platform. At the same time, a smaller force platform may have restricted how the movement was performed by the players. Therefore, it is recommended for future studies that the size of the force platform is carefully considered when creating the desired in-game scenario, while also allowing for a natural execution of the movement.

8.5 Implications

Based on the findings presented in this thesis, several implications can be formulated for future research and industry. These implications are presented in the following subsections and involve different aspects on incorporating surfaces with varying properties, as well as characterising the surface behaviour, and characterising and controlling this surface behaviour during player testing. Furthermore implications are formulated regarding the selection of player movements, measuring and controlling these movements, and incorporating in-game scenarios.

8.5.1 Incorporating Surfaces with Varying Properties

Previous biomechanical studies that investigated the effects of the surface behaviour of an artificial turf pitch has on the movement dynamics typically focussed on one surface property, either the hardness or traction properties (Meijer et al. 2007; Stefanyshyn et al. 2010). However, the player movement study showed that the effects a property (e.g. hardness) has on the movement dynamics can be affected by another property (e.g. rotational traction). Based on this, studies that incorporate surfaces with varying properties need to consider multiple properties when designing surfaces. This is necessary to ensure that when one property is modified the other properties are equal on the modified surfaces. Following this, studies need to take into account that when a single property (e.g. hardness) is modified, while controlling other properties, the effects related to this modification may not apply when the conditions of another property (e.g. traction) change. Furthermore, it is important that studies include detailed information on the surface design and behaviour to increase the current knowledge how the surface design and behaviour affect the movement dynamics during relevant manoeuvres. Especially since previous studies often have failed to provide this information.

8.5.2 Characterising Surface Behaviour

When characterising the surface behaviour two aspects are important to consider, namely: how does the surface respond during specific manoeuvres and how does the surface relate to standards set by sports governing organisations such as FIFA. During the stop and turn and jumping / heading the loading conditions to which the surfaces were exposed to were different to the loading conditions of the standard tests. Regarding this the surface response to an impact of an artificial turf system is not linear due to its visco-elastic properties. Furthermore, previous study showed that the rotational traction development of the shoe surface interface of an artificial turf system is non-linear (Livesay et al. 2006; Villwock et al. 2009). Based on this it is advisable that when characterising the surface behaviour the loading conditions of the specific manoeuvres are replicated as much as possible. This is necessary to gain understanding on what the exact differences between surfaces are during specific manoeuvres. Similar loading conditions for quantifying the hardness of the surface involve the peak forces and loading rates to which the surface is exposed, whereas for the rotational traction this involves the rotation angles and speed of the test foot.

Regarding the industry it is advisable that the sports governing bodies reconsider the standard test methods used and use a range of loading conditions to characterise the surface behaviour. This is necessary to increase the relevancy of their standards and test methods to the loading conditions experienced by athletes.

8.5.3 Characterising and Controlling Surface Behaviour During Player Testing

Previous biomechanical studies using artificial turf surfaces have failed to characterise and control the surfaces used during player testing. Doing this is important as surfaces get disturbed during the player movement and therefore the behaviour of the surface can change over time, as shown in Chapter 6. For both controlling and characterising the surfaces the infill depth can be used as an indicator of any changes in surface properties. This is an easy and quick method and also allows for checking if the state of the surface has been restored after any maintenance which is essential for maintaining similar surface conditions as the infill gets disturbed and some gets lost as a result of the executed manoeuvres. The amount of maintenance is dependent of the state of the infill. For a loose infill state, such as used in Chapter 7, light brushing after every subject proved sufficient. For a more compacted infill state more maintenance may be necessary. In addition to measuring the infill depth and performing maintenance it is advisable that the surface behaviour is measured regularly to ensure an equal behaviour over the entire test period. How frequently this has to be done is dependent on the amount of trials that are being performed and how much the player movement disturbs the surface.

8.5.4 Selecting Player Movements

Previous biomechanical studies on the effects surface behaviour has on the movement dynamics have mainly focussed on running and hopping when investigating the effects of surface hardness, and cutting / turning manoeuvres when investigating the effects of surface traction. The results of the player movement study in combination with the findings in previous research suggest that the effects of the surface behaviour on the movement dynamics can be dependent of the demands of the movements (Arampatzis et al. 2004). Therefore future studies need to consider different movements to those typically used to gain a better understanding into how the surface behaviour affects the movement dynamics of various relevant manoeuvres with different demands. This is especially relevant in relation to the current standards used by sports governing bodies as still little is known on how surface properties as quantified by these standards affect the movement dynamics of a range of relevant manoeuvres.

8.5.5 Player Movement Measurement

In the evaluation of pressure insoles (Chapter 5) it was concluded that the Tekscan F-scan pressure insoles lacked repeatability and reliability when using them to measure the ground reaction forces. Furthermore, they proved to be not robust enough to use during a prolonged running trial. Based on these findings it is advisable that future studies do not use the Tekscan F-scan pressure insoles to quantify the ground reaction forces or use them during prolonged running trials. During other movements, such as walking, the robustness of the pressure insoles may not be an issue.

