Surface interactions of soccer balls

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Surface Interactions of Soccer Balls

By

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A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

May 2008

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Abstract

A soccer ball interacts with a variety of surfaces during a game usually under varying environmental conditions; however there has been limited research in this area. This thesis reports a series of investigations aimed at developing an improved understanding of the surface interaction between a soccer ball and surfaces of interest. The main aims were to quantify the friction between the ball and surface, to assess the effect of changing the contact conditions and investigate whether the design of a ball could be optimised to perform consistently in dry and wet conditions.

Experimental and computational approaches were used in partnership to analyse the impact and rebound behaviour of soccer balls. For the experimental approach, high speed video was used to record the bounce of a ball projected on to a surface with no initial spin and a Robotic Leg was used to assess the kicking action. In both cases the resultant spin, angle and velocity of the impact were measured. The finite element (FE) models of the ball were taken from previous research and used to simulate the above experimental scenarios. Further development of the ball models enabled the sub-modelling and analysis of soccer ball surface textures under realistic loading conditions.

The dry and wet condition was found to influence the ball impact more than any other variable. The contact angle between the ball and surface was also found to be significant, however the addition of a surface texture to the soccer ball was only found to have a larger effect at lower velocity impacts and for kicking. After investigating the complex contact conditions (sliding speed and contact pressure) a friction tester was developed to test ball and surface materials with initial tests providing some similar findings to actual ball impacts. A constant coefficient of friction was also found to be sufficient to model the soccer ball impact within FE at a single velocity over a full range of contact angles. A developed FE ball model was created to determine localised loading conditions of the outer panel foam layers where prototype textures could be analysed and compared.

Keywords: soccer, football, impact, friction, spin, finite element, modelling
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I also wish to thank the adidas innovation team for funding this research and supporting the project through the regular update meetings and use of the test facilities in Germany. In particular, Dr. Tim Lucas, Harry Koerger and Karsten Westphal plus all of the interns who have helped with the practical testing and ordering of test samples (Stuart, Jim and Christoph). Also thanks to the finite element support and help from Abaqus UK in the development of the computational models.

In addition to the academic help, the support from my friends and fellow researchers in the Sports Technology Research Group has helped me in some way through the PhD.

A big thank you goes to my family who have supported and encouraged me through my years at Loughborough. And finally, a special mention to my girlfriend Jem for putting up with me especially over the last three years.
Publications arising from this work

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# Nomenclature

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BC</td>
<td>Boundary condition</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer aided design</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>COF (or $\mu$)</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>COR (or $e$)</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>EOS</td>
<td>Equation of State</td>
</tr>
<tr>
<td>EPDM</td>
<td>Ethylene-propylene-diene-monomer</td>
</tr>
<tr>
<td>FA</td>
<td>Football Association</td>
</tr>
<tr>
<td>FC</td>
<td>Football Club</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FIFA</td>
<td>Fédération Internationale de Football Association</td>
</tr>
<tr>
<td>FSI</td>
<td>Fluid structure interaction</td>
</tr>
<tr>
<td>HSV</td>
<td>High speed video</td>
</tr>
<tr>
<td>IFAB</td>
<td>International Football Association Board</td>
</tr>
<tr>
<td>LU</td>
<td>Loughborough University</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>PU</td>
<td>Polyurethane</td>
</tr>
<tr>
<td>RAM</td>
<td>Random access memory</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>STRG</td>
<td>Sports Technology Research Group</td>
</tr>
<tr>
<td>STRI</td>
<td>Sports Turf Research Institute</td>
</tr>
<tr>
<td>UEFA</td>
<td>Union of European Football Associations</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
</tbody>
</table>
\( \gamma \)  
Slip rate

\( \theta \)  
Angle

\( \theta_{\text{contact}} \)  
Angle of rotation on contact

\( \theta_d \)  
Deviation angle

\( \theta_e \)  
Elevation angle

\( \theta_{\text{in}} \)  
Angle inbound

\( \theta_{\text{out}} \)  
Angle outbound

\( \theta_{xx} / \theta_i \)  
Ball position from HSV field of view

\( \mu \)  
Coefficient of friction (COF)

\( \mu_{\text{ADH}} \)  
Adhesion component of COF

\( \mu_{\text{HYST}} \)  
Hysteresis component of COF

\( \mu_k \)  
Kinetic COF

\( \mu_s \)  
Static COF

\( \rho \)  
Density of air

\( \tau_{\text{crit}} \)  
Critical shear stress

\( v \)  
Kinematic viscosity

\( \omega \)  
Ball spin

°  
Degrees

"  
Inch

2D  
Two dimensional

3D  
Three dimensional

a or b  
Ball position from camera

A or B  
Anomalies

A_{\text{nom}}  
Nominal area of contact

A_{\text{true}}  
True area of contact

bar  
Unit of pressure

\( c_{\text{contact}} \)  
Ball circumference distance on contact

\( C_d \)  
Drag coefficient

x
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>Centimetre</td>
</tr>
<tr>
<td>(d_{\text{contact}})</td>
<td>Contact distance</td>
</tr>
<tr>
<td>(D)</td>
<td>Ball diameter</td>
</tr>
<tr>
<td>(e)</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>(E')</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>(F)</td>
<td>Frictional force</td>
</tr>
<tr>
<td>(F_{\text{ADH}})</td>
<td>Adhesion component of frictional force</td>
</tr>
<tr>
<td>(F_d)</td>
<td>Drag force</td>
</tr>
<tr>
<td>(F_{\text{HYST}})</td>
<td>Hysteresis component of frictional force</td>
</tr>
<tr>
<td>(g)</td>
<td>Gravity (in terms of acceleration)</td>
</tr>
<tr>
<td>(g)</td>
<td>Grams (in terms of mass)</td>
</tr>
<tr>
<td>(g/m^3) or (g/m^3)</td>
<td>Grams per metre cubed</td>
</tr>
<tr>
<td>(GB)</td>
<td>Giga Byte</td>
</tr>
<tr>
<td>(GHz)</td>
<td>Giga Hertz</td>
</tr>
<tr>
<td>(GPa)</td>
<td>Giga Pascal</td>
</tr>
<tr>
<td>(Hz)</td>
<td>Hertz</td>
</tr>
<tr>
<td>(K)</td>
<td>Constant dependent on asperity shape and length</td>
</tr>
<tr>
<td>(kg)</td>
<td>Kilo Grams</td>
</tr>
<tr>
<td>(kHz)</td>
<td>Kilo Hertz</td>
</tr>
<tr>
<td>(kPa)</td>
<td>Kilo Pascal</td>
</tr>
<tr>
<td>(kph)</td>
<td>Kilometres per hour</td>
</tr>
<tr>
<td>(kW)</td>
<td>Kilo Watt</td>
</tr>
<tr>
<td>(h_1)</td>
<td>Original ball height</td>
</tr>
<tr>
<td>(h_2)</td>
<td>Rebound ball height</td>
</tr>
<tr>
<td>(H)</td>
<td>Maximum value</td>
</tr>
<tr>
<td>(l)</td>
<td>Sample length</td>
</tr>
<tr>
<td>(L)</td>
<td>Minimum value</td>
</tr>
<tr>
<td>(m)</td>
<td>Metre</td>
</tr>
<tr>
<td>(M_{\text{ball}})</td>
<td>Mass of the ball</td>
</tr>
<tr>
<td>(M_{\text{leg}})</td>
<td>Mass of the leg</td>
</tr>
<tr>
<td>(mm)</td>
<td>Millimetre</td>
</tr>
</tbody>
</table>
\(m.s^{-1}\) or \(m/s\)  
Miles per hour

\(N\)  
Newton

\(N.cm^2\) or \(N/cm^2\)  
Newton's per centimetre squared

\(N.m\)  
Newton metre

\(N\)  
Newton

\(N.m^2\) or \(N/cm^2\)  
Newton's per centimetre squared

\(N.m\)  
Newton metre

\(N\)  
Newton

\(ms\)  
Milliseconds

\(n\)  
Sample size

\(N\)  
Newton

\(N.cm^2\) or \(N/cm^2\)  
Newton's per centimetre squared

\(N.m\)  
Newton metre

\(oz\)  
Ounce

\(p\)  
Contact pressure

\(Pa\)  
Pascal

\(Pa.s\)  
Pascal second

\(psi\)  
Pounds per square inch

\(R\)  
Ball radius

\(R\)  
Normal reaction force

\(R_a\)  
Surface roughness parameter

\(rad.s^{-1}\) or \(rad/s\)  
Radians per second

\(R_e\)  
Reynolds number

\(R_p\)  
Pearson’s correlation coefficient \(R\) value

\(RPM\)  
Revolutions per minute

\(rev.s^{-1}\) or \(rev/s\) or \(rps\)  
Revolutions per second

\(s\)  
Second

\(S_1\)  
Horizontal velocity before

\(S_2\)  
Horizontal velocity after

\(t\)  
Time

\(T\)  
Temperature

\(tan\theta\)  
Tangent modulus

\(u\)  
Horizontal velocity

\(U_\infty\)  
Free stream velocity

\(U_s\)  
Shock velocity

\(U_p\)  
Particle velocity

\(v\)  
Vertical velocity
$V$  Velocity
$V_{ball}$  Ball velocity
$V_{in}$  Velocity inbound
$V_{foot}$  Foot velocity
$V_{out}$  Velocity outbound
$w$  Deformation frequency
$x_1/x_2$  Horizontal distances
$X$  Horizontal position coordinate
$y$  Profile departure
$Y$  Vertical position coordinate
1 Introduction

1.1 Chapter overview
The first chapter covers the business and scale of the soccer industry and ball development. Research in to soccer ball development and testing is summarised to give an introduction to the area of study. The statement of purpose and then the research questions are described with the chapter concluding by outlining the thesis organisation.

1.2 The area of study
Soccer (or Association Football) is now a global sport with mass participation which is indicated by a recent survey by FIFA (Fédération Internationale de Football Association), the world governing body for soccer. Approximately 270 million people regularly play football around the world which is just about 4% of the total world’s population. These people are part of 1.7 million teams in 300,000 clubs (FIFA, 2007). Perhaps the most important piece of equipment for the game of soccer is the ball itself. Although designs vary, the ball is notionally a spherical shell typically consisting of a configuration of polyurethane based composite panels attached around an inflated bladder or rubber like material. Forty million balls are sold each year, in an industry worth approximately $500 million.

Recently, the 2006 FIFA World Cup Finals held in Germany generated sales of more than 15 million replica adidas Teamgeist™ balls. The top of the range replicas that are used in the World Cup games contributed 750,000 units towards the total and were sold at a retail price of approximately $120. This more than doubled the 6 million replica balls sold of the adidas Fevernova™ ball, which was developed for the 2002 World Cup Finals. This made the adidas Teamgeist one of the best selling balls of all time. Additionally, 1 million consumers bought the top of the range adidas boot, the Predator Absolute, at a retail price of $200. The ball and boot sales associated with the 2006 World Cup boosted adidas’ annual soccer equipment sales by 30% to $1.5 billion. (FT.com 2006, adidas 2007)
The ongoing soccer ball research, development and testing undertaken by the Sports Technology Research Group (STRG) at Loughborough University (LU) in collaboration with adidas has been aimed at gaining a better understanding of the behaviour of the ball during match play situations. The research within the STRG on soccer balls began with the assessment of player capabilities and perceptions (Neilson, 2003) and more recently has led to finite element (FE) models of the three most recent adidas balls for major championship balls; the Fevernova™ (2002 World Cup), the Roteiro™ (2004 European Championships) and the Teamgeist™ ball (2006 World Cup) being developed (Price, 2005). The FE models allow dynamic impacts to be simulated and analysed to assess the soccer ball's mechanical capabilities with respect to material selection and construction.

1.3 Previous research

Previous literature in to soccer ball developments and testing is very limited as compared to other ball sports such as golf and tennis. This is due the sensitive nature of the information collected allowing companies to gain an advantage over their competitors. Initially it is important to know the regulations and the quality controls concerning the ball to be used in a game. FIFA set down the rules of the game which cover the ball's weight, material, circumference, sphericity and pressure. However before a ball can be used in topflight competitions, manufacturers have the possibility to enter into a licensing agreement for the use of the prestigious 'FIFA Approved' and 'FIFA Inspected' Quality Marks on footballs which indicate the ball has passed a rigorous testing procedure, (FIFA, 2007).

The 'Quality Concept' has been established since 1st January 1996 and is part of the Denominations Programme initiated by FIFA in 1995. The idea was to introduce a high quality and consistent ball which would be distinguished through one of the Quality Marks included in the ball graphics. The laboratory based test procedure is mainly concerned with the static based testing of footballs. Additionally FIFA have now also developed a Quality Concept for the use of artificial turf surfaces as an alternative to the usual natural turf used for games.
The brief summary following indicates that the majority of literature in football or soccer is not concerned with how the ball itself is constructed, manufactured or tested. Most of the literature is concerned with using a ball to quantify the effects of pitches, kicking, heading or the aerodynamics. The most relevant recent soccer ball research to this study has been carried out by (Neilson, 2003), (Price, 2005) and (Asai et al, 2002). These concern player performance, the development of FE models and the foot-ball interaction and effects of friction.


1.4 Statement of purpose

The intention of this study is to continue the dynamic testing and develop the functionality of the FE soccer ball model further with respect to how the ball interacts with varying surfaces and conditions. During a match, the ball comes into contact with a wide variety of surfaces which include the playing surface (artificial or natural), boots, gloves, the goal frame and human skin across a wide range of environmental conditions.
Currently, FIFA does not include specifications for the surface properties for the ball or any restrictions for a player’s boots, goalkeeper’s gloves or the playing kit. The only restrictions are based on whether the match referee determines the equipment to be unfair or dangerous to other players. This research will evaluate the interactions between soccer balls and the surfaces of interest. The experimental and computational aspects of the research will allow the physical parameters of the ball-surface interaction to be fully characterised. These will include coefficients of friction, energy losses, spin production and player perceptions.

1.5 Research questions

This section outlines the questions posed in order to focus the research around the surface interactions involved with soccer balls during a game.

1) Is it possible to quantify the friction between a soccer ball and a surface of interest and relate this to impacts experienced in play?

No friction testing devices or tribometers currently exist that have been specifically designed to accommodate soccer ball contact conditions. Alternative methods have been used to measure friction values between ball and boot materials (IUP51). In the literature, methods have been published for golf balls (Ekstrom 1999 and Gobush 1996), tennis balls (Bao et al 2003, Pratt and Mahonen 2003 and Cross 2002a) and non-specific sports balls (Dunlop et al 1998).

2) How does varying the surface contact conditions, (i.e. surface texture, materials and construction) affect the dynamic performance and consistency of a soccer ball?

Little research has been published into the effect of friction on a soccer ball impact with the most relevant study involving a largely FE approach with no experimental validation, Asai et al (2002).
3) Is it possible to design a soccer ball to perform equally well and consistently in wet and dry conditions?

Through the literature, no research in sports balls has been shown to identify differences between their performance in wet and dry conditions. Details as to how a surface texture may affect ball performance are not known, for example what texture, materials and construction are required to minimise changes in ball performance in the wet during a ball-boot interaction when kicking the ball with spin. Consequently, no FIFA rules exist on soccer ball surface interactions nor are there in industry any design rules to assist ball designers to create balls with predictable performance characteristics in wet and dry conditions.

1.6 Thesis organisation

The thesis has been organised to fully illustrate the topics covered in the research and the chapters are now described.

Chapter 2 includes an extensive literature review of the topics concerning the area of research. These include the development of the game of soccer and the ball itself plus the subject of friction, sports ball impacts and finite element analysis. This chapter allowed the full understanding of the soccer ball itself and surfaces it may come into contact with plus relative technology from other industries.

Chapter 3 describes the equipment and general methodology adopted during the experimental testing. Additionally possible sources of error within a typical analysis have attempted to be quantified. The methods presented give an overview of the basis of the experimental testing and the error analysis shows the measurement accuracy encountered.

Chapter 4 describes the process of designing a friction tester or tribometer for testing soccer materials which takes into account the correct contact conditions which have been determined experimentally and theoretically through FE analysis. This chapter attempts to answer the first research question.
Chapter 5 describes the effect of adding a surface texture to a soccer ball in relation to various scenarios such as kicking and impacts on various surfaces during wet and dry conditions as compared to a standard smooth surface on a ball. Varying the surface texture of a ball is one way of modifying the surface contact conditions as mentioned in the second research question.

Chapter 6 describes the process of using a soccer ball impact on planar and cylindrical surfaces to assess the validity of a friction model within a FE model. Experimental data are used to validate FE simulations over a range of friction values. This chapter attempts to shows how varying the friction between a ball and surface may affect the rebound characteristics from an impact.

Chapter 7 describes the process of creating a FE model of the texture on a soccer ball panel and incorporating hydrodynamic effects in to the model. The existing soccer ball created by Price (2005) is developed further to include solid elements to assess how the panel compresses during impact and whether a texture will have an influence under compression. This chapter endeavours to investigate the effect of the surface texture under realistic loadings and how new designs could be developed in response to the second and third research questions.

Chapter 8 concludes the outcomes of the research by bringing together the results. It also attempts to answer the research questions posed in the previous section. Limitations of the research are discussed and areas of further work are proposed.
2 Literature review

2.1 Chapter Overview
This chapter reports the relevant literature for the research which includes the sport of soccer, the mechanics of friction, ball-surface impacts and the application of FE analysis to sport impacts. Soccer literature covers the history of the sport and ball then leading on to other areas such as biomechanical analyses of kicking and ball aerodynamics. As friction plays a major role in contacting bodies and surface interactions this has been examined with deformable material friction of particular interest. The chapter concludes by looking at the research carried out into sports ball impacts which leads on to how FE analysis has been applied to modelling of sports balls and surfaces.

2.2 Association football or soccer

2.2.1 Brief history

2.2.1.1 The origins
"There are many conflicting views on the origins of the game and the influences that certain cults may have had on its evolution, but one thing is incontestable: football has flourished for over a thousand years in diverse rudimentary forms, in the very region which we describe as its home, England and the British Isles". (FIFA.com, 2007). The following description of the history of soccer/football was compiled from the FIFA website (FIFA.com 2007) and Holliday (2004).

The history of the game of football can be traced back to the ‘Han Dynasty’ in China where various forms of playing with a ball with the feet were reported as early as the 2nd and 3rd centuries B.C. Games, rituals, customs and even fertility rituals have been associated with a ball played by a person’s foot in teams or as individuals. ‘Games’ played in the Far East were a feat of skill, for example the educational exercise, the “Tsu’Chu”. This involved kicking a ball through a small opening into a net. The Japanese, 500 to 600 years later than the ‘Han Dynasty’
had another form of the game called “Kemari”, which is still played today. It requires players to work together to keep the ball off the ground in a small space.