8.5.6 Controlling Player Movements

Controlling certain aspects of a movement in a biomechanical study, such as the jumping height and approach speed, is important to ensure the trials are repeatable. However, the results of the stop and turn in the player movement study suggested that the players used a different technique to perform the stop and turn compared to previous studies (Gehring et al. 2007; Stefanyshyn et al. 2010). This difference was related to the instructions given to the subjects as the studies by Gehring et al. (2007) and Stefanyshyn et al. (2010) instructed their subjects to plant the foot in the running direction and then perform the 180° turn, whereas the players in the player movement study were free to plant their foot how they wished. Based on the finding that all players in this study primarily rotated their foot while not in contact with the surface future studies need to carefully consider the instructions they give to subjects in order to allow them to perform the movements in an as natural manner as possible.

8.5.7 Incorporating In-game Scenarios

Few previous biomechanical studies have tried to incorporate in-game scenarios. The findings of the player movement study showed that the in-game scenarios used had significant effects on various biomechanical parameters. This is in line with previous studies that also found that an in-game scenario can have significant effects on the movement dynamics (Besier et al. 2001; McLean et al. 2004). Therefore they appear to be a valuable addition to gain insight into how the body is loaded during actual match situations and how players adjust their movement strategy to cope with these in-game scenarios.

The findings of the player movement study did not show the same mechanisms of dealing with a simulated opponent during the stop and turn as found by McLean et al. (2004) during a cutting manoeuvre. As it was thought that this may have been related to the lab set-up or realism of the in-game scenario, these aspects need to be carefully considered in future studies.

8.6 References

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APPENDIX A: Focus Group

This appendix includes an overview of the set-up and questions used for the focus group used in Chapter 4 to gain information on the player perception on different movements, in-game scenarios and surface characteristics.

Main research questions Focus group:

Movements and in-game scenarios

What movements and in-game scenarios in soccer are considered most relevant and demanding by soccer players?

Surface perception:

What surface properties and characteristics are preferred by soccer players?

Sub questions movements and in-game scenarios:

Movements:

What do you consider to be relevant movements in soccer? (5 min brainstorm)

Examples of movement:

Running (in-line?), cutting manoeuvres (sidestep, crossover), jumps, use of ball, dribbling, heading, drills?

If movements are not mentioned that are present in literature:

Point movements out after brainstorm and ask why they did not mention them.

Are any movements more important during a match than others? If so, what movements? (5 min)

Follow up: Create a top 5, first individually then on group level, and discuss top 5 (5 min)

In-game scenarios:

What do you consider to be an 'in-game' scenario and why? (5 min)

***Examples of in-game scenarios**:*

Chasing/being chased, getting past an opponent, change direction?

If in-game scenarios are not mentioned that are present in literature:

Point in-game scenarios out after brainstorm and ask why they did not mention them.

Are any in-game scenarios more important than others during a match? If so, what scenarios? (5 min)

Follow up: Create top 5, first individually then on group level, and discuss top 5 (5 min)

Overall:

Are there movements and / or in-game scenarios that are physically more demanding than others? Which? (5 min)

Do you train on the most important movements/scenarios? (5 min)
Follow up: Any specific drills?

Sub questions surface perception:

What properties and characteristics do you think is most important for a good soccer pitch? (10 min)

Examples of properties / characteristics:
Stiffness (hard/soft), traction (high/low), damping (high/low), Fast / slow, injury risk, ball bounce, ball roll

Why do you think these properties and characteristics are most important? (5 min)
Follow up: Do these properties help with executing movements? If so which movements?

If a certain property or characteristic of the pitch leads to significantly more injuries to what extent are you willing to accept that in exchange for that preferred property / characteristic? (5 min)
Follow up: Is there a difference between injuries?

APPENDIX B: Player Questionnaire (Chapter 4)

This appendix includes an overview of the questionnaire used in Chapter 4 to gain information on the player perception on different movements, in-game scenarios and surface characteristics.

Association Football Questionnaire

Despite the increased use of artificial turf in football there are still some coaches and players that are not too happy with this development due to various reasons. The goal of this questionnaire is to get an insight into your opinions on important movements, one-on-one situations, surface characteristics, and artificial turf.

General questions

Age: …………

Select your playing position:

Goal keeper	Defender	Defending Midfielder	Attacking Midfielder	Forward

At what level do you play?: …………

For how many years have you been playing football?: …………

For how many years have you been playing football on artificial turf:…………

Without infill :………….. Only sand infill :…………..

Only rubber infill:………….. Rubber and sand infill :…………..

How many hours per week do you train on

Natural grass :…………..

Artificial turf :…………..

In 1 season, how many competitive matches do you play on

Natural grass :…………..

Artificial turf :…………..

How many hours per week do you play recreationally on

Natural grass :…………..

Artificial turf :…………..

All information given will be kept confidential and only used for this research project (In accordance with Data Protection Act (1998).

Would you like to receive information on the research? Yes No

Are you willing to participate in future studies? Yes No

Name:………………………………………...

Email:……………………………………………………………………….

Movements

Please rate the following movements to how important they are to you in order to perform successfully during a match?

	Not important						Very important
Walking	1	2	3	4	5	6	7
Jogging	1	2	3	4	5	6	7
Running	1	2	3	4	5	6	7
Sprinting	1	2	3	4	5	6	7
Stopping	1	2	3	4	5	6	7
Shuffle/sidestep	1	2	3	4	5	6	7
Jumping & landing	1	2	3	4	5	6	7
Heading	1	2	3	4	5	6	7
Dribbling	1	2	3	4	5	6	7
Planting non-kicking foot	1	2	3	4	5	6	7
Diving	1	2	3	4	5	6	7
Tackle	1	2	3	4	5	6	7
General change of direction	1	2	3	4	5	6	7
Stop and turn	1	2	3	4	5	6	7
Arc run	1	2	3	4	5	6	7
Sidestep cut	1	2	3	4	5	6	7
Cross-over cut	1	2	3	4	5	6	7

Are there any movements missing from this list? If yes, which?