Versions of these ceremonious games appeared later in Greece under the name “episkyros” and then the Roman game, “Harpastum”. The Roman game perhaps has the greatest similarity to the modern game as two teams on a rectangular pitch had to get a ball to pass over the other team’s boundary line at one end. Tactics were employed and passing between team members was combined with individual trickery, although the use of the feet was minimal. Even though this game existed for 700 years and was introduced to England, it is still doubtful whether it formed the basis of the development of the modern game. Other games all over the world flourished as well as in Normandy (France), Venice and Florence (Italy) and the Celtic regions of the UK.

2.2.1.2 1700s onwards

The most important period of history of the development of soccer perhaps started in the mid 19th century. From the 8th Century up until this point the game of football had many regional variations even between neighbouring towns and villages. Rules were locally specific legitimated by traditions with the emphasis on physical force rather than skill. Games were violent, disorganised, spontaneous, lasted indefinitely and there were no limitations on player numbers. The aim was to get the ball to a specified target using any means except murder and manslaughter. The field of play was not restricted which led to games taking place through town streets and across streams and hedges. Kicking and handling of the ball were both allowed, which eventually would give rise to the formation of association football and rugby football. Kicking was not used especially for moving the ball but was employed to knock down opponents.

Several attempts were made to ban football by figures such as the Lord Mayor of London and reigning Kings. This was due to the considerable damage the games were having on the towns and even distracting the army from practicing military disciplines. Even at this time the passion for the game meant that football was never uprooted as people still played despite regulations such as riot laws.
The historic changing point came when public schools adopted the game of football from 1750-1840, where the social organisation would play a major role in the development of the rules. Football became accepted as it provided a useful distraction from other pastimes to education such as gambling or heavy drinking. Schools such as Charterhouse, Westminster, Eton and Harrow preferred the 'skilful' game of using the feet only whereas Cheltenham and Rugby schools adopted the more physical game of handling the ball. A prominent figure in the laying down of the rules in writing was Dr. Thomas Arnold, who made football compulsory at Rugby in the curriculum as it created a team spirit within the school. In 1846 the first rules were written down in Rugby which allowed handling, a process called 'Sportisation'. Eton and Harrow rejected these rules and formed their own set of rules for using the feet. It was at this stage, called incipient modernisation, that the bifurcation of the two games emerged – rugby and association.

On the 26th October 1863, 11 London clubs gathered and set down the first rules of football and created the Football Association (FA). Since the rugby version was in the minority, the rules chosen suited the association game. By the 8th December 1863 rugby and association officially split. Eventually rugby football would split again into union and league codes. At this time the rules of association football diffused into the society at large through specific organisations or churches. For example Aston Villa and Wolverhampton Wanderers football clubs were formed through the graduating public school boys introducing football in Churches. By the 1870's there were 50 member clubs of the FA which led to the introduction of the famous FA Cup competition and football leagues.

Other significant social processes were occurring such as industrialisation, embourgeoisement, urbanisation, globalisation and class development, which all interacted with the sportisation of football. Professionalism was also becoming prevalent and the FA had to legalise this as early as 1885. As the 1900s were approaching, British pioneers who took their business (and a copy of the rule book) to other countries also introduced football to the locals. For example AC Milan of Italy was founded by Englishman Alfred Edwards who ran a leather business and became the first President of the club.
The world governing body of football, FIFA, was founded in May 1904 with 7 founder members, all from Europe. In the year of the first World Cup (1930) there were 41 members. The growth continued and by 2000 at the Ordinary FIFA congress there were 204. The game has seen many developments through this time, with specialised infrastructure to accommodate clubs and the demand for high quality equipment ever increasing. The game, depending on which part of the world you are in, is known as either football or soccer. The original name is 'association football' and the word soccer was derived from the abbreviation of association, 'assoc', Oxford English Dictionary (2007).

2.2.1.3 Modern day
As indicated in chapter 1 soccer is now a global sport with mass participation with 250 million people playing regularly all over the world. The business of soccer is also huge. Fifteen million replica balls of the official match ball were sold as a result of the 2006 World Cup. In total, 40 million balls are sold worldwide in a business worth approximately $500 million. Additionally as a result of the 2006 World Cup, the ball and boot sales associated with the tournament boosted adidas's annual soccer equipment sales by 30% to $1.5 billion, (FT.com 2006, adidas 2007, FIFA.com 2007).

2.2.2 Soccer ball developments
Even before football had been recognised as a 'sport' or past-time, thousands of years ago, the South American Indians were reportedly using a light elasticised ball to kick around. It wasn't until the 1960's that a polymer was used to construct the majority of the ball. According to historical references, early 'footballs' were made up from various sources, from stitched up cloth, animal and human heads/skulls or pig or cow bladders. In Medieval times, pig's bladders were eventually covered with leather to ensure increased shape retention, which is the basis of the modern day football, (SoccerBallWorld.com, 2005).

Charles Goodyear patented vulcanised rubber in 1836 and in 1855 manufactured a football comprised of this (Figure 2-1). H. J. Lindon developed the first inflatable rubber bladder in 1862.
At the time Lindon was experimenting with oval polymer bladders since they were easier to handle, (SoccerBallWorld.com, 2005).

The FA first introduced rules and regulations regarding the size and materials of footballs in 1872. They mentioned the ball must be spherical in shape and have a circumference of 68.6 to 71.1 cm, which now forms the basis of the current FIFA criteria. Two companies supplied the balls for the English FA: Mitre and Thomlinson's, both emphasising that the crucial element in football manufacture was ensuring the ball retained its shape, (SoccerBallWorld.com, 2005).

During the first half of the 20th century the balls continued to develop with similar structure, which in fact has remained to the present day: a two-piece ball comprised of a bladder and a casing. However with the leather casing problems occurred that seriously affected play. Since leather is a porous material, water absorption was inevitable. This gave rise to manufacturers developing synthetic coatings. The shape retention issue was corrected using a 'carcass' where the leather casing was backed up by a lining of interwoven backing cloths.

The rubber bladder was eventually replaced by latex or butyl in cheaper balls. It wasn’t until the 1980s that synthetic leather took over in football manufacture. These balls were based on polyester non-woven materials, which were sometimes impregnated with Polyurethane (PU). They also had a polyurethane coating which combated the water absorption issue. The base of
many ball construction designs was the ‘Bucky Ball’. Richard Buckminster, an American architect developed the Geodesic sphere which was the basis used by manufacturers for the 32 panel soccer ball. This shape consists of 20 hexagons and 12 pentagons and is similar to the carbon atom C-60 (buckminsterfullerene), (Figure 2-2). (SoccerBallWorld.com, 2005)

![Figure 2-2: The first official FIFA football](image)

The ball has come a long way since its first use and the major companies such as adidas, Nike and Puma are continually developing high-tech materials and unique panel designs. Due to the confidentiality of the designs of soccer balls, there is little known about what each company tries to achieve with each ball.

When a ball impacts a surface the direct contact comes from the outer layer. However all of the ball material components will play a part in how the ball deforms and interacts during contact. For that reason the manufacturing of the ball is a good starting point to investigate the understanding of the mechanical properties of a ball.

The manufacturing processes involved in the production of footballs differ between manufacturers and on the quality of ball. This section will identify the general manufacturing practices of hand-stitched balls using the adidas Fevernova as an example and the thermally bonded technique used to manufacture the adidas Roteiro.
A football is comprised of 3 main components: the outer shell, the lining and the bladder. The outer shell is made of a foamed polyurethane (PU) material cut into panels. The foaming process creates a honeycomb structure and is therefore difficult to regulate with respect to layer thickness accuracy. Material thickness varies in the region of ± 0.1 mm, which therefore will give a total variance of ± 0.2 mm when considering the diameter (Jones 2003). PU offers durability and water resistance which is essential in football. When combined with the foamed infrastructure it gives a lighter weight panel with increased dimensional stability. The outer shell needs to be accurately manufactured and often specialist polymer suppliers are required to achieve the high performance standards and specifications. For example, adidas used the German based company, Bayer, to manufacture the ‘Impranil’ polyurethane used in the ‘Fevernova™’ ball (Figure 2-3). (Soccerballworld.com, 2005).

The outer shell has a PU coating which increases water resistance and can be easily printed on. The layers of PU form a smooth outer casing when glued together in sheets, which provide enough material to produce one ball. At this point any pre-printing of company brand names is carried out using screen prints with a different screen for each colour, adidas (2007)
Panels enable the ball to be constructed from 2 dimensional shapes. There are hundreds of panel configurations in the market, although the majority opt for 32 panels. There is a debate about which patterns or configurations give a ball the best sphericity or the truest flight characteristics. One argument supporting fewer panels suggests that there will be lower amounts of stitch points and angles resulting in greater sphericity and increased water resistance.

A fabric lining is glued to the back of the PU sheets to increase the stiffness. The criss-crossing of fabric fibres creates a stable framework. This framework is important when the ball is impacted as it resists any change to shape and supplies the strength and damping effect. Four linings, which are made up of a cotton-polyester blend, make up the premium footballs. The application of the fabric lining is carried out by hand, usually with two people to ensure any defects such as wrinkling are avoided. Next the panels are cut out with a knife under a hydraulic press and are pre-punched with holes for stitching.

The manufacture of the bladder differs widely between companies due to varying technologies and designs. Usually a bladder will be of natural latex, sometimes with added carbon to increase its durability. Latex has favourable energy returns when subjected to a force. The bladder is not completely impermeable, as due to its very slight porosity, air is allowed to escape slowly over time. This allows for any over inflated ball not to put strain on the stitching over a prolonged time thus increasing ball durability and shape retention. (SoccerBallWorld.com, 2005 & Jones, 2003)

The stitching process is vital to a ball performance and dynamic characteristics. The tensioning of the stitching is sealed after the joining of two panel edges by using knots to lock it. High quality waxed and twisted polyester threads are used to give tight joins, (Figure 2-4).
Before the final stitch is completed the bladder is inserted and the ball can be transported inflated or deflated as required. Un-inflated balls however create wrinkles in the outer casing when they are packed tightly, lowering the aesthetic appearance, whereas inflated balls can put unnecessary pressure on the new stitching.

The adidas Roteiro was a revolutionary ball in terms of its manufacture where no stitches were used to hold the exterior panels together (Figure 2-5). As with the Fevernova, the bladder was composed of natural latex together with a standard valve. The major difference was that the bladder was encased in a fabric carcass which formed the base onto which the PU based panels are thermally bonded. The fabric carcass controlled, to a major extent, the ball’s mechanical properties, such as the overall stiffness. Due to the warp and weft of the carcass panels, they were orientated by their anisotropic fibre directions to control the deformation shapes. In Figure 2-5, the carcass panels are shown through a cut away illustrating the varying orientations.

The panels were made of a PU composite of a foam backed thin film layer. The PU coating surface layer was provided by the company Bayer. This gave high abrasion resistance and water resistance. Additionally the coating provided an ideal base onto which the artwork and logos could be printed. The Fevernova employed an under-glass effect where the printed detail is then covered with a transparent PU layer. Similarly, a syntactic PU foam of equal sized micro-cells filled with a gas are used to create the majority of the panels. The two layers are adhered to one another with glue and are then thermally bonded to the carcass, (Azom.com, 2005). The result of
this new construction was an increased sphericity due to the elimination of stitching causing minimal seams. The thermal-bonding technology enabled a greater automation in production to the manual production method.

Figure 2-5: The composition of the adidas Roteiro

2.2.3 Soccer surfaces
This section will describe the surfaces which a ball is likely to come into contact with. The playing surfaces are first described through their materials and construction. In addition the common materials used for football boots/footwear and goalkeeper gloves are discussed.

2.2.3.1 Pitches

2.2.3.1.1 Natural playing surfaces
Grass has always been the traditional and most popular playing surface for football. In the Laws of the Game document (FIFA 2005); the only reference made to the playing surface type is that it can either be natural or artificial turf. However the only performance measures and standards produced for the playing surface are for artificial pitches which are discussed in the next section. The quality of the natural playing surface is dependent upon the season and other environmental
factors. Surprisingly there is very little recently published research on the playing quality of football pitches. Bell et al (1985) state that: “the playing quality of a sports surface is controlled by the physical properties of both the immediate surface layer and the underlying material.” They continue to say that “on sports turf it is the characteristics of the soil and the sward (grass blades) which govern the mechanical attributes of the playing surface.” Bell and Holmes (1988) concentrated their research primarily on football pitches, surveying 49 pitches and categorising them by their construction in 5 types: sand carpet (12%), sand/soil ameliorated (16%), silt-drained (14%), pipe drained (31%) and no built-in drainage system (27%). For the first 4 categories, up to 4 sub-layers are found: sand rootzone, aggregate backfill, binding layer and the topsoil. Bell and Holmes used the soil property tests and compared these with the player perceptions of the ball behaviour. Mooney and Baker (2000) stated that the playing quality of soccer pitches is influenced by method of construction, changes in pitch conditions (such as sward density and moisture content) and maintenance practices. They also found that the suggested sward height varied from source to source: heights of 18-32 mm and 25-38 mm.

2.2.3.1.2 Artificial playing surfaces

The development of artificial pitches has increased exponentially since their infamous introduction to the English football leagues in the 1980’s at QPR, Luton and Preston. These primitive surfaces produced extreme ball rebound behaviour and high incidents of injuries to players such as abrasion and heavy falls. As a result of these installations, artificial pitches were then abolished for use in the game of football and also affected public and player perceptions alike. There is however, a demand and need for surfaces that simulate the playing qualities of natural grass which have the benefits of lower maintenance demands, consistent ball behaviour and are weather/seasonal independent, (TheFA.com, 2004). This has been addressed by the development of 3rd generation pitches, as they are known, which are based on top of a typical artificial pitch infrastructure: sub-base layers, asphalt layers and the shock pad, Young et al (2003). However the development has taken place on the turf top layer where pile length is now up to 65 mm and supported by a quartz sand and rubber crumb infill, illustrated in Figure 2-6 and Figure 2-7. The acceptance of these pitches led to extensive pilot studies carried out by UEFA
since 2002/2003 at 5 clubs in different countries, including Dunfermline Athletic FC in the Scottish Premier League.

Figure 2-6: The development of artificial pitches (UEFA.com 2004)

THE FIELDTURF SYSTEM

Fibre
Polyethylene fibre is treated with UV inhibitors and is abrasion resistant so that athletes can slide on the fibres without fear of turf burns.

Infill
Similarly sized particles of washed silica sand and rounded cryogenic rubber infill hold each other in suspension, compress and expand to provide stability, long life resiliency and proper energy restitution.

Backing
The backing is made of a combination of permeable woven and non-woven polypropylene fabrics to provide exceptional strength and unmatched vertical drainage.

Figure 2-7: structure of a typical 3rd generation pitch used for football (FieldTurf.com 2007)

As a result of these pilot studies and research two important announcements were made by the International Football Association Board (IFAB) in February 2004 and UEFA in November 2004. The IFAB announced that the Laws of the Game would now include artificial turf as an alternative to grass surfaces as long as it passes FIFA standards as discussed in 2.2.4.2. The idea to accept artificial turf was to allow countries in climatic extremes to have acceptable playing surfaces whereas normally the conditions would mean the grass had little growth, (FIFA.com, 2007).

UEFA confirmed later that year that artificial pitches would be allowed in the UEFA Champions League, UEFA Cup and the qualifying matches for World Cups and European Championships,
Even though the 2003 Under-17 World Championship in Finland was held on artificial turf, well known professional players have criticised playing competitive matches on this new surface. Incidentally, the National stadium in Russia currently has an artificial pitch which has already been used regularly for International and European Champions League matches.

2.2.3.2 Footwear

During the 1890s a pair of strong, stout ankle boots were seen as acceptable footwear for the game of football. These were constructed from hard leather and a toecap reinforced with iron. Similarly with the early footballs, the leather of the boots increased massively in weight in the wet. Studs were present and in the form of either layers of leather or metal. In the mid 1900s a low cut boot was introduced to enable ankle movement. This boot was given the name ‘slipper’ or ‘soccus’. This was possibly another source where the alternative name for football, soccer appeared. Modern day boots are described generically as being “based on a leather construction, generally cut below the ankles with a hard outsole to which studs are attached,” (Lees and Nolan, 1998). Lees and Nolan continue to say that the thinness of the outsole provides the boot with its flexibility but also has areas of increased hardness to mount the stud configuration.

With regard to the contact area, several key developments have occurred to maximise player comfort and feel with the ball. These include asymmetric lacing towards the lateral side of the boot, extended tongues to cover the laces and contact materials to increase grip with the ball. An example of this is the adidas Predator boot series which was conceived initially by ex-Liverpool FC footballer Craig Johnson who experimented by putting table tennis bat rubber onto boots. However the effectiveness of the contact area has never been included in published scientific literature. Several studies have been conducted into the area of ground reaction forces of boots, (Lees and Kewely 1991, Lees and Nolan 1998 and Martínez et al 2004 and Sterzing and Hennig 2005).

Recently there have been two further developments to the football boot. ‘Nomis’ have developed a wet and dry technology for leather which allows superior grip between the boot and the ball.
Craig Johnston who developed the adidas Predator boot has again produced a new boot which claims to improve the grip between boot and ball. In this case the boot has an array of soft rubber spikes on the kicking area of the boot. More recently, the ball-boot contact area has become further developed by brands such as Umbro, Mizuno, Nomis and Kelme. Each has a unique grip increasing component ranging from rubbers, to polymer grills, treated leathers and even applying biomimetics to replicate a shark skin.

2.2.3.3 Goalkeeper gloves

Gloves are now an essential part of the game for a goalkeeper as it is not their technique alone which enables them to catch the ball. The palm of a typical glove consists of latex foam which provides grip properties, some abrasion resistance and padding. The latex when slightly damp provides excellent ball-glove grip. After a thorough searching through the literature, there are no studies investigating the performance of gloves.

Goalkeeper gloves are worn in order to capture and distribute the ball with greater ease in all conditions. The gloves also serve a purpose to protect the hands from traumatic injury. Gloves commonly use a latex layer on the palmar region which acts as a shock damper as well as providing improved ball retention properties. As well as these functional properties of the gloves, they are also needed to be designed to not be too stiff to allow freedom of movement, comfortably fit the hand and provide a wrist strap to keep the glove in place, (Hochmouth, 2003).