How frequently do you perform the following movements during a match?

	Rarely						Very often
Walking	1	2	3	4	5	6	7
Jogging	1	2	3	4	5	6	7
Running	1	2	3	4	5	6	7
Sprinting	1	2	3	4	5	6	7
Stopping	1	2	3	4	5	6	7
Shuffle/sidestep	1	2	3	4	5	6	7
Jumping & landing	1	2	3	4	5	6	7
Heading	1	2	3	4	5	6	7
Dribbling	1	2	3	4	5	6	7
Planting non-kicking foot	1	2	3	4	5	6	7
Diving	1	2	3	4	5	6	7

Tackle	1	2	3	4	5	6	7
General change of direction	1	2	3	4	5	6	7
Stop and turn	1	2	3	4	5	6	7
Arc run	1	2	3	4	5	6	7
Sidestep cut	1	2	3	4	5	6	7
Cross-over cut	1	2	3	4	5	6	7

Loading on the body can be defined as the amount of stress and strain that is put on the body (joints, muscles etc.) during a certain movement.

How much loading do the following movements put on your body during a single movement in a match?

	No loading					Very high loading	
Walking	1	2	3	4	5	6	7
Jogging	1	2	3	4	5	6	7
Running	1	2	3	4	5	6	7
Sprinting	1	2	3	4	5	6	7
Stopping	1	2	3	4	5	6	7
Shuffle/sidestep	1	2	3	4	5	6	7
Jumping & landing	1	2	3	4	5	6	7
Heading	1	2	3	4	5	6	7
Dribbling	1	2	3	4	5	6	7
Planting non-kicking foot	1	2	3	4	5	6	7
Diving	1	2	3	4	5	6	7
Tackle	1	2	3	4	5	6	7
General change of direction	1	2	3	4	5	6	7
Stop and turn	1	2	3	4	5	6	7
Arc run	1	2	3	4	5	6	7
Sidestep cut	1	2	3	4	5	6	7
Cross-over cut	1	2	3	4	5	6	7

One-on-one situations

How frequently do you encounter the following one-on-one situations during a match?

	Rarely					Very often	
Mark opponent	1	2	3	4	5	6	7
Chasing opponent	1	2	3	4	5	6	7
Getting away from opponent	1	2	3	4	5	6	7
Get past opponent	1	2	3	4	5	6	7
Avoiding tackle	1	2	3	4	5	6	7
Heading duel	1	2	3	4	5	6	7

Are there any one-on-one situations missing from this list? If yes, which?

How much loading do the following one-on-one situations put on your body during a single situation in a match?

	No loading						Very high loading
Mark opponent	1	2	3	4	5	6	7
Chasing opponent	1	2	3	4	5	6	7
Getting away from opponent	1	2	3	4	5	6	7
Get past opponent	1	2	3	4	5	6	7
Avoiding tackle	1	2	3	4	5	6	7
Heading duel	1	2	3	4	5	6	7

Surface preferences

For you ideal pitch how important is it that has the following characteristics?

	Not important						Very important
Flat/even	1	2	3	4	5	6	7
Smooth ball roll	1	2	3	4	5	6	7
Predictable ball bounce	1	2	3	4	5	6	7
Stud penetration	1	2	3	4	5	6	7
Uniformity	1	2	3	4	5	6	7

Which of these characteristics do you prefer?

Low ball bounce — **High ball bounce**

1 2 3 4 5 6 7

Short grass/fibres — **Long grass/fibres**

1 2 3 4 5 6 7

Does not give in — **Gives in a lot**

1 2 3 4 5 6 7

Very soft — **Very hard**

1 2 3 4 5 6 7

Very low Shoe-surface traction — **Very high Shoe-surface traction**

1 2 3 4 5 6 7

Very low shock absorption — **Very high shock absorption**

1 2 3 4 5 6 7

What kind of boots do you prefer? Boots with

Short circular moulded studs	Short circular metal studs	Short moulded blades
Short metal blades	Long circular moulded studs	Long circular metal studs
Long moulded blades	Long metal blades	Artificial turf studs

Opinion artificial turf

The university has a couple of artificial pitches: the PEC pitch, at the university main entrance, and the EHB pitch, next to the cricket ground and field hockey pitch.

How do you rate **PEC** pitch on the following characteristics?

	Very bad						Very good
Flat/even	1	2	3	4	5	6	7
Smooth ball roll	1	2	3	4	5	6	7
Predictable ball bounce	1	2	3	4	5	6	7
Stud penetration	1	2	3	4	5	6	7
Uniformity	1	2	3	4	5	6	7

How do you rate the **PEC** pitch on the following characteristics

Low ball bounce — **High ball bounce**

1 2 3 4 5 6 7

Short grass/fibres — **Long grass/fibres**

1 2 3 4 5 6 7

Does not give in — **Gives in a lot**

1 2 3 4 5 6 7

Very soft — **Very hard**

1 2 3 4 5 6 7

Very low Shoe-surface traction — **Very high Shoe-surface traction**

1 2 3 4 5 6 7

Very low shock absorption — **Very high shock absorption**

1 2 3 4 5 6 7

What kind of boots do you wear on the PEC pitch? Boots with

Short circular moulded studs	Short circular metal studs	Short moulded blades
Short metal blades	Long circular moulded studs	Long circular metal studs
Long moulded blades	Long metal blades	Artificial turf studs

How do you rate **EHB** pitch on the following characteristics?

	Very bad						Very good
Flat/even	1	2	3	4	5	6	7
Smooth ball roll	1	2	3	4	5	6	7
Predictable ball bounce	1	2	3	4	5	6	7
Stud penetration	1	2	3	4	5	6	7
Uniformity	1	2	3	4	5	6	7

How do you rate the **EHB** pitch on the following characteristics

Low ball bounce						**High ball bounce**
1	2	3	4	5	6	7
Short grass/fibres						**Long grass/fibres**
1	2	3	4	5	6	7
Does not give in						**Gives in a lot**
1	2	3	4	5	6	7
Very soft						**Very hard**
1	2	3	4	5	6	7
Very low Shoe-surface traction						**Very high Shoe-surface traction**
1	2	3	4	5	6	7
Very low shock absorption						**Very high shock absorption**
1	2	3	4	5	6	7

What kind of boots do you wear on the EHB pitch? Boots with

Short circular moulded studs	Short circular metal studs	Short moulded blades
Short metal blades	Long circular moulded studs	Long circular metal studs
Long moulded blades	Long metal blades	Artificial turf studs

Overall opinions

The loading on my body on

	Very low						Very high
my **match** pitch is	1	2	3	4	5	6	7
the **PEC** pitch is	1	2	3	4	5	6	7
the **EHB** pitch is	1	2	3	4	5	6	7

I believe I can move freely on

	Completely disagree						Completely agree
my **match** pitch	1	2	3	4	5	6	7
the **PEC** pitch	1	2	3	4	5	6	7
the **EHB** pitch	1	2	3	4	5	6	7

I do not worry about injuries when I play on

	Completely disagree						Completely agree
my **match** pitch	1	2	3	4	5	6	7
the **PEC** pitch	1	2	3	4	5	6	7
the **EHB** pitch	1	2	3	4	5	6	7

I move cautiously when I play on

	Completely disagree						Completely agree
my **match** pitch	1	2	3	4	5	6	7
the **PEC** pitch	1	2	3	4	5	6	7
the **EHB** pitch	1	2	3	4	5	6	7

Players are likely to get injured when playing on

	Completely disagree						Completely agree
my **match** pitch	1	2	3	4	5	6	7
the **PEC** pitch	1	2	3	4	5	6	7
the **EHB** pitch	1	2	3	4	5	6	7

Please have a quick check to see if you have answered every question.

If you have any other comments on movements or surfaces please write them on the back.

Thank you for filling out this questionnaire.

APPENDIX C: FIFA Requirements

This appendix contains detailed information on all standards for the FIFA one star and FIFA two star qualification for ball-surface and player-surface interaction as presented in the FIFA Quality Concept for Football turf: handbook of test requirements (January 2012 edition). The handbook can be found at:

http://www.fifa.com/aboutfifa/footballdevelopment/pitchequipment/footballfields/documents/index.html

Property	Test Method	Test conditions			Requirements	
		Preparation	Temperature	Condition	FIFA Recommended Two Star	FIFA Recommended One Star
Vertical ball rebound	FIFA 01 & FIFA 09	Pre-conditioning	23ºC	Dry	0.60m - 0.85m	0.60m - 1.0m
				Wet		
		Simulated Wear – 5,200 cycles			0.60m - 0.85m	N/A
		Simulated Wear – 20,200 cycles		Dry	N/A	0.60m - 1.0m
Angle ball rebound	FIFA 02	Pre-conditioning	23ºC	Dry	45% - 60%	45% -70%
				Wet	45% - 80%	
Ball roll	FIFA 03	Pre-conditioning	23ºC	Dry	4m - 8m	4m - 10m
				Wet		
Shock Absorption	FIFA 04 & FIFA 09	Pre-conditioning	23ºC	Dry	60% - 70%	55% - 70%
				Wet		
		Simulated Wear – 5,200 cycles		Dry	60% - 70%	N/A
		Simulated Wear – 20,200 cycles		Dry	N/A	55% - 70%
		Pre-conditioning	40ºC	Dry	60% - 70%	55% - 70%
	FIFA 04 1st impact	-	-5ºC	Frozen	60% - 70%	55% - 70%

Property	Test Method	Test conditions			Requirements	
		Preparation	Temperature	Condition	FIFA Recommended Two Star	FIFA Recommended One Star[3]
Vertical Deformation	FIFA 05a & FIFA 09	Pre-conditioning	23ºC	Dry	4mm – 10mm	4mm – 11mm
		Pre-conditioning		Wet		
		Simulated Wear – 5,200 cycles		Dry	4mm – 10mm	N/A
		Simulated Wear – 20,200 cycles		Dry	N/A	4mm – 11mm
Rotational Resistance	FIFA 06 & FIFA 09	Pre-conditioning	23ºC	Dry	30Nm - 45Nm	25Nm - 50Nm
				Wet		
		Simulated Wear – 5,200 cycles		Dry	30Nm - 45Nm	N/A
		Simulated Wear – 20,200 cycles		Dry	N/A	25Nm - 50Nm