The characteristics of latex based goalkeeping gloves are most affected by the pattern from which the dorsal (top of the hand) and palmar regions are cut. Figure 2-8 was taken from a patent which shows the traditional or flat goalkeeper glove design. Two single sections of latex foam make up the palmar (12) and dorsal (11) elements. Extra fabric elements which are not shown are used to connect the two sides of the glove between the fingers to provide room for the hand to fit. A separate flexible fabric is sewn on to provide the dorsal thumb region (15). This design has a relatively flat palmar region and the seam (14) on the palm can decrease ball control and durability respectively. However this design remains popular and is simple and cheap to manufacture. (Staihar et al, 2001)
There are many more popular glove designs, for example the roll finger design has the palmer latex section wrapped around the top of the fingers to give extra grip when throwing the ball. Another common design was known as the Gunn cut glove. Here the palmer section is cut wider for the two outer fingers and wrapped around to meet the dorsal section before being sewn, reducing the seams on the palm region in the areas most critical to ball control (Staihar et al., 2001).

Many glove manufacturers also offer other features such as adidas with their ‘fingersave’ range. The gloves are designed to prevent hyperextension (bending backwards) of the fingers when saving or deflecting a well struck football whilst allowing the fingers to flex forwards to catch the ball. Figure 2-9 shows the reinforcing element, made of a lightweight plastic and inserted into the glove above each finger, (Meuller et al., 2006).
A further example of other technologies being applied to goalkeeper glove design comes from British company Sells. The ‘Contour d3o’ glove includes a ‘rate sensitive microcellular composite’ which translates as a material which exhibits properties of a normal elastomer until an impact occurs whereupon it stiffens within 10 milliseconds (ms) to absorb more impact and protect the hand. The glove features the material across the knuckles to aid punching the ball (Reade, 2006).

The latex foam used to manufacture goalkeeper glove palms is made by first taking a latex concentrate and reducing the ammonia content which was used to preserve the natural latex and stop it coagulating. Various chemicals are then added including vulcanising and foaming agents and antioxidants. At this stage, glove manufacturers may add extra ingredients to produce particular qualities in the foam.

2.2.4 Soccer test methods

2.2.4.1 FIFA ball tests

The most detailed and technical laws, with respect to equipment used in football, relate to the ball itself. The ball is the key element in any game and the standard of it can affect not only the game quality but its result and outcome too. Therefore testing was implemented for any new football was justified. Taken from the FIFA ‘Laws of the Game’ document (FIFA.com, 2007), the ball must be:

- Spherical – derived from the variation of ball diameter measurements,
- Made of leather or other suitable material,
- Of a circumference of between 68 cm to 70 cm (27” to 28”),
- The weight shall lie between 410 g and 450 g before the start of play (14 oz and 16 oz),
- The pressure shall be equal to 0.6 to 1.1 atmospheres (600 to 1100 g/cm3).

What is noticeable about these measurements and qualities is that they leave scope for innovation and development for ball manufacturers. However before a ball can be used in topflight competitions, manufacturers have the possibility to enter into a licensing agreement for the use of
the prestigious 'FIFA Approved' and 'FIFA Inspected' Quality Marks on footballs which have passed a rigorous testing procedure, (FIFA.com, 2007).

The 'Quality Concept' has been established since 1st January 1996 and is part of the Denominations Programme initiated by FIFA in 1995, (FIFA.com, 2007). The idea was to introduce a high quality and consistent football. The laboratory based test procedure is mainly concerned with the static based testing of footballs. A ball submitted for testing can achieve one of two awards depending on the number of tests undertaken. For the 'lower' quality level to gain the 'International Match Ball Standard'/'FIFA Inspected', 6 tests are carried out: ball weight, circumference, sphericity, loss of pressure after 3 days, water absorption and rebound height. To gain the FIFA 'Approved' status the submitted ball type must pass these 6 tests mentioned and at a more stringent level plus an extra test, known as the shape and size retention test. After 2000 cycles through a machine firing the ball at 50 kph (via two counter rotating drums) onto a steel plate the ball is observed at its seams, air valve and circumference for sphericity and pressure loss. According to FIFA statistics, the failure rate of balls decreased between 1996 and 1998, from 75% to 65%. The water absorption test is the most failed with 50% of balls in 1998 not satisfying the criteria, (FIFA Magazine, 1998). In 2007 the overall failure rate was 9% with the ball rebound the most failed test, (EMPA 2007).

2.2.4.2 FIFA artificial turf tests

Just as the footballs have a quality concept, the development of 3rd generation artificial pitches led to the introduction of test criteria and grading for artificial turf in 2001. Initially FIFA and UEFA went their own ways in the research into a quality control test procedure. Consequently there were 2 documents available with conflicting test protocols. However in February 2005, FIFA and UEFA collaborated with their research and published a single quality concept for artificial turf. The aim of these tests is to have a consistently high standard of installed pitches which are safe for the players and the environment whilst simulating the ball behaviour typical of natural turf. Again, as with the ball tests, the pitch manufacturers are able to enter a licensing agreement to show they have achieved a FIFA approved status which is either 1 or 2 stars. To date 15 FIFA Recommended artificial turf manufacturers have installed 75 pitches worldwide,
The Quality Concept covers six areas of tests: the ball/surface interaction, player/surface interaction, effects of artificial weathering, joint strength, water permeability and to correctly classify the turf.

2.2.4.2.1 Ball-surface interaction

This area addresses how the surface affects the ball behaviour through three tests: vertical ball bounce, ball roll and angled ball behaviour. The angled ball behaviour is perhaps the most complex of these interactions as it combines both the vertical and tangential components of an impact. This represents how a player would receive a ball in the game. The vertical ball bounce is similar to the rebound test for the ball quality concept. However a FIFA Approved ball is used to assess the vertical bounce height of the surface, (FIFA 2005 and BS 7044-2.1:1989). A ball release system is required which operates smoothly, without imparting any impulse to the FIFA 'Approved' ball. This is set at a height of 2 m between the bottom of the ball and the top of the surface. Methods to measure the rebound height in use are acoustic timing, infrared timing gates and from a video camera and scale, (Figure 2-10). The value stated is the coefficient of restitution (COR), a ratio between the two heights and is explained further in section 2.3.

Figure 2-10: The vertical ball rebound test (acoustic method), FIFA (2005)

The ball roll gives a deceleration value or the total distance rolled across the turf. The ball is released from a ramp at a certain height and angle, with the ball passing through a set of light
gates a set distance apart, to get a velocity change and a distance calculated (shown in Figure 2-11), (BS 7044-2.1:1989). This test indicates rolling friction between the ball and the surface.

The angled ball behaviour is perhaps the first true dynamic test that FIFA have developed. Also it is one of the most important features of a game for any player as the ball nearly always bounces at an angle to the playing surface and is a combination of the previous two tests (ball bounce and roll). The test is more commonly known as football ‘surface pace’. The need to attempt to quantify this measure led to an adaptation of a test originally developed for tennis surfaces by Dunlop (2000) where a radar was used to measure the ball pace after a bounce. Since tennis is played on several surfaces (e.g. grass, clay, synthetics), the differences in bounces can be extremely noticeable, especially on the first bounce after the serve, (Figure 2-12). A compressed air cannon is used to launch an ‘Approved’ football at 50 ± 5 kph at 15 ± 2° to the horizontal with no initial spin. The value used to assess the angled ball behaviour is:

\[ \text{Angle ball rebound} = 100 \times \left( \frac{S2}{S1} \right) \]  

[Equation 2-1]

Where \( S1 \) is the horizontal velocity before rebound and \( S2 \) is the velocity after in kph.

![Figure 2-11: The ball roll test launch apparatus, FIFA (2005)](image-url)
2.2.4.2.2 Other related tests

Other tests of interest include elements of the player/surface tests and identification tests. Shock absorption, vertical deformation, linear friction of studs and skin/surface friction are found in the player/surface tests. The compressive modulus of the identification tests gives the mechanical properties of the shock-pad sub-layer which relates also to the shock absorption and vertical deformation tests which use an artificial athlete to quantify the energy characteristics of the artificial turf. The linear friction of studs utilises a stud configuration on the end of a pendulum. Skin friction is found using a ‘Securisport® sport surface tester’ where a test foot covered in silicon, an imitation of skin, is rotated across the surface to enable a coefficient of friction value to be found.

2.2.5 Biomechanics

Extensive research has been carried out into the biomechanics of kicking and heading a ball. Understanding the player/ball interaction is an important part of this project especially the foot/ball collision.
2.2.5.1 Kicking

There are three main areas which have been studied; the approach, the kinematics and the kinetics of the kicking action.

2.2.5.1.1 The approach

For a maximal kick a player instead of a straight 'run up' will angle their approach. Isokawa and Lees (1988) investigated varying the angle of approach and its effect on leg and ball velocities. No significant differences in ball velocity were found between the approach angles (0, 15, 30, 45, 60 and 90°) of six male footballers. However, the trend of data suggests an optimum angle of 30-45° as the fastest leg velocity occurred at 30° and the maximal ball velocity at 45°. The angled approach enables the kicker to tilt the kicking leg in the frontal plane allowing a plantar flexed foot to strike further underneath a stationary ball, (Lees and Nolan, 1998). Another interesting factor is the length of the approach. Opavsky (1988) found that using a 5 to 6 stride approach rather than being stationary behind the ball resulted in 31% faster ball velocities for a maximal instep kick (up to 30.8 m/s)

2.2.5.1.2 Kinematics

Kinematics is the study of body motion and in this context is an extremely complex movement. During the kicking motion, the foot rotates about both the medial-lateral (frontal) and longitudinal axes of the body, (Lees and Nolan, 1998). As the motion is through two axes it would indicate the need for 3-dimensional analysis but the majority of the studies have concentrated on the motion in the posterior/anterior plane. Studies on 3-D analysis include Nunome et al (1999 & 2002) and Rodana and Tavana (1991). Lees and Nolan (1998) in a summary of the literature in this area concludes that 20-30 m/s maximal ball velocity for an instep kick is widely agreed (Asai et al 2002, Ireson 2001, Asami and Nolte 1983, Rodana and Tavana 1991, Nunome et al 2002 and Luhtanen 1994). In a more recent study, Nielson (2003) recorded ball velocities of up to 35 m/s for a maximal instep kick from players belonging to 5 professional English clubs.
Ireson (2001) describes a simple collision equation to show the velocity of the ball is dependent on the foot velocity:

\[ V_{ball} = V_{foot} \left( \frac{M(1 + e)}{M + m} \right) \]  

[Equation 2-2]

Where \( V_{ball} \) and \( V_{foot} \) are the ball and foot velocities respectively, \( M \) is the mass of the leg, \( m \) is the mass of the ball and \( e \) is the COR. Ireson states that approximate values of the masses and COR gives an equation (2-3) that illustrates a ball to foot velocity ratio greater than unity, Lees and Nolan (1998),

\[ V_{ball} = ( > 1) \times V_{foot} \]  

[Equation 2-3]

The range of ratios seen in research varies from 1.06 (Asami and Nolte, 1983) to 1.29 (Plagenhoef 1971). However, Lees and Nolan (1998) state that the ratio is dependent on two factors: the type of kick executed and the analysis method. The analysis method is the way foot velocity is calculated indicating that the velocity at the toes is greater than the velocity at the ankle, which is in turn greater than at the knee and hip, (Figure 2-13). The graph shows the hip is relatively stationary compared to the accelerations of the knee and lower extremities.

![Figure 2-13: An example of the linear velocities of the leg for a maximal instep kick, (Lees and Nolan, 1998)](image)
Barfield (2002) conducted a study to investigate the differences between male and female football players. As expected the males displayed "greater kinematic variables" than females including faster ball velocities and toe/ankle velocities. Additionally studies have been conducted into the differences between kicking with the preferred and non-preferred leg (Dörge et al 2004) and kicking abilities of children (Gámez et al 2004).

2.2.5.1.3 Kinetics

The kinematics as described in section 2.2.5.1.2 can be used to calculate the net joint forces and net muscle moments of the kicking motion. Additionally another important kinetic aspect is the force transferred from the foot to the ball. The kinetics of the kick is much less researched in comparison to the kinematics, probably due to the fact that the values are calculated estimates from the kinematic data. The only stated way to validate the data is to use an isokinetic muscle function dynamotor. Lees and Nolan (1998) summarised the literature in this field and found values ranging between 103-126 Nm and 95-147 Nm for the knee extension and hip flexions respectively. Differences again are down to the experimental procedure and kick type performed. Tsaousidis and Zatsiorsky (1994 & 1996) have contributed a great deal to the understanding of the collision phase of the ball and the foot. They have determined 3 sub-phases of the ball-foot interaction: the initial compression of the ball (but no ball movement on the whole), ball compression with initial ball movement and finally the decompression of the ball. A typical contact time between the foot and the ball for a maximal instep kick is 16 ms (Tsaousidis and Zatsiorsky, 1996). Tsaousidis and Zatsiorsky also state that more than 50% of the ball's velocity and at least 30% of its kinetic energy is imparted to the ball without any contribution of the potential energy of the ball deformation.

Asami and Nolte (1983) found forces acting on the ball from the foot on average to be 1100 N and contact times of 12 ms. Asai et al (2002) through finite element analysis of a simple ball and foot models estimated forces for the instep kick and in-front curve kick. Peak values of the horizontal, vertical and lateral forces reached 2439 N, 853 N and 452 N respectively. For the curve kick, horizontal and vertical forces were slightly less (2206 N and 1221 N respectively), however lateral forces were over twice as much (1143 N). This is due to the ball impacting the
medial side of the foot. Lees and Nolan state that the in-front curve kick could produce a higher ball to foot velocity ratio as the larger bones would provide a better surface for impact.

2.2.5.2 Heading

The majority of reported investigations into the biomechanics of heading have been focussed on establishing whether repetitive impacts to the head from a ball would cause long term (or even short term) brain damage. Kirkendall et al (2001) describe the mechanics of heading as using precise timing of the hips, trunk, neck and arms. The hips are flexed to bring the trunk and head toward the ball with the arms drawn backwards and the neck flexors and extensors fix the position of the head on impact with the ball. Kirkendall et al also state that failure to isometrically contract the neck muscles (sternocleidomastoid and trapezius) leads to undesirable linear head accelerations backwards upon impact. When children are taught the skill of heading, they are told to hit the ball rather than letting the ball hit them. Bauer et al (2001) discovered that heading of the ball relates to 4-22% of all injuries and state that the accelerations rather than the peak force of impact that cause the injury. However Gámez et al (2004) have found that an increase of 20% of inflation pressure of the ball increases the magnitude of the impact by 30% for children. Levendusky et al (1988) stated that brain damage can occur from 2 sources:

- Direct impact leading to excessive linear acceleration of the brain, which causes compression waves and high internal pressures,
- A glancing impact leading to rotational accelerations of the brain, which cause shearing between the brain and the skull.

For direct impacts, Lees and Nolan (1998) have discovered a tolerance of around 80 g is thought to lead to loss of consciousness and rotational accelerations of 5500 to 7500 rads\(^2\). Burslem and Lees (1988) used a twin accelerometry system to investigate heading and found direct impacts to be 15 g and rotational accelerations to be 200 rad.s\(^{-2}\), thus well below the limits stated. A range of 15-25 g for direct impacts and 200-366 rad.s\(^{-2}\) for rotational accelerations was found by Lees and Nolan (1998). Levendusky et al (1988), when using a force plate to measure impact forces,
found peak forces of 851 and 912 N for two types of ball construction, moulded and stitched respectively.

2.2.6 Aerodynamics

Although this project is not directly concerned with the flight of the ball, the aerodynamics is still important. The ball manufacturers often use various seam and panel configurations and vary the ball’s surface texture in an attempt to create more stable flight characteristics for the ball. However these features are just as likely to influence the impact conditions as they do to the flight of the ball.

Spampinato et al (2004) created a device to test a spinning football in an air tunnel to assess its aerodynamics. They also described the basic physics of football aerodynamics. When a ball travels through the air after being kicked for example, the air flow splits at the front of the ball to go round it. As the air goes around the ball, the air pressure decreases due to the acceleration of the air flow. However as this air flow travels around the pressure begins to increase again and eventually separates from the ball creating a ‘wake’ of very low pressure. This ‘wake’ is what slows down the ball in flight, (Figure 2-14).

Another important feature is the boundary layer. This is a layer of air very close around the surface of the ball. At the front of the ball before the separation point as seen in Figure 2-14, the boundary layer is considered to be laminar. After the separating point the increase in pressure,
increases the thickness of the boundary layer and the flow is now considered to be turbulent. The separation point is often known as the ‘transition’. A Reynolds number can be calculated to determine at which velocity ranges the ball is in laminar, turbulent or transitionary flow regimes:

\[ R_e = \frac{U_\infty D}{v} \quad \text{[Equation 2-4]} \]

Where \( R_e \), is the Reynolds number, \( U_\infty \) is the free stream velocity, \( D \) is the ball diameter, and \( v \) is the kinematic viscosity. Asai et al (2006) determined through wind tunnel tests that the critical \( R_e \) (transition of laminar to turbulent flow) of a soccer ball is about \( 2.2 \times 10^5 \). Spampinato et al (2004) continue to say that since a football has seams and a certain level of surface roughness, this causes an increase in the shear stress in the boundary layer. Deeper seams cause the air flow to trip causing increased turbulence. This turbulence draws energy from the free stream flow and causes the air to flow further around the ball by as much as 50% more. This is why golf balls have dimples on the surface to increase the ball flight. A drag coefficient, \( C_d \) is used to determine the force of drag, \( F_d \), equation (2-5):

\[ F_d = \frac{1}{2} C_d \rho A v^2 \quad \text{[Equation 2-5]} \]

Where \( \rho \), is the density of air and \( A \), is the cross-sectional area of the ball. With the force of the drag calculated this can be plotted as a function of ball velocity. Figure 2-15, from Ireson (2001) shows that the drag force peaks at 20 \( \text{ms}^{-1} \) ball velocity. It is interesting to see that at the maximal ball velocity a player is capable of, the drag decreases dramatically. This is due to the \( C_d \) varying with the velocity of the ball.

![Figure 2-15: Graph illustration the drag force of a football for a range of velocities (Ireson 2001)](image-url)
For a spinning soccer ball, there are additional forces that act on the trajectory of the flight. A deflecting force arises due the spin of a moving ball which can be associated with the Magnus effect, Bray and Kerwin (2003). For a non spinning ball, the wake is typically symmetrical about its line of flight. Here the separation points, as shown in Figure 2-14, are in equivalent points around the balls surface. For a spinning ball the separation points can be in different positions. The separation point occurs earlier on the side of the ball with the air flow moving in the same direction as the relative motion of the spin. However, on the side against the spin it occurs later. This produces non-symmetrical wake and therefore a resultant force normal to the plane containing the velocity vector and the spin axis of the ball (Bray and Kerwin, 2003 and Carré et al., 2005).