Property	Test Method	Test conditions			Requirement	
		Preparation	Temperature	Condition	FIFA Recommended Two Star	FIFA Recommended One Star[3]
Linear Friction - Stud Deceleration Value	FIFA 07	Pre-conditioning	23ºC	Dry	3.0g - 5.5 g	3.0g - 6.0 g
				Wet		
Linear Friction - Stud Slide Value		Pre-conditioning	23ºC	Dry	130 - 210	120 – 220
				Wet		
Skin / surface friction	FIFA 08	Pre-conditioning	23ºC	Dry	0.35 - 0.75	0.35 - 0.75
Skin abrasion	FIFA 08	Pre-conditioning	23ºC	Dry	± 30%	± 30%

APPENDIX D: Surface Materials

This appendix contains detailed information on the Tiger turf carpet and Berleburger and Recticel shockpads used for the surface sample design in Chapter 6.

Carpet: Tiger Turf

TigerTurf:Data Sheet

Product	Code	FR50MS
Soccer Real 50 MS		
Application(s)	**Issue No.**	3
Football	**Date**	27/04/2010
Accreditations and Testing	FIFA 2 Star, EN.	

Product Description

Soccer Real MS is the latest edition to the ever evolving Soccer Real legacy. Mostly installed in Schools and Colleges due to its balance of high performance standards teamed with its exceptional value. Part filled with rubber and sand.

Yarn Description

A third generation, surface consisting of 2 profiled, 4-ended fibres which have been specifically designed to encourage blade recovery. The yarn colours are olive and sports green and are stitched using alternate needles to give a more natural appearance.

Yarn Characteristics

Yarn 1	Monofilament	**Yarn 2**	Monofilament
Material	Polyethylene	**Material**	Polyethylene
Type	Profiled	**Type**	Profiled
Dtex	8500	**Dtex**	8500
Filaments	4	**Filaments**	4

Product Specification

Total Dtex	8500	**Total Filaments (m^2)**	201600
Pile Weight (g/m^2)	1250	**Stitch Rate/metre**	120
Pile Height (mm)	50	**Stitches (m^2)**	12600
Total Height (mm)	52	**Tufts (m^2)**	25200
Machine Gauge	3/8"	**Total Weight (g/m^2)**	2046

Backing Characteristics

Backing Cloth	100% woven polypropylene with needle punch fleece. UV resistant
Coating	Ultrabond

Manufactured Rolls

Width	4 metres	**Shipping Weight (kg)**	8.2

Playing Lines

Play lines using a different coloured fibre can be incorporated into the surface during manufacture, or provided such that they can be installed on site.

Line Colours	Yellow, White, Blue, Rust

Guarantee

TigerTurf can offer a guarantee of 8 years for Soccer Real 50 MS, please refer to TigerTurf for conditions.

Installation and Maintenance

Product guarantees are subject to correct installation and continual maintenance of surface, details available on request.

Disclaimer

Please note the values quoted are within the tolerance accepted by the national governing bodies and industry standards. TigerTurf reserve the right to amend product specifications at their discretion. All products are manufactured to weight specification.

TENCATE materials that make a difference

Supplier & Manufacturer

Founding Member European Synthetic Turf Organisation

SO 9001 FM99545

TigerTurf UK
T: 01299 253966
F: 01299 253977
E: info@tigerturf.co.uk
W: www.tigerturfworld.com

Shockpad: Berleburger (14 mm)

Regupol® SP for Sand/Rubber-Filled Artificial Turf

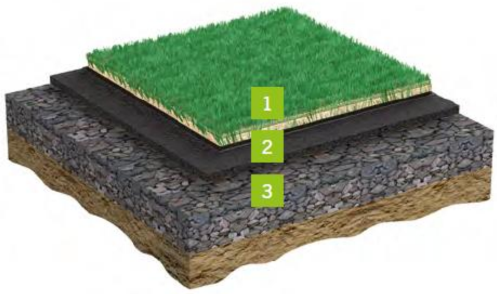
Regupol® SP Shock Pads are made of PUR-bonded rubber granules; they are supplied in prefabricated rolls.

Regupol® SP has a non-dimpled surface texture, thus it is particularly suitable for the installation on unbound sub-bases.

Regupol® SP has been specifically developed for use under artificial turf systems with sand or sand and rubber infill compositions. **Regupol® SP** is distinguished primarily by being so versatile that force reduction values can be individually modified to meet project-specific requirements. **Regupol® SP** is the perfect solution wherever there are specific characteristics on ball rebound, force reduction and other cushioning properties required. **Regupol® SP** consists of high-quality PUR-bonded rubber fibres which can be adjusted in density and thickness according to sports requirements.

Recommended Thickness
8-14 mm, depending on turf system.

Features and Technical Data
Variable, depending on material composition and thickness. You can find further detailed information at our website for download.



1 Artificial turf with sand/rubber infill composition • 2 **Regupol® SP Shock Pad** for artificial turf • 3 Unbound sub-base

See page 253 for more details.

Contact: Thomas Beitzel, Phone: +49 2751 803-130 • t.beitzel@berleburger.de;
Peter Breuer, Phone: +49 2751 803-131 • p.breuer@berleburger.de • Downloads at www.berleburger.com: Tender Texts, Technical Information, Certificates

BSW

Shockpad: Recticel (12 mm)

re-bounce Football

Class 4 | **Foam for non specific customers or markets. Distribution not limited.** | **re-bounce® uni F 82.16**

published on 16/11/2009 rev. 04

Product description

re-bounce® uni F 82.16 is a shock absorbing underlay for artificial grass. The product consists of polyurethane flexible foam and contains occasionally also rubber.

Technical specifications

Properties	Specifications	Unit	Test method
Foam properties			
Density	250 ± 15 %	kg/m³	ISO 845
CDH-40%	> 90	kPa	ISO 3386
Ultimate Elongation (ER)	TV 50	%	ISO 1798
Tensile Strength (RR)	> 160	kPa	ISO 1798
Tear resistance (TR)	> 5.0	N/cm	ISO 8067
Functional properties			
Thickness 10 mm			
Dimensional stability	TV +/- 0,35	%	EN 13746
Water permeability	TV 400	cm/h	pr EN 12616
Shock absorption	44	%	EN 14808
Vertical deformation	3.9	mm	EN 14809
Energy restitution	47	%	-
Thickness 6 mm			
Shock absorption	30	%	EN 14808
Vertical deformation	2.3	mm	EN 14809
Energy restitution	59	%	-
Thickness 8 mm			
Shock absorption	37	%	EN 14808
Vertical deformation	3.1	mm	EN 14809
Energy restitution	54	%	-
Thickness 12 mm			
Shock absorption	48	%	EN 14808
Vertical deformation	4.5	mm	EN 14809
Energy restitution	45	%	-
Thickness 14 mm			
Shock absorption	51	%	EN 14808
Vertical deformation	5.3	mm	EN 14809
Energy restitution	43	%	-
Cylindrical block, peeled to rolls			
Production Plants : Langeac (France) & Wijchen (The Netherlands)			

The foam properties are typical values provided by our internal control system.
TV : Target values - only for information purposes

Research for the suitability of a foam layer for use in sport constructions at ISA Sport Innovation & Quality.
Based on the material characteristics following foam layers are suitable for use in sport constructions :
°re-bounce uni F 82.16 -12mm : Project number : 250 80104 May 2008
°re-bounce uni F 82.16 -14mm : Project number : 250 80259 March 2009

Strengths

* excellent shock absorption and ball rebound.
* good dimensional stability.
* ageing resistant :
  - the shock absorbing properties remain constant in time.
  - the foam does not rot nor pulverise.
* good water permeability.
* very easy to install.
* widths of > 2 m are possible.

signature of responsible - effective from date of issue	P. Tytgat

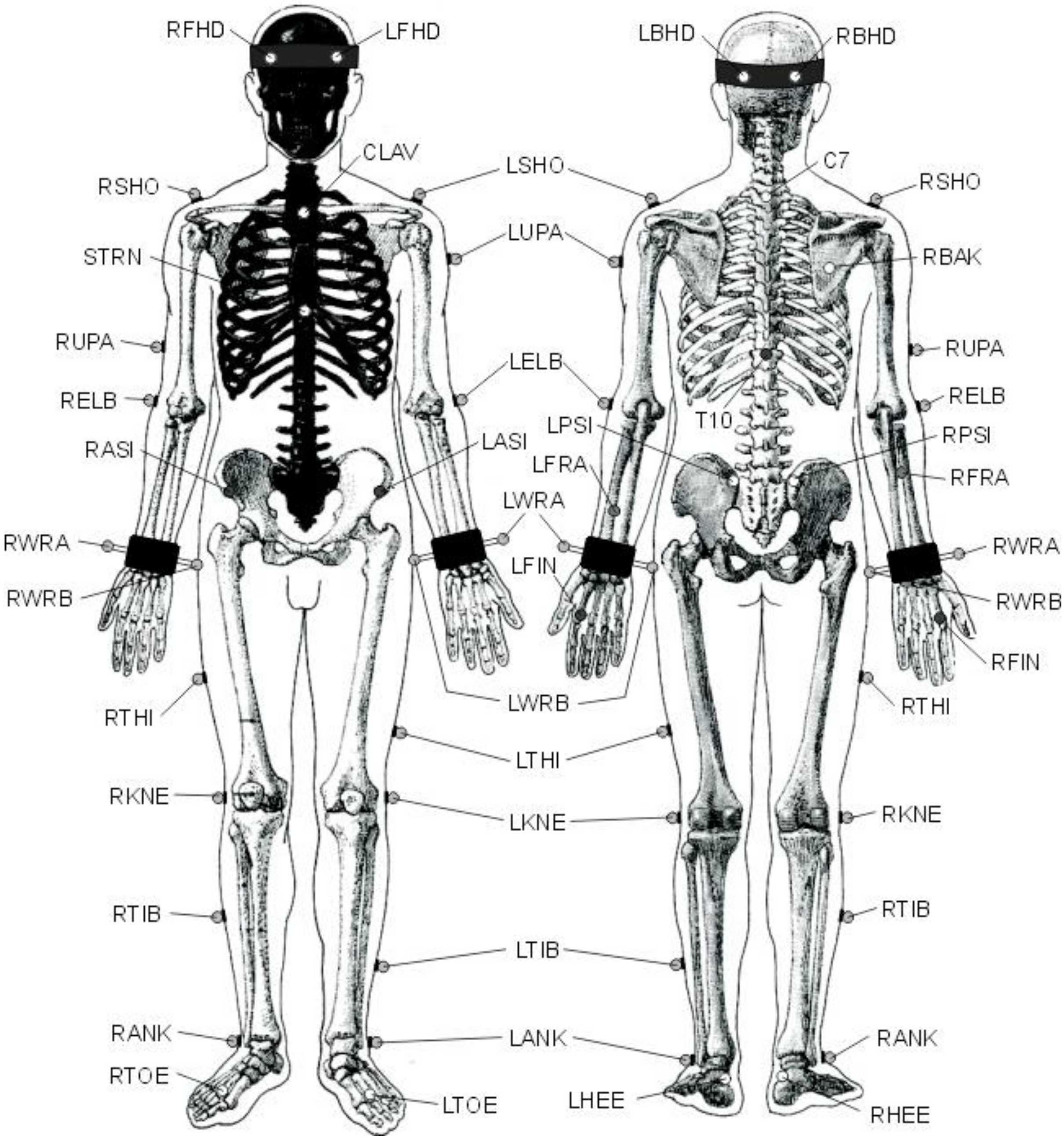
For more information, please contact
Recticel Composite Foams
www.recticel.com
www.re-bounce.com info@re-bounce.com