The magnitude of the Magnus force has been estimated to be 3.93 N for a typical free kick with a ball velocity of 25-30 m.s\(^{-1}\) and ball spin of 8-10 rev.s\(^{-1}\) (Asai et al 1996) and which equates to a lateral ball movement of approximately 4 m over 30 m. Nielson (2003) found that professional players can impart 14 rev/s to ball for a free kick thus increasing the possibility of more swerve in flight. Therefore the interaction of the ball and foot is important as the ability to impart more spin through either technique or ball surface modifications could increase ball movement.

Barber and Carré (2006) investigated the effects of surface geometry on sports balls. Using a smooth and dimpled hockey ball as a case study it was found that the shapes, sizes and spacing of dimples on the balls surface caused changes to the critical \(R_e\) and \(C_d\). Carré et al (2005) conducted a study in to the effect of soccer ball seams on the aerodynamics. It was found that the presence of seams encouraged turbulent flow resulting in lower \(C_d\) and more predictable Magnus force behaviour as compared to a totally smooth ball.
2.3 Friction

2.3.1 Basic theory

Friction is the resistance to motion during sliding or rolling that is experienced when one solid body moves tangentially over another with which it is in contact, Bhushan (2002). Bhushan also goes onto describe the two main theories of friction: dry friction and fluid friction. Dry friction, also called Coulomb friction, describes the tangential component of the contact forces when two bodies tend to or move over one another in a dry environment. Fluid friction applies when the two bodies are in a fluid or a fluid is in between the contact. Additionally there is a third theory: rolling friction which applies when a body tends to roll on a solid surface. The normal force to contact is otherwise known as the normal reaction ($R$). The coefficient of friction ($\mu$, COF) is the ratio of the forces resisting tangential motion between two bodies to the normal force pressing those bodies together, Blau, (1996). The COF is a useful value to compare the interaction of different pairs of materials.

The COF can also be split into two categories depending on the motion of the two bodies. The static COF ($\mu_s$) is the instance at which motion between the two bodies begins as it overcomes static frictional force, $F_s$. Therefore if $R$ is fixed, it is the peak value at which $F$ has to increase to initiate sliding. Once sliding between the bodies is created, the force required to maintain sliding is the kinetic frictional force, $F_k$. Therefore the COF for this magnitude of force is $\mu_k$. Below, equations (2-6) and (2-7) describe these relationships:

$$
\mu_s = \frac{F_s}{N} \quad \text{[Equation 2-6]}
$$

$$
\mu_k = \frac{F_k}{N} \quad \text{[Equation 2-7]}
$$

The COF can illustrate the interaction between two contacting bodies but it is important to keep in mind that the COF is not material property but is a property of a system in which the materials operate, Plint (2005b). Other authors have their own thoughts on the standing of the COF. Blau
(1996) iterates the importance that the equations (2-6 and 2-7) are not laws or models of friction but simply define a proportionality or quotient between the two force components of contact. Bhushan (2002) describes friction as not a material property but a system response. However Savkoor (1977) states that friction can be regarded as a characteristic property of a material and its surface. Moore (1975) has summarised the 4 assumptions of friction as devised by Da Vinci, Amontons and Coulomb:

- Friction force is proportional to load
- COF is independent of apparent or nominal contact area
- COF, is greater than COF,
- COF is independent of sliding speed.

However many authors (Bhushan 2002, Halling 1976, Hondros 1971 and Moore 1975) state cases where these initial friction 'laws' do not hold true in most interactions and identify polymeric friction as an example.

2.3.2 Deformable material friction

2.3.2.1 Theory

The basic friction theory is typically applied to solid and rigid objects. However a football deforms upon impact thus soft material friction needs to be considered. Deformable friction is much more sensitive to normal forces/pressures and sliding velocities in particular. However the basic theory of solid friction is simply extended to accommodate the nature of a deforming object over a solid body. The tangential or frictional force \( F \), is split into two components: deformation (or hysteresis), \( F_{HYST} \), and adhesion, \( F_{ADH} \) (Moore 1975 and Bhushan 2002):

\[
F = F_{ADH} + F_{HYST}
\]  

[Equation 2-8]

The component that has the most effect on the overall friction is dependent upon the polymer and other contacting material. Bikerman (1974) suggests that the work done during the deformation of the material during the tangential motion is the main component of frictional work in polymer
Moore (1975) describes the contact between an elastomer and a rough solid as the 'soft' elastomer draping over the asperities of the solid body. The adhesion term is concerned with the relative surface condition whereas the deformation term involves the bulk mechanical and material properties. For a football impact, the deformation component is likely to be the major factor of the frictional interaction especially if the other body is deformable as well like a foot. Bowden and Tabor (1974) state that if the major component of friction is deformation then the maximum energy dissipation will occur just below the surface where the maximum shear stresses occur. Therefore the structure of an outer panel of a football may play a role in the frictional interaction as well as the surface condition. Bowden and Tabor (1974) illustrate the energy loss process of friction in a polymer in Figure 2-16, where a cylindrical solid body ploughs across the top of the polymer causing an elastic input and recovery.

Briscoe and Sinha (1999) state that when a solid body has no adhesion component, the work is done at the front edge of the interaction and energy is returned to the rear edge. Therefore as the solid body slides across the deformable surface, it is putting in energy to deform the surface and then any energy recovered through hysteresis is released back to the solid body. Apart from hysteresis, Bowden and Tabor (1974) found that energy return is related to the temperature at the contact, the contact pressure and rate of deformation. Moore (1975) then relates these two components to the viscoelastic properties of the polymer, for example, rubber. If equation 2-8 is divided by \( R \) throughout then COF for the whole contact is a sum of the adhesion and hysteresis coefficients, \( \mu_{ADH} \) and \( \mu_{HYST} \).
\[ \mu = \mu_{\text{adh}} + \mu_{\text{hyst}} \]  

[Equation 2-9]

Then (equation 2-9) can show the \( \mu_{\text{hyst}} \) depends on the viscoelastic properties (equation 2-10), (Bhushan 2002), where \( \tan \delta \) is the tangent modulus of the polymer, \( p \) is the contact pressure in the normal direction, \( E' \) is the secant modulus, and \( k_h \) is a constant dependent on the shape of the asperity and contact length. \( E' \) and \( \tan \delta \) should be measured at the frequency of deformation.

\[ \mu_{\text{hyst}} = k \left( \frac{p}{E'} \right) \tan \delta \]  

[Equation 2-10]

The friction of rubber has been studied in great detail over a long period and the relation to the viscoelastic properties of the polymer, (Savkoor 1965, 1974 and 1977) and (Grosch 1962). The phenomenon of rubber friction is of great interest due to the many factors that can effect the contact interaction. These include temperature, area of contact, normal pressure, normal load and sliding velocity (Savkoor 1965, 1974 and 1977, Bikerman 1974, Throne 2005, Braghin 2002 and Grosch 1962). Figure 2-17 shows three graphs for the material PTFE (polytetrafluoroethylene) for different operating conditions on steel. As seen, the graphs clearly show that polymer friction is very susceptible to the environment it is in. Rubber friction has been widely researched due to its application in automobile road tyres where knowledge of grip is of great importance.

![Graphs showing the dependency of COF on operating conditions for PTFE](image)

Figure 2-17: Shows the dependency of the COF on the operating conditions for PTFE (Bhushan 2002)
The deformable nature of a polymer will mean that with greater normal load over the same contact area, the pressure of contact will increase. Therefore if a rubber is pressed against a rough rigid surface, the softer rubber will form around the asperities of the other surface. For metal on metal contact the area of contact is likely to be much less than a polymer on polymer contact. There are two definitions used: nominal and true area of contact (Figure 2-18).

Figure 2-18: The definition of nominal and true areas of contact, (www.engin.brown.edu)

Figure 2-19 illustrates the effect of increasing the normal load from an example taken from InsideRacingTechnology.com where the theory of rubber tyres interacting with the road surface is of great importance for automobile sports. The similarity between the friction of wheels rolling on roads and ball rolling/sliding on a surface is discussed in 2.3.2.3.

Figure 2-19: The effect on friction hysteresis as a function of normal load, (www.InsideRacingTechnology.com)

2.3.2.2 Stick-slip

The ‘stick-slip’ phenomenon is often seen when a body slides over another due to a constant tangential force and causes fluctuations in velocity. “If the friction force or sliding velocity does not remain constant as a function of distance or time and produces a form of oscillation” stick-slip occurs, (Bhushan 2002). Figure 2-20 shows the nature of the slip-stick mechanism.
Bowden and Leben discovered the phenomenon in 1939 and it is commonly used to describe the motion seen in Figure 2-20. For stick-slip to appear, $\mu_s$ has to be significantly greater than $\mu_k$. This means that when the pulling force reaches $\mu_s$, the body starts to move and $\mu_k$ is required to maintain the motion. However the transition between the two COFs is not smooth and causes a stop-start-stop-start motion between sticking and sliding. Bhushan (2002) has found that stick-slip is the source of some oscillations and thus vibrations in contact situations which are often audible. For example an ‘audible squeal’ ($\approx 0.6-2$ kHz) and chatter ($<0.6$ kHz) are common in many sliding systems. Stick-slip as a result of friction can be both a negative aspect and positive. For example, Bhushan states that stick-slip is the cause of the noise produced by earthquakes, the squeaking of windscreen wipers on windows and jerking of car brakes. However stick-slip is needed to produce the noise from stringed musical instruments.

2.3.2.3 Automobile tyres

The way a sports ball rolls and slides upon impact with a flat surface has some similarities with the frictional properties of a car tyre on a road surface. Moore (1975) has extensively discussed the theories of the interaction of a deformable rubber tyre on a solid surface. For a dry impact and therefore dry friction, the components of polymer friction: adhesion and hysteresis, determine the friction. Again the two components can be associated with two types of tyre behaviour. The rolling tyre (i.e. non slip) is due to “the adhesional forces created by macro and micro-slip in the contact area”, (Moore 1975). When a tyre is braked sufficiently to lock the wheels causing the tyre to slide, the hysteresis friction is accountable for the majority of the
frictional mechanism, Moore (1975). Additionally, the tread pattern of the tyre has less of an
effect on the frictional mechanism than the texture and structure of the road. Figure 2-21, shows
the effects of increasing the sliding velocity on the hysteresis of the rubber.

![Figure 2-21: Diagram illustrating the effects of increasing sliding velocity on the rubber/asperity interaction on hysteresis (adapted from Moore 1975)](image)

From Figure 2-21, it is seen that as velocity increases the hysteresis increases until a certain point
where it then decreases. Figure 2-22 combines both the adhesional and hysteresis components of
friction on one graph for increasing sliding velocity.
Figure 2-22: The viscoelastic nature of adhesion and hysteresis (adapted from Moore 1975)

Here it is seen that as velocity, \( v \), or the deformation frequency, \( w \), increases the COF (\( F \), as stated in this example) peaks for adhesion at low frequencies and hysteresis at high frequencies. Again if the operating temperature, \( T \), is increased, \( T+\delta T \), the peaks are shifted towards higher frequencies. If the tyre is stiffened at the surface there is less chance of the rubber ‘draping’ over the asperities of the solid body thus decreasing the effects of the viscoelasticity on friction. Another important condition is that of fluid friction, i.e. a layer of water on the road. This means the kinetic energy through sliding can not be dissipated through the adhesional component and the hysteretic friction increases significantly.

Automobile tread design has been widely researched since the early 1950s when drivers complained of the car “lightening off” in wet road conditions when driving at high speeds with smooth tyres. Typically to obtain maximum grip on a clean dry road a completely smooth tyre would be required to give the greatest possible area of contact in terms of nominal and true areas. (Setright, 1972). However, the tyre manufacturer Dunlop became one of the main frontrunners in the development of tread pattern designs to eliminate the problem now known today as aquaplaning. Dunlop designed a ribbed pattern with high concentrations of knifeslots (known as the WH2) as shown in Figure 2-23(a). By the late 1950s the interest by car and tyre manufacturers in providing high grip tyres was widespread all over the world. At the beginning of the 1960s Dunlop released a new tyre (named the “Elite”), as shown in Figure 2-23(b). This
tyre was designed to increase safety for general road cars. Dunlop claimed that it gave 45% more resistance to wheel spin, 24% better wet hold in cornering and 15% more braking grip. However the one drawback was that the new treaded design increased fuel consumption by 2%, (Tompkins, 1981).

As increased research was carried out into wet grip, the phenomenon of aquaplaning or hydroplaning became better understood. It is now known that hydroplaning occurs when a tyre encounters more water than it can dissipate. Water pressure in front of the wheel forces a wedge of water under the leading edge of the tyre, causing it to lift from the road. The tyre then glides on a sheet of water with little, if any, direct road contact, and loss of control results. Figure 2-24 shows how and why aquaplaning occurs at high speeds. The process can be split into three stages. In the first stage where the tyre is rolling at a slow speed, the tyre sinks into the water achieving full contact with the road. The second stage is when the speed of the tyre increases and creates a water wedge in front of the tyre which reduces the road contact. The third stage, at high speeds, is when the time for water dispersion or clearance is too short and the water wedge extends the full length of the tyre contact patch and becomes waterborne. Resistance to motion becomes negligible, Tompkins (1981).
Figure 2-24: The process of aquaplaning (or hydroplaning), (Tompkins 1981)

Figure 2-25: The zones of aquaplaning, (Moore 1975)

Figure 2-26: Hydrodynamic pressure between the tyre and road, (Moore 1975)
Figure 2-25 shows the zones of aquaplaning during the second stage as described by Tompkins (1981). Moore (1975) explains the 'squeeze film zone' as where the water wedge creates an upward thrust driving the tyre front away from the road. The second zone, named the 'draping zone' is where the tyre-road contact is minimal and the tyre rubber just catches the asperities of the road. The final zone is where the tyre makes full contact with road resulting in traction. Figure 2-26 shows the build of hydrodynamic pressures between the asperities of the road when the tyre is draping over the tips. It can be seen that the rise in pressure coincides with the increase in gradient (or uphill) part of the asperity. This increase in pressure is likely to force the tyre upwards if sufficiently large.

Test methods were further developed to assess various loading and speed conditions on new tyre tread patterns. A common approach was to drive a vehicle in wet conditions over a glass plate where a photograph would be taken to show the dispersion of the water. To make the water more visible, fluorescein was added to illuminate the water when photographed with a flash (Tompkins 1981). Examples of this technique can be seen in Figure 2-27.

Figure 2-27: The photos show the car driving over the water and glass plate (left) and the resultant photo from beneath during contact (right), (Tompkins 1981)

Another approach was to mount a single wheel and tyre on free spinning axle and then load it onto a large drum which is driven at high speeds (Figure 2-28). When dry the tyre spins at the same speed as the drum. However in simulated extreme wet road conditions, an operator can
freely spin the wheel independently of the drum motion. As a consequence of the general research in this area, the UK government introduced The Motor Vehicles (Construction and Use) regulations in 1968. These included specifications on tyre tread depths, sustainability, inflation pressure and a requirement for the tyre to be free from damage. The tread depth regulation was set at 1 mm due to testing carried out by Dunlop on worn tyres in wet conditions. The results can be seen in Figure 2-29.

![Figure 2-28: The drum and tyre test set up to simulate the aquaplaning problem, (Tompkins 1981)](image)

![Figure 2-29: Graph showing the initial Dunlop tread wear test on wet roads, (Tompkins 1981)](image)

The nature of tread design is nowadays a highly confidential operation to allow companies to gain an advantage over one another by designing a tyre that allows optimum grip between wet
and dry roads. A heavily treaded tyre will have good wet characteristics but will increase fuel consumption, road noise and minimise tyre-road contact areas on dry roads.

The Yokohama tyre company have produced a guide to how different areas of tread are designed to improve certain aspects of tyres, (Yokohama 2007). Yokohama states that an optimum tread design will improve traction, handling and durability but also take into consideration noise levels, ride comfort and fuel efficiency. Figure 2-30 illustrates these areas.

The majority of the tyre is taken up by the blocks which are determined by the grooving. The blocks provide the main contact areas during traction. The sipes are slits cut into the side of the tyre allowing the blocks to move slightly to provide extra traction. Ribs provide a continuous circumferential contact band during rolling and dimples provide extra cooling as the tyre heats up in dry conditions. The shoulder of the tyre is curved to allow a better contact when cornering. Grooving provides the majority of the water channelling, with circumferential patterns providing the shortest channelling route when travelling in a straight line. Lateral grooves provide a better way of channelling water when cornering at high speeds. The void ratio is determined by the height of the tread (i.e. how worn it is). The larger the void ratio the better the channelling or dispersion of water is during wet conditions. There are three main areas of tread patterns which
are determined by the orientation of the grooving. Asymmetric tread patterns differ across the tyre profile where larger blocks are used on the outer for grip and smaller blocks on the inside for water dispersion. A unidirectional pattern means that the tyre will only provide traction in one direction as the grooves are directed out and towards the rear of the contact area. A symmetric pattern tyre will provide the same traction going forwards or backwards, i.e. the pattern favours either direction.

2.3.3 Surface roughness

Surface roughness is considered to be the principle factor in the causes and magnitude of friction, (Moore 1975, Halling 1976 and Bhushan 2002). Surface roughness, $R_a$ is the international parameter for roughness and is described in BS 1134-1:1988. $R_a$ is the arithmetic mean of the absolute departures of the roughness profile from the mean line of a scanned surface.

Figure 2-31 depicts a 3D image of a scanned sample, illustrating the waviness and roughness parameters. The $R_a$ is taken from this sample by taking a 2D profile. Figure 2-32 shows an example of this and illustrates the parameters taken from this profile to calculate $R_a$. 

![Figure 2-31](image.png)

Figure 2-31: A diagram showing the waviness and roughness parameters of a scanned sample, (BS 1134-1 1988)
In Figure 2-32, \( l \) is the sample length, \( y \) is the profile departure and \( n \) is the number of profile departures. From this \( R_a \) is calculated by (equation 2-12):

\[
R_a = \frac{1}{l} \int_0^l y(x) \, dx
\]  

[Equation 2-11]

The roughness value calculated gives an indication of magnitude of the peaks and valleys that are away from the mean line through the profile. Higher \( R_a \) values will indicate that there are high peaks and steep valleys over the sample and therefore a rougher surface.