RECTICEL The passion for comfort

a black area indicates the parameters which have modified versus previous edition

APPENDIX E: Plug-in-Gait Marker Model

This appendix contains detailed information on the marker placement of the Plug-in-Gait Model used in Chapter 7.



The following describes in detail where the Plug-in-Gait markers should be placed on the subject. Where left side markers only are listed, the positioning is identical for the right side.

Upper Body

Head Markers

LFHD	Left front head	Located approximately over the left temple
RFHD	Right front head	Located approximately over the right temple
LBHD	Left back head	Placed on the back of the head, roughly in a horizontal plane of the front head markers
RBHD	Right back head	Placed on the back of the head, roughly in a horizontal plane of the front head markers

The markers over the temples define the origin, and the scale of the head. The rear markers define its orientation. If they cannot be placed level with the front markers, and the head is level
in the static trial, tick the "Head Level" check box under options on "Run static model" in the pipeline when processing the static trial. Many users buy a headband and permanently attach markers to it.

Torso Markers

C7	7th Cervical Vertebrae	Spinous process of the 7th cervical vertebrae
C10	10th Thoracic Vertebrae	Spinous Process of the 10th thoracic vertebrae
CLAV	Clavicle	Jugular Notch where the clavicles meet the sternum
STRN	Sternum	Xiphoid process of the Sternum
RBACK	Right back	Placed in the middle of the right scapula. This marker has no symmetrical marker on the left side. This asymmetry helps the autolabeling routine determine right from left on the subject.

C7, T10, CLAV, STRN define a plane hence their lateral positioning is most important.

Arm Markers

LSHO	Left shoulder marker	Placed on the Acromio-clavicular joint
LUPA	Left upper arm marker	Placed on the upper arm between the elbow and shoulder markers. Should be placed asymmetrically with RUPA
LELB	Left elbow	Placed on lateral epicondyle approximating elbow joint axis
LFRA	Left forearm marker	Placed on the lower arm between the wrist and elbow markers. Should be placed asymmetrically with RFRA
LWRA	Left wrist marker A	Left wrist bar thumb side
LWRB	Left wrist marker B	Left wrist bar pinkie side

The wrist markers are placed at the ends of a bar attached symmetrically with a wristband on the
posterior of the wrist, as close to the wrist joint center as possible.

LFIN	Left fingers	Actually placed on the dorsum of the hand just below the head of the second metacarpal

Lower Body

Pelvis

LASI	Left ASIS	Placed directly over the left anterior superior iliac spine
RASI	Right ASIS	Placed directly over the right anterior superior iliac spine

The above markers may need to be placed medially to the ASIS to get the marker to the correct position due to the curvature of the abdomen. In some patients, especially those who are obese, the markers either can't be placed exactly anterior to the ASIS, or are invisible in this position to cameras. In these cases, move each marker laterally by an equal amount, along the ASIS-ASIS axis. The true inter-ASIS Distance must then be recorded and entered on the subject parameters form. These markers, together with the sacral marker or LPSI and RPSI markers, define the
pelvic axes.

LPSI	Left PSIS	Placed directly over the left posterior superior iliac spine
RPSI	Right PSIS	Placed directly over the right posterior superior iliac spine

LPSI and RPSI markers are placed on the slight bony prominences that can be felt immediately below the dimples (sacro-iliac joints), at the point where the spine joins the pelvis.

SACR	Sacral wand marker	Placed on the skin mid-way between the posterior superior iliac spines (PSIS). An alternative to LPSI and RPSI.

SACR may be used as an alternative to the LPSI and RPSI markers to overcome the problem of losing visibility of the sacral marker (if this occurs), the standard marker kit contains a base plate and selection of short "sticks" or "wands" to allow the marker to be extended away from the body, if necessary. In this case it must be positioned to lie in the plane formed by the ASIS and PSIS points.