2.4 Ball-surface impacts

The angle of incidence of a ball impacting against a surface can be either normal or oblique. A simple example of a normal impact is when a ball is dropped vertically onto a floor as in the case of the FIFA drop test. An oblique impact is perhaps much more common in game situations. It has both horizontal and vertical inbound velocity components and therefore the rebound of the ball is dependent on the resistance to motion in both directions. This section describes the two impact types through existing sports ball impact experiments. Firstly the coefficient of restitution is defined. Since the research of ball-surface impacts is varied over a wide range of approaches to analysis, only the most relevant to this project are stated.
2.4.1 Coefficient of Restitution

When a ball impacts a surface, the elasticity of the two can determine the rebound of a ball. Elasticity is “the property of a body to return to its original shape once it has been deformed”, as defined by Hay (1993). Some energy is lost in the deforming bodies whether it is just the ball or a combination of the surface and ball. Elasticity is also used to define a collision i.e. one where all kinetic energy is returned. The energy lost through deformation is called hysteresis, (Daish, 1972). Newton’s Law of Impact describes COR (or ‘e’) through a relationship between velocities before and after the impact to give an approximation. It is based upon a ratio of velocities of separation and approach of two impacting bodies, (Daish 1972):

\[
\text{COR or } e = \frac{\text{velocity of separation}}{\text{velocity of approach}} = \frac{V' - V'}{V - v}
\]  [Equation 2-12]

Therefore in a perfectly elastic collision, the impacting bodies will rebound with the same inbound velocities, resulting in no energy loss and COR = 1. If the impacting bodies contact and do not separate then this will be totally inelastic and thus COR = 0. In most cases, COR will lie somewhere in between 0 and 1. (Equation 2-13) can then be derived so that e is a function of distances through considering the ball’s motion before and after impact with a surface. This uses the laws and equations of constant acceleration of motion. This gives COR as a function of initial height and rebound height if dropped:

\[
\text{COR} = \sqrt{\frac{\text{rebound height}}{\text{initial height}}} = \sqrt{\frac{h_r}{h_i}}
\]  [Equation 2-13]

Hay (1993) conducted a simple experiment to illustrate how different balls and surfaces affect COR. Figure 2-34 shows the COR values for a range of sports balls bouncing onto a hardwood floor from 1.83 m. Figure 2-34 shows how changing a surface for a volleyball affects it’s COR.
<table>
<thead>
<tr>
<th>Type of Ball</th>
<th>Height Bounced (m)</th>
<th>COR</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Super ball&quot;</td>
<td>1.44</td>
<td>0.89</td>
</tr>
<tr>
<td>Basketball</td>
<td>1.06</td>
<td>0.75</td>
</tr>
<tr>
<td>Soccer</td>
<td>1.05</td>
<td>0.76</td>
</tr>
<tr>
<td>Volleyball</td>
<td>1.01</td>
<td>0.74</td>
</tr>
<tr>
<td>Tennis - well worn</td>
<td>0.91</td>
<td>0.71</td>
</tr>
<tr>
<td>Tennis - new</td>
<td>0.81</td>
<td>0.67</td>
</tr>
<tr>
<td>Lacrosse</td>
<td>0.7</td>
<td>0.62</td>
</tr>
<tr>
<td>Field hockey</td>
<td>0.46</td>
<td>0.5</td>
</tr>
<tr>
<td>Softball</td>
<td>0.18</td>
<td>0.31</td>
</tr>
<tr>
<td>Cricket</td>
<td>0.18</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 2-33: The COR of a selection of sports balls, Hay (1993)

<table>
<thead>
<tr>
<th>Type of surface</th>
<th>Height Bounced (m)</th>
<th>COR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proturf</td>
<td>1.05</td>
<td>0.76</td>
</tr>
<tr>
<td>Wood</td>
<td>1.03</td>
<td>0.75</td>
</tr>
<tr>
<td>Uniturf</td>
<td>1.03</td>
<td>0.75</td>
</tr>
<tr>
<td>Steel plating</td>
<td>1.02</td>
<td>0.75</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.00</td>
<td>0.74</td>
</tr>
<tr>
<td>Tumbling mat</td>
<td>0.83</td>
<td>0.67</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.67</td>
<td>0.61</td>
</tr>
<tr>
<td>Grass</td>
<td>0.34</td>
<td>0.43</td>
</tr>
<tr>
<td>Gymnastics mat</td>
<td>0.33</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Figure 2-34: The COR for a volleyball on a selection of surfaces, Hay (1993)

As stated in 2.2.4.1, the FIFA Quality Concept for balls assesses the ball’s COR. For a FIFA approved ball the COR value must lie between 0.675 and 0.775 (which equates to a rebound height of 1.35 m and 1.55 m respectively) when dropped from a height of 2 m onto a steel plate. For the artificial turf tests, a FIFA Approved football must have a COR between 0.325 and 0.425 (0.65 m and 0.85 m) for the turf to gain the FIFA 2* rating.

2.4.2 Normal impacts

Perfectly normal impacts are very rare within a game situation for most ball sports. Most impacts of a ball and surface involve a second component of motion. The normal impact of a ball onto a rigid surface doesn’t occur throughout a typical football match. However such a situation provides an effective means of validating both computational and numerical models of impact, (Price, 2005).
Research into normal ball impacts can be split into various categories: purely experimental and a combination of theoretical modelling and validation using experimental data. The impact of a football until now has been researched mainly using simple experimentation. The development of a complex finite element model at Loughborough University is one of the exceptions.

The Sports Turf Research Institute (STRI) in the UK has carried out many studies into the rebound and playing performance of a football on playing surfaces. Gabrielson (2004) investigated the relationship between the actual roll distance and the calculated roll distance through velocity change for the ball roll test. He found an uncertainty in the correlation between the two methods but stated that the velocity change method does not take into account environmental factors such as the wind.

Holmes and Bell (1985) conducted an experiment on the effect of ball inflation pressures (0.6 to 1.1 bar) on the vertical ball rebound for 17 different FIFA Approved footballs. Balls were dropped onto concrete and natural turf (from 3.0 m) and found that in both cases the ball type was of a greater influence on the rebound height than the inflation pressure. However since this is an old study the test would need to be repeated with modern day footballs to account for developments in design, materials and construction. To illustrate this point the measured COR on concrete in the study at the correct inflation pressure would have meant that only 1 of the 17 balls would have gained the FIFA Approved status.

The vertical ball rebound and rolling resistance was also investigated by the FA in 1985 due to the introduction of artificial pitches. Lees (1996) has summarised the findings. The 1st generation artificial turf pitches used gave a higher vertical rebound (up to 6%) and a lower ball roll distance (by 20%) than natural pitches. This indicates that the 1st generation turfs were hard with high frictional properties. Lees and Nolan (1998) again summarised more research into the differences between natural and artificial pitches and found results following similar trends to before.

Mooney and Baker (2000) looked at the effects of natural turf preparation (sward height, watering and rolling) on ball behaviour. Watering the turf (which many football clubs do before
a game) gave a slower ball roll and lower rebound heights but gave the impression of fast surface for angled ball behaviour due to the ball skidding on impact. Rolling and cutting the pitch gave higher ball roll speeds but caused damage to the pitch. Biomechanical differences of players on pitches were examined by Stanitski et al (1974) and Martínez et al (2004).

Bell and Holmes (1988) conducted a study into the playing quality of association football pitches. COR mean was found to be 0.325 for a range of pitches for a single FIFA Approved ball. However the range of results was relatively large, a minimum value of 0.0 was attained and a maximum of 0.588. When compared to soil tests, the COR correlated well (using Pearson's correlation coefficient) with ground hardness \( R_p = 0.8 \). Additionally variations across a pitch are seen. Central areas such as the goal mouth and centre circle are likely to be compacted more due the majority of play being there and this is shown by higher COR values than the wing area, (0.345, 0.339 and 0.291 respectively). In the modern game at the elite level the differences between areas of the pitch are relatively small as compared to the 1980s due to clubs employing full-time groundsmen and new turf technologies.

Bell et al (1985) summarised COR values for footballs on professional club pitches across the UK. Figure 2-35 below illustrates the differences between professional football club pitches in terms of ball COR. At that time of first generation artificial turfs it is clear to see the variation in their construction, quality and playing performance which results in a wide range of COR compared to natural turf.

<table>
<thead>
<tr>
<th>Football Club</th>
<th>COR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crewe Alexandra</td>
<td>0.34 - 0.44</td>
</tr>
<tr>
<td>Wigan Athletic</td>
<td>0.35 - 0.45</td>
</tr>
<tr>
<td>Rochdale</td>
<td>0.33 - 0.38</td>
</tr>
<tr>
<td>Coventry City</td>
<td>0.43 - 0.49</td>
</tr>
<tr>
<td>Wembley Stadium</td>
<td>0.32 - 0.39</td>
</tr>
<tr>
<td>Fulham</td>
<td>0.40 - 0.44</td>
</tr>
<tr>
<td>Blackburn Rovers</td>
<td>0.40 - 0.49</td>
</tr>
<tr>
<td>Everton</td>
<td>0.42 - 0.50</td>
</tr>
<tr>
<td>Various synthetic turf surfaces</td>
<td>0.21 - 0.57</td>
</tr>
</tbody>
</table>

Figure 2-35: UK football club pitches in terms of ball COR, (Bell et al 1985)
Lees (1996) reported a summary of the literature regarding football impacts on natural and artificial turf in terms of COR from the work of Winterbottom (1985). COR was found to be 3-6% higher on artificial turf than on natural turfs. Additionally the variation between ball types at the same pressures gave a 3-7% variation in COR. Ball pressure changes accounted for a variation of 4-5%. It should be noted that these figures for artificial turf are from 1985 and thus would have been assessing the 1st generation artificial pitches.

The remaining studies found on the normal impacts of footballs are dated pre 1990 and the development of footballs since has increased dramatically. However it provides a useful benchmark for new footballs and an introduction to the experimentation methods. Levendusky et al (1988) reported the findings of the differences between 20 moulded and stitched footballs in terms of their peak force, impulse, contact time and force rise time. A force plate (sampling at 1000 Hz) was used and balls were dropped from a height of 18.09 m thus achieving impact velocities of 17-18 m/s. Contact times of 10.24 and 10.76 ms were seen for the moulded and stitched balls respectively. Peak forces were 851 N and 912 N for moulded and stitched balls respectively however the stitched balls were 2.5% heavier on average. Levendusky et al stated that “stitched balls tend to be subjectively favoured over moulded balls because they possess a better feel or ‘touch’ to play with” due to the differences in force rise time thus giving greater control of the ball.

Armstrong et al (1988) conducted a similar experiment with a force plate but compared the influence of ball inflation pressure and wetness on the peak force, force rise time and impulse. 20 balls at pressures of 6, 9 and 12 psi were dropped from 6 m either dry or wetted. The wetness of a ball was important before 1990 as many balls did not have the water resistance of modern balls. The FIFA water absorption test fails balls at the Approved level with a weight gain of more than 10% after 250 compressions in different orientations in 2 cm of water. Balls wetted before impact had a 5.01% increase in peak impact force compared to dry impacts. However stitched balls were susceptible to water absorption and this is shown through a peak force increase of 8.46%. Increasing inflation pressure was also found to increase peak forces. Impact times were found to be in the 11-12 ms range.
Johnson (1973) conducted a set of experimental tests (impact area and contact time) and compared these to a mathematical model based on the measurements of the football and the internal pressure. A football was projected vertically onto a rigid surface. The contact area was measured using a chalk covered board and the contact time assessed using a ball covered in copper foil which would complete an electrical circuit on contact. Contact areas were found to increase and contact times to decrease with increasing velocity. Differences between the model and experimental results were due to the fact that not all energy losses were accounted for in the equations.


Bridge (1998) discusses the influence of the dissipation of energy in an impact. Bridge states that as a ball impacts a surface, the kinetic energy is transferred into internal energy. A major area of losses in the internal energy is due to the damping on the waves of the ball surface which propagate through it. Bridge also identifies the effect of friction as an energy loss and the importance of hysteresis in sports ball materials when compressed.

Carré et al (2004) modelled a normal impact of a cricket ball with respect to a mass connected to a Hertzian spring in parallel to a damper. The damping coefficient was made to vary as the contact area changed. This model setup is commonly used for most sports ball mathematical modelling. Experimental data was collected from a cricket ball dropped onto a load cell at a velocity of 6 ms$^{-1}$. Load cell specifications were not given but force-deflection curves were produced to analyse the differences between a cricket ball impacting on its seam or perpendicular to the seam. Both positions gave nonlinear responses with a significant degree of hysteresis. Experimental and theoretical results were found to show good agreement.
Cross (1999a) conducted an experiment to determine the force-deflection behaviour of a tennis ball. Cross states that the energy loss can be predicted by a static compression test but a dynamic test must be conducted to find the dynamic energy losses. A piezo element was mounted onto a brass rod which was then mounted on a rubber layer. The brass rod separated the impact from the reflections from the floor and the rubber acted as a dampener. Figure 2-36 shows the differences between the force deflection curves for soft (tennis) and stiff (cricket) sports balls.

![Figure 2-36: Force vs. deflection for different sports balls, Carré et al (2004)](image)

Dowell et al (1991) present an experimental study on 7 sports balls (including a football) to ascertain their impact forces and areas at 4.88, 6.9 and 8.4 ms\(^{-1}\). They discuss that it is impossible to quantify the force of a compressible ball using theories and only experimentation can determine the true magnitude. Contact area was determined by using carbon paper attached to a force plate to measure the force. For a football, the average peak force was 1659.85 N for 8.4 ms\(^{-1}\) and maximum contact area of 129.64 cm\(^2\). Compared to other compressible and non-compressible sports balls, a football had the 2\(^{nd}\) lowest force per unit area. A football impacting at 8.4 ms\(^{-1}\) had a mean force per area of 12.8 N.cm\(^2\), only 2% force per area of a golf ball.

Haake and Goodwill (2002) again used a piezoelectric force plate along side a high speed video to analyse the impact properties of tennis balls and to compare the 'feel' of the impact perceived by a player. For 6 tennis balls over 5-45 ms\(^{-1}\) impact velocities, the contact time and COR
decreased as velocity increases. COR tended to decrease linearly with increasing velocity. Haake and Goodwill suggest that a tennis ball should have a high stiffness and high COR to give a better feel to the player. It was found that decreasing the internal pressure gave a 20% decrease in COR and 15% increase in contact time. Miller and Messner (2003) also looked at the ‘dynamic’ COR of tennis balls, i.e. COR that is velocity dependent. Tennis balls were fired at a range of velocities of 20-40 m s\(^{-1}\) using pressurised air. It was found that COR drops from 0.75 at low speeds to 0.4 at 40 m s\(^{-1}\). Additionally a worn tennis ball will result in a lower COR, after approximately 50-100 impacts. Shaing \textit{et al} (2002) conducted a similar study on the dynamic COR of baseballs. Again it was found that COR decreases (from 0.525 to 0.4) with increasing velocity from 50-90 mph.

In more general experiments of spherical objects impacting flat surfaces, Sondergaard \textit{et al} (1990) found that increasing the diameter of a sphere decreased the COR for the same material. Additionally they reaffirmed previous research that COR again decreases with an increasing impact velocity for normal impacts. Tatara (1983) used a high speed video (5000 Hz) to obtain data from bouncing rubber spheres. It was due to the contact times, that the Hertzian theory of impact for metal spheres does not hold true for elastic spheres.

### 2.4.3 Oblique impacts

The oblique impact is the most common for ball impacts in sports. In football it is represented by a bouncing pass between players, the impact on the boot and the impact on the framework of the goal. There is limited research into the oblique impacts of footballs as any previous research was conducted with normal impact for ease of analysis. The only research that has been found is an undergraduate project carried out by the author and other work carried out Loughborough University. Firstly the oblique impact is described through the different forces acting on a ball in general.

When a ball initially touches the surface at a certain angle and velocity to the horizontal, it will want to maintain its velocity and continue moving in the same direction, i.e. into the surface, part of Newton’s First Law. As the ball exerts a force onto the surface, the surface will oppose this
force equally causing the reaction force vertically, part of Newton's Second Law. The frictional force takes the form of the horizontal component opposing the horizontal velocity. Hay (1993) describes that a ball with no inbound spin will leave the surface with spin imparted by the frictional force component. A ball with spin will have an influence also on the horizontal force opposing motion. For example a ball with a high topspin, the bottom of the ball will be travelling backwards with respect to the centre of the ball; therefore the frictional force will oppose this on impact and will act in the overall direction of motion of the ball (forwards). This will mean the ball will maintain its horizontal velocity or even gain speed depending on the rate of spin, (Hay, 1993).

Secondly for oblique impacts it is important to identify the correct velocity components and spin nomenclature. Figure 2-37 shows the general set up for a ball bouncing obliquely. Before impact the horizontal velocity is $u_1$, the vertical velocity is $v_1$ and the inbound spin is $\omega_1$. During impact the frictional force is $F$ and the normal reaction force is $R$ as previously stated in the friction section. After impact, the horizontal velocity becomes $u_2$, the vertical velocity becomes $v_2$ and the imparted spin is $\omega_2$. The radius of the ball may be expressed as $r$.

![Figure 2-37: The velocity, spin and force components of an oblique bounce from left to right](image)

What happens during the contact phase is of great interest to many sports. Golf and tennis have led the way with the amount of research due to the importance of a good contact in a golf shot or the reaction of a tennis ball off a court surface. Surprisingly the interaction between surfaces in football has not been well researched. Next will be a general summary of what happens when a sports ball bounces obliquely and then this will be followed by research carried out in this area.
A theoretical ball bounce model has been created initially by Daish (1972) where two cases of ball impact are formed where a ball will simply slide throughout impact or a case where the ball slides then rolls off the surface. The equations are formed based on Newton’s Laws on the change in momentum in which are formed for the two force impulses:

\[-F' = M(u_2 - u_1)\]  \[\text{[Equation 2-14]}\]

\[R' = M(v_2 - v_1)\]  \[\text{[Equation 2-15]}\]

Using (2-7) or (2-8) and substituting in (2-14) and (2-15) and considering the angular momentum gives equations for pure sliding ($\mu_1$) or an equation for sliding and rolling ($\mu_2$), Daish (1972):

\[\mu_1 = \frac{u_1 - u_2}{v(1 + \varepsilon)} = \frac{u_1 - u_2}{v_1 + v_2}\]  \[\text{[Equation 2-16]}\]

\[\mu_2 = \frac{2\alpha(\omega_1 + \omega_2)}{5(v_1 + v_2)}\]  \[\text{[Equation 2-17]}\]

In reality, the frictional force is difficult to determine and under what conditions the ball will do what. In (2-16) and (2-17) there are several assumptions like ignoring gravity and assuming the ball and surface are totally rigid, which are not replicable of a compressible sports ball bouncing on a compressible surface. Brody et al (2002) state the three types of friction to affect ball bounces:

- Sliding friction – acts only when the ball is sliding
- Rolling friction – much smaller than sliding friction and acts to keep a ball totally rolling
- Static friction – the level of force required to initiate movement from rest

Out of the three, the most important is static friction. This is because if a ball initially slides throughout impact the ball will eventually grip the surface and the bottom of the ball will come to
rest thus causing the top of the ball to rotate about the bottom causing spin, (Brody et al 2002). Typically balls with a low angle of incidence will tend to slide and balls with a higher angle will tend to roll or grip after initially sliding. Brody et al (2002) also state three important factors that will influence the magnitude of $F$;

- The magnitude of $R$ and the angle of incidence (see 2.3.1)
- The smoothness or roughness of the surface
- Whether the ball slides throughout or grips the surface, which depends on:
  - The angle of incidence
  - $\mu_k$ (or sliding friction)
  - The amount of spin before impact

Brody (1987) refers to the perception of court speed by tennis players. He states that experienced players will judge the pace of the court by how high and how fast the ball comes off the surface. A slow court is represented by low speed and steep angles and a fast court is represented by high speeds and keeping low off the surface.

Cotton (2004) reported an experimental procedure to show the surface interaction properties of a football varied with inbound velocities at different angles. High speed video (10,000 Hz) was used to analyse impacts of an adidas Fevernova football impacting against a boot rubber and a 1st generation artificial turf. Up to 8 impact velocities were used (20 - 70 mph) each for 6 inbound angles (15 - 40°). Spin production, surface pace, contact ball rotations and distance travelled were taken from the impact. Additionally a ratio comparing the angle rotated by the ball on impact compared to the distance travelled was calculated and called ‘roll-slip’ ratio. For the roll-slip a value of 0 meant pure sliding whereas a value of 1 meant pure rolling. Figure 2-38 shows a typical colour map graph of the spin produced ($\omega_2$) by the football having no inbound spin ($\omega_1$). It is clear to see that an optimum set of inbound conditions produce the most spin, of up to 1300 rpm. At high velocities, changing the inbound angle from 15° to 30° increases the spin by as much as 800 rpm. Additionally it was found through Pearson’s correlation coefficient that the magnitude of impact velocity was the dominant factor in the impact and rebound characteristics.
Figure 2-38: Colour map graph showing how spin produced by an artificial turf changes with impact velocity and angle, Cotton (2004)

With the impact and rebound characteristics calculated, the results could be summarised onto one graph or ‘surface interaction map’. Figure 2-39 shows how areas are formed for different impact conditions. For example, the area of high spin relates to also a very low surface pace, mid roll-slip ratio and high rotations of the ball on impact.

Figure 2-39: A surface interaction map grouping the football rebound and impact characteristics together in areas, Cotton (2004)
Maw (1976) uses a Hertzian theory of impact for the normal component of an elastic sphere bouncing. Maw describes the impact phase with regards to contact area and frictional force. Initially as the contact area increases there will be areas of the sphere being laid down on the surface free of tangential stress but changes in the applied tangential force will involve a redistribution of stress, (Maw 1976). Additionally work done against the frictional force through tangential displacements will result in stored elastic strain energy which is recoverable when the force is taken away as the ball bounces off the surface.

Cross (2002a and 2002b) has been a principal investigator into the mechanics of a bouncing ball in recent times. Cross (2002a) examined the oblique impacts for a tennis ball and a ‘superball’ by dropping them from 0.3 and 0.6 m onto an angled platform to gain angles of 20, 45 and 90°. Velocity, angle and spin where taken from a standard video camera (100 Hz). Results from ball friction tests (see section 4.2.2) were compared to ball bounce models such as (2-16) and (2-17) and found to agree only for some inbound conditions.

Cross (2002b) examined whether the frictional force acting on the ball was sliding, rolling or static friction and summarised the research into the relationship of a ball rolling off an impact and resultant spin. In previous research it was found in some cases that the spin rate ($\omega_2$) was faster than the rolling rate on contact. The difference was related to the partial recovery of elastic energy stored in the tangential direction. Another phenomenon is the reversal of the frictional force on a low friction surface for a compressible ball. Cross (2002b) used a custom built force plate to assess the normal and tangential forces and discovered that a basketball impacting at 66° at approximately 3 ms$^{-1}$ had 6 reversals of the frictional force during an impact. Through further analysis measuring the oscillations of the ball through piezo sensors mounted on top of the ball, it was concluded that the reversals were due to tangential displacements during impacts. The reversal of the frictional force was again confirmed by Haake et al (2003) for obliquely impacting tennis balls on a force plate.

Tennis research into oblique impacts is concerned with two main areas: the impact with the strings (Goodwill and Haake 2002 & 2004 and Cross 2000) and the court surface (Cox 2000 &
2003, Pratt 2000, Carré et al 2002, Dignall and Haake 2000, Dignall et al 2000 and Haake et al 2003). Goodwill and Haake 2002, reaffirm the theory that the spin resultant from an impact (this time with the strings of a racket) is of greater magnitude than the rolling angular velocity during the impact. More spin was found not to be a function of string material, gage or tension but players perceived that more spin was generated by a high tension racket. The transition from sliding to roll was found to be halfway during impact. Cross (2000b) found that the strings had the ability to store elastic potential energy efficiently and return with minimal energy loss for any tension or age. \( \mu \) of sliding friction of 0.3 was found to be a critical value. Less than 0.3 gave a significant change in rebound angle whereas greater than 0.3 gives a slight change in spin and rebound angles.

Dignall and Haake (2000) discuss the importance of the court surface deforming as well as a tennis ball and suggest that stiffness and damping should be incorporated into any ball-surface impact as the surface absorbs energy and forms a ramp for the ball to roll up at the end of impact. The International Tennis Federation (ITF) uses the basis of equation (2-16) or \( \mu_i \) to analyse the surface pace of tennis courts, Cox (2000). Pratt (2000) reported that the coefficient of sliding friction was the main influence behind the pace of tennis courts. Additionally, Pratt uses a second damped spring mass system to numerically model the surface. It was found that only the COR is affected by a ‘soft’ court. Cox (2000) conducted surface pace ratings for a range of court surfaces and artificial turfs. Cox found that for rubber infill artificial turf, the ball performance is very dependent on the top layer and any moisture tends to coagulate the rubber crumbs causing wide variations between wet and dry conditions.

Cricket and especially golf are well researched with regards to the oblique ball-surface impact; however the relevance for soccer ball impacts is limited due the stiffness of the ball. James et al (2002) compared soil characteristics to the surface pace of a cricket ball impact during a bowling delivery. Carré et al (2000) created a modified model of Daish (1972) to incorporate the ball deforming the pitch. Predictions from this model fell within one standard deviation of the experimental data.
Studies for golf have looked at the interaction of the ball with the turf (Hubbard and Alaways 1998 and Haake 1991 & 1994), the frictional characterisation of golf wedges (Monk et al 2002) and the impact forces (Gobush 1990 & 1996, Ekstrom 1999 and Johnson and Ekstrom 1998). Gobush (1996) used a three component force transducer under a 100 x 200 x 300 steel block and fired golf balls at 29 ms\(^{-1}\) at 20 and 40\(^\circ\), the tangential and normal forces were recorded for different ball compositions and force differences were explained. Haake (1994) studied the impact of a golf ball on natural turf. One of the main discrepancies between the modelled and experimental data was that the velocity dependent COF was not incorporated into the numerical model.

2.5 Finite element analysis and modelling

2.5.1 Introduction

Finite Element (FE) Analysis (or FEA) is a theoretical mathematical method of solving partial differential equations for the prediction of mechanical problems. An object is discretised into a mesh of nodes and elements which are analysed using relatively simple mathematics but due to the large number of these calculations is well suited to processing using a computer. As computers have evolved to incorporate greater processing power and memory, the more complex finite element applications have become.

An FEA model is constructed from computer aided geometry (CAD) which is then seeded into a mesh of a desired density. The nodes which form the joints of the elements are then assigned degrees-of-freedom to allow them to move in certain directions in space. The nodes are then assigned boundary conditions to apply external forces or displacements. Mechanical material properties are assigned according to the materials used (linear and non-linear) and the final solution is solved within a matrix. Larger matrices will lead to longer processing times which are due to highly refined meshes, complex non-linear material models and a large number of degrees-of-freedom.
Abaqus, a commercially available FEA software, which was used for this research has two types of solvers depending on the nature of the problem. Abaqus/Standard is a general-purpose solver that uses traditional implicit integration whereas Abaqus/Explicit uses explicit integration scheme to solve highly nonlinear transient dynamic and quasi-static analyses, (Abaqus 2007).

2.5.2 Sports finite element applications

2.5.2.1 Ball impacts

The FE modelling of sports ball impacts has been used to simulate ball impacts and also to change various material properties or contact conditions to develop new balls. For this project, the modelling area will be based on an existing set of soccer ball models but FE modelling has been applied for other sports balls and these applications will be reviewed.

Perhaps the study that is the most relevant to this research was published by Asai et al (2002 and 2004). In this study an FE simulation of a soccer being kicked was modelled using MSC/PATRAN. In the modelling, hexahedron solid elements were used for the leg and foot whereas the ball was comprised of shell elements. The total number of elements was 268 for both parts. The lower leg was split into two areas (foot and calf) to which separate Young's Modulus and Poisson ratios were assigned. The model was first validated by comparing the foot velocity through an impact in high speed video. Figure 2-40 shows the model during a kick. Further experiments indicated that for a curve kick (applying spin to the ball) changing the COF from 0 to 1 gave an increase of spin of 13 rads\(^{-1}\) (or 124 rpm). Additionally keeping the COF constant and varying the kick offset distance from the centre of the ball gave increased spin at 100 mm. This work was the development of previous studies by Asai et al (1996).
Cordingley et al (2004) conducted a study into the development and analysis of an FE model of a tennis ball impacting normal to a rigid surface. Experimental work was used to validate the model of high speed impacts and strain rate dependent stiffness and damping material data are included in the ball model which allowed good correlation with the experimental data. The accuracy of the model would allow material variations and testing to be carried out without actually manufacturing a tennis ball. Other tennis FE work has been carried out by Kanda et al (2002) where the effect of different string tensions and frame stiffness were successfully modelled. More recent research carried out by Kanda (2005) investigated the effect of the COF on the oblique bounce of a tennis ball on a flat rigid surface using the FE approach. The FE model consisted of 16-noded isoparametric solid elements which equated to 184 elements and 1108 nodes. The through thickness was 3.2 mm modelled using 1 layer of elements. A short model verification study resulted in the model agreeing well with the experimental data at 8 velocity and inbound angle combinations \((v = 10.8 \text{ to } 16.5 \text{ m/s and } \theta = 90^\circ \text{ to } 14.8^\circ)\). The COF for the model verification was reverse engineered to match the experimental outbound spin values \((\mu = 0.31)\). For the main study the FE model was then used to simulate the impact of a tennis ball on a flat rigid surface at 40 m/s but varying the inbound angle \((10 \text{ to } 90^\circ)\) and COF \((0 \text{ to } 1 \text{ in } 0.1 \text{ steps})\).

Price (2005) constructed and developed a set of soccer balls based on the recent adidas balls, for the 2002 World Cup (Fevernova), the 2004 European Championship (Roteiro) and the 2006 World Cup (Teamgeist). The first ball model was a simple shell and with basic mechanical
material properties, such as stress-strain data of the panels and carcass. Once this basic model had been completed and validated through experimental data of impacts, other features such as the stitching and valve were included together with panel and carcass materials. Price (2005) successfully incorporated anisotropic and viscoelastic material data which again was validated through experimental ball impacts (normal).

2.5.2.2 Sports surfaces

The attempt to model a sports playing surface in football/soccer and compare ball performance to the author’s knowledge has never been carried out. This section describes briefly the research aimed at modelling other sports surfaces. The study of running tracks has been the subject of modelling due to the energy return benefits to an athlete, (Baroud et al 1999a and 1999b, Thomson et al 2001, Durà et al 2002, Miller et al 2000, and Stefanyshyn and Nigg 2003). Stefanyshyn and Nigg (2003) conducted an FEA on the different directional structures of the underlying surface material and compared energy returns. A viscoelastic constitutive model simulated the surface and ground reaction forces of athletes were used as inputs. Various directional structures were used of same material that would be found in a typical running track. It was found that changing the homogenous structure to a structured surface resulted in a ten fold plus energy return, (Figure 2-41).

![Figure 2-41: Above shows the surface structure and running direction. Below shows how the surfaces compare with respect to energy return, Stefanyshyn and Nigg (2003)](image-url)
2.6 Summary

This chapter has reviewed the literature that had similarities and implications for the experimental and computational testing to answer the research questions posed in Chapter 1. These include the development of the game of soccer and the ball itself plus the subject of friction, sports ball impacts and finite element analysis. Understanding the role of friction and its application in other industries has allowed a better understanding of the mechanics of interactions and what measures can be taken to optimise performance. However it is apparent that there is a gap in the knowledge regarding the soccer ball oblique impact, which involves friction and is perhaps the most common impact scenario but the least researched.
3 Equipment, methodology and measurement uncertainty identification

3.1 Chapter overview

This chapter outlines the equipment and the methodology used to capture the experimental data. In addition the analysis procedures and techniques will be described to illustrate how the experimental data is collected from high speed video recording. The chapter will conclude by assessing levels of accuracy and possible sources of uncertainty within these measurements.

3.2 Soccer ball launching and kicking systems

3.2.1 Ball Launcher

In 2003, the STRG manufactured a machine capable of launching a sports ball at high speeds onto a target plate which allows the study of ball behaviour at speeds comparable to those experienced during play. The machine launches sports balls by the use of two counter rotating 40 kg balanced drums with a maximum rotational velocity of 2800 RPM. The two wheels are independently controlled enabling spin to be put onto the ball. The main features of the ball launcher are shown in a photo in Figure 3-1 and schematically in Figure 3-2.

The ball loading device runs between 2 sets of rails towards the gap between the two 'drums'. Two adjustable blocks hold the ball securely in position but still allow the ball to be taken through the rollers. The ability to position a ball in various orientations means that the ball can be launched in a controlled manner to study impacts at different positions around the ball.
The drums are each independently driven by a 2.2 kW motor and controlled by an inverter. The drums are secured in mounting blocks which can be adjusted vertically by an opposite double screw thread to allow the separation between the rollers to be adjusted. As the ball is pushed towards the rollers with the loading device, the ball comes into contact with both roller surfaces and is accelerated through the gap between the rollers. This is typically 0.18 m for FIFA
Approved soccer balls and creates approximately 0.02 m of compression either side of the ball. Depending on this gap and additionally the surface texture and condition of the rollers and the ball itself, ball velocities of up to 35 ms$^{-1}$ can be achieved. For this research, the contact between a soccer ball and a surface is of interest so the ball launcher is set up to fire balls with no initial spin towards an adjustable rigid plate (600 x 400 mm). The machine launches balls downwards towards the target at an angle of 15° to the horizontal. In addition the target can rotate about its centre to create an infinite amount of orientations between a normal ball impact (90°) and a shallow oblique impact of 15°. Depending on the nature of the soccer surface used for the impact, different attachments are used to secure the surface to the target. For example, an artificial turf can be accommodated in a specially manufactured tray which is secured by bolts though the base of the target (See Figure 3-3(a)). Alternatively thin sheets of material, i.e. samples of a soccer boot upper material can be attached using industrial strength double sided tape as shown in Figure 3-3(b).

Figure 3-3: (a) The tray used to secure artificial or natural turf to the target plate and (b) the double sided tape approach to attach thin sheets of material.
The impact between the ball and the target surface is recorded using a high speed video (HSV) camera which is setup perpendicular to the target plate. The HSV camera, system and analysis are described in the next section.

An alternative to the STRG Ball Launcher, which is limited to be used in a fixed position in the laboratory, is the ‘Jugs’ machine. Similarly to the STRG machine, it has two counter rotating tyres but these are now placed horizontally. It is portable and can be used out in the field as well as around the laboratory. However, the ball orientation can not be controlled as it is rolled down two guide rails towards the tyres which also cause considerable damage to the surface of the ball. The ‘Jugs’ machine was used to launch balls towards floor mounted force plates to gain more accurate force measurements than by using a portable force plate.

3.2.2 Robotic Kicking Leg

For the second type of dynamic ball experimentation, a robotic leg was used to simulate a ‘foot’ impacting a stationary ball. The robotic leg used for the majority of work completed, was based at the adidas Global Testing Centre in Scheinfeld, Germany. As seen in Figure 3-4 and Figure 3-5, the Robotic leg is a steel bar which acts as a swinging pendulum and is pivoted at its upper end. The leg is driven at the pivot through a rack and pinion system by pneumatic air cylinders. The leg is braked by a dampening pneumatic cylinder which slows the leg down after impact. With the air pressure set to 900 kPa (9 bar), a leg rotational velocity of approximately 15 rad.s$^{-1}$ can be achieved. The leg speed is monitored by a laser based light gate which records the time the leg takes to pass through the beam. This laser also triggers any HSV recording equipment for ball flight analysis.

Various different interchangeable end effectors can be attached to the kicking leg. For the majority of the testing in this research an aluminium cylinder (as pictured in Figure 3-4) with a diameter of 92 mm x 250 mm in length was positioned with its cylindrical axis in line with the length of the leg. The method used to attach small sheets of the boot upper material was similar to that of the STRG ball launcher. The ability to attach materials allowed different boot upper materials to be compared in a repeatable way. Again industrial strength double sided tape
covering all of the material backing allowed a strong and durable method of securing the material.

Figure 3-4: The Robotic leg – labelled photo

Figure 3-5: The Robotic leg - systematic diagram
The ball is positioned on a tee based on top of a plate which can be adjusted in 3 orthogonal axes. The lightweight, disposable tee allows the cylinder to come into full contact with the ball as it can be kicked away with the ball without affecting the impact or subsequent ball flight (Figure 3-6).