Leg Markers

LKNE	Left knee	Placed on the lateral epicondyle of the left knee

To locate the "precise" point for the knee marker placement, passively flex and extend the knee a little while watching the skin surface on the lateral aspect of the knee joint. Identify where knee joint axis passes through the lateral side of the knee by finding the lateral skin surface that comes closest to remaining fixed in the thigh. This landmark should also be the point about which the lower leg appears to rotate. Mark this point with a pen. With an adult patient standing, this pen mark should be about 1.5 cm above the joint line, mid-way between the front and back of the joint. Attach the marker at this point.

LTHI	Left thigh	Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical.

The thigh markers are used to calculate the knee flexion axis location and orientation. Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical. The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. Try to keep the thigh marker off the belly of the muscle, but place the thigh marker at least two marker diameters proximal of the knee marker. Adjust the position of the marker so that it is aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis. There is also another method that uses a mirror to align this marker, allowing the operator to better judge the positioning.

LANK	Left ankle	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis
LTIB	Left tibial wand marker	Similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis

The tibial marker should lie in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis. In a normal subject the ankle joint axis, between the medial and lateral malleoli, is externally rotated by between 5 and 15 degrees with respect to the knee flexion axis. The placements of the shank markers should reflect this.

Foot Markers

LTOE	Left toe	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
LHEE	Left heel	Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker

APPENDIX F: Player Questionnaires Chapter (7)

This appendix contains an overview of the questionnaires used during the player movement study (Chapter 7).

The first is a generic medical questionnaire that was used to make sure that the players did not have any medical conditions that could affect the outcomes of the study.

The second questionnaire is a general questionnaire with questions on their age and experience. The questionnaire also includes the question if they had any major injuries in the past. This in addition to the medical questionnaire to make sure that their movements would not be affected by any previous injuries.

The third questionnaire was used to get some insight into the player perception of the four different surfaces used. In this questionnaire the players were asked to rate the traction and hardness of the surface as well as indicate which of the four surfaces they preferred and which they disliked the most.

PRE-SELECTION MEDICAL QUESTIONNAIRE

LOUGHBOROUGH UNIVERSITY
SPORTS TECHNOLOGY INSTITUTE

Please read through this questionnaire, BUT DO NOT ANSWER ANY OF THE QUESTIONS YET. When you have read right through, there may be questions you would prefer not to answer. Assistance will be provided if you require it to discuss any questions on this form. In this case please tick the box labelled “I wish to withdraw” immediately below. Also tick the box labelled “I wish to withdraw” if there is any other reason for you not to take part.

	tick appropriate box
I wish to withdraw	☐
I am happy to answer the questionnaire	☐

If you are happy to answer the questions posed below, please proceed. Your answers will be treated in the strictest confidence.

1. Are you at present recovering from any illness or operation? YES/NO*

2. Are you suffering from or have you suffered from or received medical treatment for any of the following conditions?

a.	Heart or circulation condition	YES/NO*
b.	High blood pressure	YES/NO*
c.	Any orthopaedic problems	YES/NO*
d.	Any muscular problems	YES/NO*
e.	Asthma or bronchial complaints	YES/NO*

3. Are you currently taking any medication that may affect your participation in the study? YES/NO*

4. Are you recovering from any injury? YES/NO*

5. Are you epileptic? YES/NO*

6. Are you diabetic? YES/NO*

7. Are you allergic to sticking plasters? YES/NO*

8. Do you have any other allergies? If yes, please give details below YES/NO*
…………………………………………………………………………………………….
…………………………………………………………………………………………………….
…………………………………………………………………………………………….
…

9. Are you aware of any other condition or complaint that may be affected by participation in this study? If so, please state below;
…………………………………………………………………………………………….
…………………………………………………………………………………………………….
…………………………………………………………………………………………….
…………………………………………………………………………………………………….

* Delete as appropriate

Effect of surface hardness and traction on musculoskeletal loading during ‘stop and turn’ and ‘jumping/heading’ on artificial turf

General questionnaire

Name : …………………………..

Age : …………………………..

Select your playing position:

Goal keeper	Defender	Defending Midfielder	Attacking Midfielder	Forward

For which of the university teams do you play? : …………………………..

For how many years have you been playing football? : …………..

For how many years have you been playing football on artificial turf? : …………..

How many hours per week do you train on

Natural grass **:** …………..
Artificial turf **:** …………..

On average how many competitive matches do you play in a month on

Natural grass **:** …………..
Artificial turf **:** …………..

How many hours per week do you play recreationally on

Natural grass **:** …………..
Artificial turf **:** …………..

Did you ever had any major injuries in the past? Please state injury type, location and duration below:

All information given will be kept confidential and only used for this research project (In accordance with Data Protection Act (1998).

Would you like to receive information on the research? Yes No

Effect of surface hardness and traction on musculoskeletal loading during ‘stop and turn’ and ‘jumping/heading’ on artificial turf

End questionnaire

Name : ………………………….

What surface did you prefer the most? : ………….

What surface did you dislike the most : ………….

Please rate the surfaces on hardness on the lines below

Surface 1	Very soft	|————————————|	Very hard
Surface 2	Very soft	|————————————|	Very hard
Surface 3	Very soft	|————————————|	Very hard
Surface 4	Very soft	|————————————|	Very hard

Please rate the surfaces on traction (grip) on the lines below

Surface 1	Very low	|————————————|	Very high
Surface 2	Very low	|————————————|	Very high
Surface 3	Very low	|————————————|	Very high
Surface 4	Very low	|————————————|	Very high