Figure 3-6: Disposable tee during contact

3.3 Sample preparation

The material samples used were acquired immediately prior to manufacture of the end product. For example, the Kangaroo Leather boot upper material arrived in a large sheet after all the treatments had been carried out. From the large sheets the samples were cut using paper templates to get the correct sizes. The leather was visually inspected for defects and was discarded if any holes were present or if the material was damaged. The artificial turf used for the ball launcher was of a carpet type and was cut from one large sheet. Again the samples were visually inspected before used in the experimental testing.

3.4 Imaging

3.4.1 Cameras

A Photron Fastcam Ultima APX 120K HSV camera was used to record impacts from the ball launcher and a Photron Fastcam APX RS was used for the Robotic leg. Both had capabilities of
recording at over 100 KHz, with the APX RS version recording in colour and the APX 120K in monochrome. However the majority of the testing required a frame rate of 500-1,000 Hz for spin measurement and 2,000-10,000 Hz for high speed ball impacts. Such frame rates were found to give a balance between image quality, lighting required, image size and file size. For example, whilst a higher frame rate gave an improved quality, extra lighting was required, the image size was small and the file size was large.

Both Photron camera systems were operated in a similar manner and were connected to a processor (the APX RS processor was built into the camera where as the APX 120K was a separate component) and then to a laptop via a FireWire cable. The capturing was conducted through the Photron Fastcam viewer software. Recording was started in a variety of ways either manually through the PC or with the use of automatic triggers, i.e. tripping a laser. Manually, the user clicked a record button within the software and the processor captured a certain amount of frames dependent on the frame rate. The processor then stored all the frames until the user selected the required duration and saved the recording to disk, usually in .avi form.

For the ball launcher, the typical frame rate was 10 kHz which allowed a maximum image size of 512 by 256 pixels. To examine spin rates for the Robotic leg, the frame rate was set to around 500 to 1,000 Hz giving larger image sizes with less lighting required to track the ball through a whole revolution in its flight. More information on the spin rate measurement can be found in section 3.4.2.2. Image sizes for spin measurement were typically 1024 by 512 pixels.

3.4.2 Image Processing

3.4.2.1 High Speed Video capturing software

As mentioned in the previous section, the Photron Fastcam viewer was used to control the capturing, editing and saving of the HSV recording. This software allowed the saving of .avi video files, which were compatible with the image analysis software used (Image-Pro Plus).
3.4.2.2 Image-Pro Plus

The Image-Pro Plus software allows a user to interrogate images by extracting details from individual pixels or groups of pixels to enable dimensions of features in the field of view to be recorded. Brightness, contrast and other manipulations can also be carried out to improve the visual clarity of captured images. It can be used for both monochrome images (greyscale values between 0 and 255) and colour (values in the RGB colour channels). Macros were set up to automatically adjust the video recording in terms of brightness, contrast and gamma values to obtain the clearest possible image for dimensional analysis. Dimensional data recorded during IPP analysis was automatically exported to a spreadsheet program for further data processing, as explained fully in section 3.4. This time saving tool allowed large numbers of videos to be analysed efficiently over the course of the research which provided the basis of the experimental work.

3.5 Analysis techniques

This section describes the measurement techniques used for the ball launcher and the Robotic Leg to assess the ball rebound and flight characteristics.

3.5.1 Ball Launcher

3.5.1.1 Introduction

The research carried out by Price (2005) concentrated on the normal impact where COR, contact time and ball deformation in the tangential and longitudinal directions were considered the main metrics for determining general ball impact behaviour.

The angled impact, with no initial spin causes the ball initially to slip on the surface then as the frictional force increases the ball contact area grips the surface and the ball is seen to roll off the surface. Depending on the impact conditions, the quantity of the slipping and gripping is varied as sometimes the ball will slip throughout impact as seen for very shallow, high velocity impacts, Cotton (2004). A series of metrics were chosen, based on those previously cited in the literature review and personal experience built up over analysing oblique impacts in the initial testing. The
analysis metrics are split into primary and secondary categories. The secondary metrics are based on two or more primary (or direct) measurements. Figure 3-7 (a-d), illustrates these. Image (a) shows the inbound or the motion of the ball before impact. The contact phase is shown in image (b) and the outbound or rebound measurements are shown in images (c) and (d). No measurements are shown in figure (c) to allow the ball to regain its original shape after the deformations seen during the contact.

![Figure 3-7: The typical frames required for the analysis of a ball launcher oblique impact](image)

**3.5.1.2 Primary metrics**

The primary metrics include the ball velocity inbound and outbound in the tangential and normal directions, contact translational distance, contact rotation, contact time and angle rotated after impact. From these the secondary metrics can be derived. These are the COR (normal,
tangential and from the velocity magnitude), outbound spin rate, contact spin rate and the roll-slip ratio.

Ball velocity, either inbound or outbound (as shown in Figure 3-7(a) and (d)), can be determined by measuring the ball centre to centre distance over the time period. The IPP software allows the ball to be encompassed in a circle in two positions and the centre to centre distance is an automatic measurement function. All dimensions extracted using IPP are measured in pixels. The diameter in pixels of the circle drawn around the ball can be used to derive a scale factor relating the dimension of a pixel to the equivalent distance in the field of view since the diameter of the ball is known (0.22 m). This scale factor can then be applied to further measurements made with the same apparatus set-up. The velocity in the normal and tangential directions can be obtained by using the dimension components in the respective direction. The angle of impact and rebound can be derived from the velocity vectors tangential and normal to the surface. Alternatively the angles can be calculated by using the ball centre-to-centre positions before and after impact (Figure 3-7(a) and (b)). The ball contact translational distance is obtained by using the centre to centre points of the two circles drawn firstly when the ball initially touches and secondly as it leaves the surface (see Figure 3-7(b)). Again this distance is calibrated using the scale factor. Ball rotations during this contact period are determined from the pre marked circumferential lines. This assumes that all ball rotations occur only around an axis passing orthogonally through the image. In reality, there is a minimal compound rotation due to small errors in the target plate alignment and due to the deformation of the ball although these are negligible compared to the measured spin rate.

3.5.1.3 Secondary metrics

The secondary metrics are derived from these initial measurements. The COR (as described in the literature review) is the quotient of the velocity before and after an impact. For the oblique impact it can be in three forms; tangential COR (or surface pace), normal COR and magnitude COR. Spin rates (either outbound or during contact) are calculated by dividing the appropriate angle rotated by either the contact time or time monitored after impact. The roll-slip ratio compares the circumferential distance rotated during contact to the translational ball distance on contact, see Figure 3-8.
The formula for the ratio is described as,

\[
\text{Roll - Slip Ratio} = \frac{c_{\text{contact}}}{d_{\text{contact}}}
\]  
[Equation 3-1]

Therefore, if the ball rolls for 100% of the contact, the arc length \(c_{\text{contact}}\) will be equal to the translational distance travelled \(d_{\text{contact}}\) and a value of 1 would be pure roll. On the other hand if the ball slides throughout the impact, the value will tend towards 0. This value will give a quantitative value to the grip and slip phenomenon that occurs during an oblique ball-surface impact commonly described in the literature.

3.5.2 Robotic Kicking Leg

The robotic leg experimental setup has two main areas of analysis which are explained in this section

3.5.2.1 Flight Repeatability

The flight repeatability of the ball during robotic leg testing is monitored by the impact position of the ball on a target goal a fixed distance away. As Figure 3-9 shows, the target goal is positioned perpendicular to the orientation of the robotic leg. Repeatability testing was carried out for a straight kick, where the line of kicking action passed through the ball centre as well as for impacts where the kicking action was offset from the ball centre. Depending on the leg to
ball offset, shown in Figure 3-10(a) causing an angled kick with spin, the goal is positioned accordingly to accommodate the ball trajectory.
The flight repeatability data were captured using a 50 Hz digital camera positioned normal to the target goal as seen in Figure 3-10(b). Additionally the camera was located as far away as possible from the target to minimise any lens effect errors. The 50 Hz recording frequency was found to be adequate to capture the ball location position with a high shutter speed set to minimise blurring as the ball will travel relatively large distances during each frame. The high shutter speed would normally require extra lighting but this was already in place with the lighting from the HSV requirements for spin rate data. The camera was operated manually by recording each kick in sequence. These data were then converted from .moi format to .avi through converter software\(^1\). Next the sequence of videos was edited so that a video was produced containing only the impact location frames of each kick in sequence. IPP was then used to digitise the video. As mentioned in section 3.4.1, the ball centre position was obtained automatically by drawing a circle around the ball at the moment of touching the target. As the ball on this video type was a smaller number of pixels in diameter, the goal frame was used as a calibration scale factor to convert pixels to metres. To relate the ball centre coordinates to the real life situation an origin reference coordinate point was nominated. The bottom corner of the outside of one of the posts was used to transform the ball position in relation to the goal position. This automatically provided the height (Y) of the kick. The horizontal distance (X) was calculated using the distance from a straight line from the robotic leg to the origin point plus the X coordinate position.

3.5.2.2 Ball spin rate measurement

Measurement of the spin rate induced by the robotic leg kick is a complex problem. The nature of the swinging leg introduced compound spin to the ball. Ball launch monitoring systems as mentioned in the literature are either expensive or require the balls to be marked with complex patterns. Therefore it was decided to simplify the spin rate analysis by only measuring the magnitude and not the axis of spin. The magnitude of spin was determined by measuring the time taken for the ball to complete a full revolution in flight. HSV recording at 500-1,000 Hz offered a resolution which compromised between requirements for data storage and lighting. Lighting was a problem as the ball needed to be illuminated and filmed over a long distance.

\(^1\) Converter software used is CyberLink PowerDirector
Ball markings were typically circumferential lines or high visibility spots which enabled the user to count the number of frames for one revolution.

3.6 Quantifying the possible sources of measurement uncertainty

Within the experimental work, various uncertainties exist which influenced the measurements taken. It is important to consider the sources and contributions of these to fully understand the possible influence on the data gained and to minimise these uncertainties through careful experimental setups.

3.6.1 Ball launcher oblique impact studies

During an oblique ball impact, the configuration of the HSV equipment with respect to the target and direction of the inbound ball travel may lead to uncertainties in the measurement. Additionally, errors are also likely to be introduced during the analysis of the video recording as spatially and temporally distributed information concerning the position of the ball is digitised. Each of the major sources of uncertainty will be considered in turn.

Camera lens effects, known as “spherical spreading” will cause the apparent diameter of the ball to change as it passes across the width of the frame, as shown in Figure 3-11.
Figure 3-11(a) attempts quantify the spherical spreading in its worst case and two ball positions are compared as shown. The angle $\theta_{ss}$ is $8.13^\circ$ and the angles $\theta_{ss1}$ and $\theta_{ss2}$ are $6.00^\circ$ and $5.80^\circ$ respectively. The error is calculated by comparing $\theta_{ss2}$ to $\theta_{ss1}$ and gives $2.7\%$. This error can be reduced by maximising the distance from the ball motion to the camera. Additionally keeping the setup dimensions consistent can minimise the impact on results as the error would be the same across trials. Compensating for this uncertainty in the measurements taken would be difficult to achieve and the example error stated showed that it is minimal with a good setup.

When digitising, three sources of uncertainty occur, due to spatial position measurements, angular measurements and the contact time frames. The contact time is calculated by determining when the ball first touches then leaves the surface. Table 3-1 shows the percentage
error when the number of frames is misjudged at different recording frequencies for a typical ball impact of 0.01 s. For a standard impact, 10,000 Hz is used and the quality of the HSV means that the certainty is usually around 2 frames resulting in an uncertainty of 1.96%.

<table>
<thead>
<tr>
<th>Contact time (s)</th>
<th>Frame Rate (Hz)</th>
<th>No. of frames</th>
<th>+ 1 frame</th>
<th>+ 2 frames</th>
<th>+ 3 frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>2000</td>
<td>20</td>
<td>4.76</td>
<td>9.09</td>
<td>13.04</td>
</tr>
<tr>
<td>0.01</td>
<td>4000</td>
<td>40</td>
<td>2.44</td>
<td>4.76</td>
<td>6.98</td>
</tr>
<tr>
<td>0.01</td>
<td>10000</td>
<td>100</td>
<td>0.99</td>
<td>1.96</td>
<td>2.91</td>
</tr>
</tbody>
</table>

Table 3-1: Table showing the % errors when determining the contact time

The contact time is important as the contact distance and contact angle rotated are determined from the contact time frames. The spatial position measurements include all the distances and therefore velocities. Due to the high quality images produced by the Photron Fastcam system, it is estimated that the ball diameter can be determined to within ± 1 pixel. For an oblique impact recorded at 10,000 Hz, the resolution is 512 by 256 pixels. From this video setup a ball diameter is usually around 120 pixels. This results in a measurement uncertainty of 1.67%. This is slightly more than the error stated by Price (2005) using the same system for normal impacts (1.14%) as the oblique impact needs to monitor the ball before and after the impact on both sides of the screen and therefore requires a wider field of vision. For a normal impact, the ball returns in the same direction meaning the user can focus on a smaller area of interest.

Angular position measurements are perhaps the most important as from this spin rates are derived. Again, using the typical screen resolution and ball size and with ± 1 pixel uncertainty, the angular uncertainty is ± 0.95°. This results in a percentage uncertainty of 0.53%. As velocities and spin rates are differentiated with respect to time, the percentage values are doubled giving values of 3.34% and 1.06% respectively.

3.6.2 Robotic Leg flight repeatability

As mentioned in section 3.5.2.1, the repeatability of a kick is determined by the position a ball impacts a pre-positioned target a certain distance away. From the digital 50 Hz camera, the ball position on the target at the moment it touches can be quantified by IPP through the centre...
position coordinates of the circle around the ball. However, as in the previous section where human error leads to small spatial positioning uncertainty of the ball in the image, these also exist for this analysis. Imaging errors are minimised through positioning the camera as far away as possible and in line with the impact. For a typical image see Figure 3-12. As seen the target fills the whole image enabling as many pixels as possible for the ball.

![Figure 3-12: Example of the image used for the Robotic leg trajectory accuracy analysis](image)

The resolution offered by the camera is 640 by 480 pixels which gives a ball diameter of approximately 52 pixels. If the user accuracy is ± 1 pixel to determine the ball edges, the measurement uncertainty is 3.85%. If the user uncertainty increases to ± 2 pixels for a poor image, the uncertainty rises to 7.69%. However the important factor is that the ball centre is correct rather than the exact size of the ball. This is true if the equipment is set up accurately. If the target is not perpendicular to the plane in which the robotic leg swings then these accuracy measurements will be distorted even further. In this research, to ensure the target was set up as accurately as possible a laser guidance system was used to ensure the perpendicular distance (Figure 3-9) was inline with the kicking motion of the leg.
3.6.3 Robotic Leg Spin Measurement

As mentioned the measurement of compound spin in sports balls is complex. The launch method using the robotic leg is possibly the simplest but it is also just as prone to uncertainties as complex systems. Throughout initial testing, two main sources of error could be identified and quantified. These include human error and errors due to imaging and perspective. Another possible source which has not been examined could lie within the drive mechanism of the leg.

To recap, the method of measuring the magnitude of the compound spin was to capture the ball flight on HSV (usually around 500 to 1,000 Hz) and count the number of frames for a reference spot on the ball to complete one ball revolution. The HSV is positioned side on or behind the trajectory. Filming from behind allows the ball size to appear larger. The human error occurred when the analyser decided what frame the reference spot coincides with the centre of the ball. Depending on the image quality such as lighting and ball glare this was sometimes not an easy process. Additionally the magnitude of error was increased when using a lower recording frequency.

As seen in Table 3-2, the effect of misjudging when the ball reference spot arrives at the centre of the ball is shown. For example, at 250 Hz (Table 3-2(a)), at a typical trajectory RPM of 300, 50 frames were required for one revolution with $+5.9$ RPM for each frame counted. This gave a measurement uncertainty of 1.9%.
<table>
<thead>
<tr>
<th>RPM</th>
<th>No. of frames</th>
<th>+ 1 frame</th>
<th>+ 2 frames</th>
<th>+ 3 frames</th>
<th>+ 4 frames</th>
<th>+ 5 frames</th>
<th>+ 10 frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>150</td>
<td>0.66</td>
<td>1.32</td>
<td>1.96</td>
<td>2.60</td>
<td>3.23</td>
<td>6.25</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>2.63</td>
<td>5.19</td>
<td>7.69</td>
<td>10.13</td>
<td>12.50</td>
<td>23.53</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>5.88</td>
<td>11.54</td>
<td>16.98</td>
<td>22.22</td>
<td>27.27</td>
<td>50.00</td>
</tr>
<tr>
<td>400</td>
<td>38</td>
<td>10.39</td>
<td>20.25</td>
<td>29.63</td>
<td>38.55</td>
<td>47.06</td>
<td>84.21</td>
</tr>
</tbody>
</table>

(a) 250 Hz

<table>
<thead>
<tr>
<th>RPM</th>
<th>No. of frames</th>
<th>+ 1 frame</th>
<th>+ 2 frames</th>
<th>+ 3 frames</th>
<th>+ 4 frames</th>
<th>+ 5 frames</th>
<th>+ 10 frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>300</td>
<td>0.33</td>
<td>0.66</td>
<td>0.99</td>
<td>1.32</td>
<td>1.64</td>
<td>3.23</td>
</tr>
<tr>
<td>200</td>
<td>150</td>
<td>1.32</td>
<td>2.63</td>
<td>3.92</td>
<td>5.19</td>
<td>6.45</td>
<td>12.50</td>
</tr>
<tr>
<td>300</td>
<td>100</td>
<td>2.97</td>
<td>5.88</td>
<td>8.74</td>
<td>11.54</td>
<td>14.29</td>
<td>27.27</td>
</tr>
<tr>
<td>400</td>
<td>75</td>
<td>5.26</td>
<td>10.39</td>
<td>15.38</td>
<td>20.28</td>
<td>25.00</td>
<td>47.06</td>
</tr>
</tbody>
</table>

(b) 500 Hz

<table>
<thead>
<tr>
<th>RPM</th>
<th>No. of frames</th>
<th>+ 1 frame</th>
<th>+ 2 frames</th>
<th>+ 3 frames</th>
<th>+ 4 frames</th>
<th>+ 5 frames</th>
<th>+ 10 frames</th>
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<tr>
<td>100</td>
<td>600</td>
<td>0.17</td>
<td>0.33</td>
<td>0.50</td>
<td>0.66</td>
<td>0.83</td>
<td>1.64</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
<td>0.66</td>
<td>1.32</td>
<td>1.98</td>
<td>2.63</td>
<td>3.28</td>
<td>6.45</td>
</tr>
<tr>
<td>300</td>
<td>200</td>
<td>1.49</td>
<td>2.97</td>
<td>4.43</td>
<td>5.88</td>
<td>7.32</td>
<td>14.29</td>
</tr>
<tr>
<td>400</td>
<td>150</td>
<td>2.65</td>
<td>5.26</td>
<td>7.84</td>
<td>10.39</td>
<td>12.90</td>
<td>25.00</td>
</tr>
</tbody>
</table>

(c) 1,000 Hz

Table 3-2: Showing at 3 recording frequencies the effect of frame error on RPM measurement

The second quantifiable source of uncertainty in this measurement of spin concerned the imaging system. The problems occurred regarding the path of the ball across the screen and whether the centre of the ball, as seen on screen, was actually the centre of the ball. Figure 3-13(a) shows how a ball moving across a screen (and away from the camera) gave errors in the position of the centre spot (shown as a yellow dot). The movement created two angles from ball position 1 ($\theta_1$) and position 2 ($\theta_2$). Combined, as shown in Figure 3-13 (b), they indicated that monitoring the centre spot of a ball may under estimate the magnitude of spin and dimensions are added in Figure 3-13 (c).
Figure 3-13(a): The spin measurement problem showing (a) an aerial diagram illustrating the set up and (b) the effect of the two angles (inset top right)
From this set up and simple trigonometry, the angles were calculated. The distances $x_1$ and $x_2$ were calculated by using the centre line of the screen and the appropriate ball diameter to scale the distance. Distance ‘$b$’ was estimated by applying Pythagoras’ Theorem to $x_2$ and the ball distance in flight between positions 1 and 2 (using the approximate ball velocity and time taken for the ball to appear to rotate one revolution). However, the only distance that would not be calculated is ‘$a$’. In initial testing, the approximate angle $(\theta_{1f} + \theta_{1s})$ was found to be around $10^\circ$ which gave an RPM value of 10 RPM. This gave a measurement uncertainty of about 3%.
This value of 10° was approximated assuming distance a, to be around 2 m. However it was then found that if one kick was analysed and distance, a, is varied then significant errors were seen. Table 3-3 shows the effect of varying the position from the camera of ball position 1 on the resultant spin rate.

<table>
<thead>
<tr>
<th>a</th>
<th>Measured Spin</th>
<th>Actual Spin</th>
<th>Difference</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>372.67</td>
<td>334.13</td>
<td>38.5</td>
<td>11.5</td>
</tr>
<tr>
<td>1</td>
<td>372.67</td>
<td>350.87</td>
<td>21.8</td>
<td>6.2</td>
</tr>
<tr>
<td>1.5</td>
<td>372.67</td>
<td>357.56</td>
<td>15.1</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>372.67</td>
<td>361.09</td>
<td>11.6</td>
<td>3.2</td>
</tr>
<tr>
<td>2.5</td>
<td>372.67</td>
<td>363.26</td>
<td>9.4</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>372.67</td>
<td>364.73</td>
<td>7.9</td>
<td>2.2</td>
</tr>
<tr>
<td>3.5</td>
<td>372.67</td>
<td>365.80</td>
<td>6.9</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>372.67</td>
<td>366.61</td>
<td>6.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 3-3: Showing the effect of varying distance ‘a’ on spin rate measurement from HSV

It can be seen that the error with approximation of distance, a, will have a major effect on the derivation of the magnitude of spin. Column a, gives a value of a from 0.5 to 4 m in 0.5 m increments; the measured spin rate (RPM) is the value gained by counting the frames from the HSV; the actual spin is that calculated by taking into account angles $\theta_{11}$ and $\theta_{12}$; and the difference and % differences are then shown in the final two columns. If the initial distance varies by 3.5 m for example between two identical kicks with identical spin rates, the spin rate measured by the HSV system may differ by over 30 rpm (10% measurement uncertainty)

3.7 Summary

This chapter has given an overview of the equipment to be used and typical setups and also assessed the potential presence of uncertainties within the measurements taken. All of the techniques, with the exception of the HSV spin measurement of the robotic leg, have a low measurement uncertainty. Therefore caution should be taken with the results obtained with the HSV technique with the robotic leg spin rate. Small differences in the spin rate data are unlikely to be significant when the measurement uncertainty is added to the spread of data for a particular setup.
4 Design of a friction tester for soccer materials

4.1 Chapter overview
The laws of the game do not provide any guidelines on the surfaces of boots, gloves, player’s kit and goal posts which may be important in terms of performance benefits and safety. Provided equipment is deemed safe by the match referee, the specification for materials used and surface textures or features included are at the discretion of the manufacturers. This chapter aims to describe the theory behind the development of a friction tester specifically for soccer materials. Many boot manufacturers have developed grip areas on the boot uppers to improve dry to wet performance but evidence supporting these developments is based on simple experiments which do not match the real life conditions. Firstly, the theory of friction testing and tribology are considered, then a concise literature review of existing sports ball friction testing devices. Next the contact conditions of an impact are quantified to aid in the design and development of a friction tester. The chapter concludes by describing the calibration procedures required to ensure the data acquisition is accurate.

4.2 Friction testing

4.2.1 Examples of friction testing
Friction between two surfaces has been subject to scientific investigation for hundreds of years. The need to establish friction coefficients has been driven by a wide range of applications from general material science through to safety engineering. Friction measurements required to characterise an interface may be simple (i.e. a sloped surface) or complicated depending on the materials and application. A tribometer is the common name used to describe a friction measurement device.
Blau (1996) describes a way to classify a tribometer into one of two categories depending on the conformity of the macro-contact.

- Conformal Surfaces – “fit together such that the nominal area of contact essentially does not change as wear occurs”. An example of this is a brake shoe interacting with a brake disc.
- Non-conformal surfaces – “whose centres of curvature are on opposite sides of the interface”. An example of this is two rollers touching tangentially or two gears interlocking.

Tribometers are designed specifically for their application and material pairing. They are designed to accommodate the material pair properties and the operating conditions under which the friction is to be measured. The operating conditions include the sliding velocity, temperature, normal pressure and/or load. Figure 4-1 illustrates 8 common tribometers. The sled device is perhaps the simplest form of measuring the static COF. Here a flat material sample is secured to the bottom of a block of mass and movement is initiated either by applying a force tangentially ($P$ as depicted in Figure 4-1) or by tilting the supporting surface by a certain angle. If the surface is raised at one edge to initiate the sample slipping then the coefficient of friction, $\mu$, is a function of $\tan \theta$.

![Tribometer Geometries](image)

Figure 4-1: Eight common types of friction testing geometries, Blau (1996)
For a soccer ball impact the operating conditions are complex. There is a combination of dry and fluid friction, varying normal pressures during each impact, high deformations and low to very high sliding velocities. Next follows a summary of tribometers with specific applications to sports balls.

adidas, the collaborating company for this research, has developed a tribometer for testing the friction coefficients of shoe sole materials. This conformal tribometer uses a constant sliding velocity and normal load to determine the pulling/pushing force required to move a sample against another sample.

The tribometer is built around a mechanical arm which securely holds two 40 mm disc samples of a test piece; one on the top of the arm and the other on the bottom. The mechanical arm slides at a fixed velocity between a clamp of two sample plates of the second test piece. A vertical force is applied to the clamp which provides the normal force to the motion. The vertical force can be adjusted depending on the needs of the testing. A load cell measures the horizontal force which is required to move the arm back and forwards. A customised LabView program on a PC connected via an amplifier to the tribometer simultaneously monitors the forces involved and produces a graph of the COF over a time period. A single cycle involves push and pull of the arm and the velocity of the motion can be adjusted up to approximately 6 mm.s\(^{-1}\). The COF is automatically halved due to having two contact surfaces. Figure 4-2 shows the set up of the tribometer and Figure 4-3 shows a schematic diagram of the mechanism and the forces involved. Figure 4-4 shows a typical output for a single cycle of a push and a pull of the arm.
Figure 4-2: The adidas tribometer illustrating the major components

Figure 4-3: Diagram showing the motion of the arm and the location of the forces

Figure 4-4: A typical graph output from the tribometer showing the COF as a function of time
The tribometer does not have a standard method of analysing the data output. However from the graph it is possible to assign where the $\mu_s$ and $\mu_k$ are located on the trace. $\mu_s$ is the peak at the start of each movement due to the force required to move the arm initially being greater than when it is sliding, $\mu_k$. The ‘noise’ of the signal is attributable to the ‘stick-slip’ mechanism. BS ISO 15113:1999, is the standard associated with the determination of rubber frictional properties. It describes a way to calculate values of $\mu$ from time-COF graphs. Figure 4-5 shows the parameters that are to be taken from a typical graph such as figure 4-4.

![Figure 4-5: British Standard determination of $\mu$ for rubber friction from a time-COF graph](image)

(Ref: BS ISO 15113:1999)

Where $H$ is the maximum point over a sample, $L$ is the minimum value, $A$ and $B$ are anomalies to be ignored and $F_n$ is the midpoint frictional force value for each cycle. The standard states the COF should be given as a range and a mean which are calculated as (4-1) and (4-2):

$$\text{Mean}(\mu) = \frac{F_1 + F_2 + F_3}{3} \quad \text{[Equation 4-1]}$$

$$\text{Range}(\mu) = H - L \quad \text{[Equation 4-2]}$$

The standard describes a protocol in which 3 material sample pairs are tested for 3 cycles as in Figure 4-5. For directional surface textures (i.e. grooves) the samples should be tested but in both directions.
4.2.2 Examples of friction testing of sports balls

The measurement of sports ball friction is extremely complex due to the operating conditions, the varying surfaces of contact and how to replicate impacts in lab conditions. Next follows a summary of research conducted in the field of sports ball friction measurement.

Bao et al. (2003) conducted an experiment to see whether the $\mu_s$ of a material was related to the spin of a tennis ball when bouncing off the strings of a racket. The basis of the friction material testing was taken from a standard regarding the friction on plastic film and frictional characteristics of textile (IS08925). The tribometer used is shown in Figure 4-6 and operates in a similar manner to the adidas tribometer. The strings were tensioned at 23 N and the normal pressures range from 5 to 22 kPa. Bao et al. state that the $\mu_s$ is the condition which imparts spin to the ball. Friction results indicated that as the contact pressure increased the $\mu_s$ decreased for three types of nylon tennis strings.

![Figure 4-6: Tribometer used for testing the $\mu$ of a tennis ball material on racket strings, Bao et al. (2003)](image)

For the ball-racket impacts carried out by Bao et al. (2003), a test was used where the balls were dropped from various heights to gain differing impact velocities onto an angled tennis racket of differing string types. The results from high speed video (frame rate not stated) showed that as the impact velocity increased the spin produced also increased. A speed ratio was derived (spin rate divided by impact velocity) to assess how well the strings imparted spin to the ball. As the speed ratio increased the COF also increased as indicated in Figure 4-7. This means that as more spin was generated the $\mu_s$ increased relatively. However the experiment only holds for low
velocity (<9 ms\(^{-1}\)). Therefore it cannot be assumed that higher velocities as seen in the game of tennis will be influenced by \(\mu\) in spin production.

![Graph showing how the static COF effects spin production, Bao et al (2003)](image)

**Figure 4-7: Graph showing how the static COF effects spin production, Bao et al (2003)**

The angled ball behaviour as described in 2.2.4.2.1 is often seen as the measure of friction between a ball and a surface for tennis (Pratt and Mahonen 2003) and general sports balls (Dunlop et al 1998). These two papers describe ways to measure the angled ball behaviour (or surface pace for tennis) without using a ball canon to launch a ball onto a surface with no initial ball spin.

Dunlop et al (1998) constructed a rotating drum onto which a ball is dropped. The drum is covered in the desired surface (e.g. synthetic tennis surface) and is rotated at the desired speed to simulate high speed ball impacts. Inbound angles are adjusted by moving the ball drop position horizontally. To gain results the drum speed is adjusted so that the falling ball rebounds vertically after impacting the drum. Spin and rebound velocity are measured and ratios of inbound conditions calculated. Dunlop et al stated that their results compare favourably to existing experimental data but the major drawback is that infill artificial turfs would not stay together on a rotating drum.
Pratt and Mahonen (2003) reported a technique and device to take measurements of the coefficient of sliding friction and the tennis surface pace rating. Three tennis balls were secured in a triangular configuration on the bottom of a heavy mass (13.6 kg). Accelerometers were attached to the plate to measure velocity changes of the device when struck by a 45 kg sledgehammer mounted as a pendulum and released at 45°. Pratt and Mahonen named the device the "friction sled". A mathematical equation of motion was formed to validate results. Reproducibility of the results is stated at 0.4% although no comparison was made to existing surface pace rating data for the experimental ball and surface. One concern raised by the author over the device was the part played by the damping and stiffness of the tennis balls and whether it affected the motion of the sled.

Golf is now a highly researched area for both clubs and balls. Ekstrom (1999) and Gobush (1996) describe ways to measure the coefficient of friction for golf balls. Ekstrom uses a type of tribometer where as Gobush uses a force plate to determine the COF of an oblique golf ball impact. Figure 4-8 shows the tribometer used by Ekstrom. A ball is held and driven into a set of clamps and the strain gauges measure the resistance to motion. Results showed that differences between balls could be seen and as the clamp surface roughness increased the COF increased also but then levelled off. However, since a golf ball is fairly rigid compared to a football it is doubtful whether this technique could be used for a deformable ball.

Figure 4-8: The tribometer designed by Ekstrom (1999),
where 1 = insert seats, 2 = inserts, 3=clamps and 4 = ball holder
Gobush (1996) used a force plate with piezoelectric force transducers to measure the normal and tangential forces of a golf ball oblique impact and then compared the measured COF against a mathematical equation based on the inbound and rebound conditions and ball inertia properties. The force plate COF was calculated by averaging the two forces and dividing as usual. Figure 4-9 shows good correlation between theoretical results and force plate results.

<table>
<thead>
<tr>
<th>Ball type</th>
<th>Incoming tangential speed (FPS)</th>
<th>Friction coefficient (photograph)</th>
<th>Friction coefficient (transducer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wound Balata</td>
<td>88</td>
<td>$0.280 \pm 0.02$</td>
<td>$0.300 \pm 0.02$</td>
</tr>
<tr>
<td>Two piece</td>
<td>85</td>
<td>$0.073 \pm 0.002$</td>
<td>$0.077 \pm 0.002$</td>
</tr>
<tr>
<td>Wound Balata</td>
<td>42</td>
<td>$0.370 \pm 0.03$</td>
<td>$0.380 \pm 0.02$</td>
</tr>
<tr>
<td>Two piece</td>
<td>42</td>
<td>$0.160 \pm 0.02$</td>
<td>$0.160 \pm 0.02$</td>
</tr>
</tbody>
</table>

Figure 4-9: COF comparison between two methods for golf balls, Gobush (1996)

Cross (2002a) describes two simple tests to determine the COF of sliding and rolling for a tennis ball. The COF of sliding was measured by inserting 4 tennis balls in a tray which was then pulled ball side down using a spring balance to get the force required to enable sliding. The normal force was provided by a 7.5 kg weight placed on top of the sled. The COF of rolling was found by again placing 4 tennis balls on the surface without the tray but with a weight platform on top. The platform was then pulled with a spring balance to enable the balls to roll. The results gained were compared to mathematical theories but not actual force readings of impacts.

Phoenix Tribology has developed a friction testing machine to test the interaction between soccer ball materials and artificial turfs for the Korea Institute of Sports Science, (Plint, 2005a). The machine, as shown in Figure 4-10 consists of a driven drum (in green) and a contacting flat plate. The maximum possible load is 1 kN and the maximum rotating speed is 750 RPM. The motor power for the drum is 4.4 kW. The friction is measured by monitoring changes in torque through the use of an inline torque transducer.
4.3 Soccer ball impact conditions

The objective for designing a friction tester or tribometer should be to match the exact contact conditions of the system under investigation, i.e. to simulate the real life situation. This is due to the fact that friction is not a material property but it is a property of a system in which the materials operate. This means that the data gathered from a test device are generally only valid for that tribometer, so if the machine has modelled the contact conditions sufficiently the data gathered can be considered representative of the real life system. Many people use machines that are inappropriate just because they are available and in doing so can obtain misleading results. This section outlines the contact conditions for a soccer ball impact making particular reference to sliding speeds and contact pressures.

4.3.1 Overview

The soccer ball comes into contact with many surfaces and materials during a game. The two main situations are a ball impacting a playing surface at an angle (oblique impact) and a foot impacting a stationary ball. In both cases, if the ball has no initial spin, the ball will initially start to slip against the other surface as the ball begins to deform. Depending on the friction between the two outer surfaces, the ball will continue to slip or it will grip the other surface. If it grips, the ball will lose tangential velocity and the ball will start to turn or roll during impact. As the ball leaves the surface the roll causes the ball to continue its rotation as spin during flight. If it
continues to slip, as in a wet contact, the tangential velocity will be maintained with little to no ball roll seen. Low friction situations cause a ball to maintain its tangential velocity and rebound at a near equal (and opposite) angle to its inbound direction. A ball with a higher friction condition will lose tangential velocity with some of this energy transferred into spin generation. Additionally the ball gripping the surface causes a steeper rebound angle. Therefore in a situation where a player is receiving a pass which bounces before the player, the friction between ball and surface can cause significant changes in the rebound characteristics.

The most critical phase during a game for ball and boot interaction is during a set piece kick where spin is usually applied. In the 1998 World Cup Finals, almost half of the 108 goals scored from open play used the instep spin kick, Grant et al (1999). Nielson (2003) discovered that for a maximal and instep kick the ball velocities averaged 27.05 ± 2.23 and 23.52 ± 2.31 m/s respectively for professional players. Average spin rates for an instep kick averaged 474.6 ± 136.2 RPM with a maximum of 833.4 RPM.

4.3.2 Contact pressure

4.3.2.1 Whole Ball

In order to determine the coefficient of friction it is necessary to quantify the contact pressures during a soccer ball impact a FE model created by Price (2005) was used. The model was a simple form of the adidas Roteiro ball used in the 2004 European Championships. The ball consists of a pressurised single layer shell which represents the various layers in the ball construction. Two hyperelastic materials (reduced polynomial) form the shell, the bladder and the outer panels. To assess the contact pressures, an oblique impact onto a flat rigid plate was simulated, as shown in Figure 4-11. With this setup the inbound variables were changed to gain a complete picture of the contact pressures involved for a variety of contact angles and velocities. The inbound angle, $\theta$ was changed from 10 to 80° in 10° steps and the inbound velocity, $V_i$ was changed from 5 to 35 m/s in 5 m/s steps. A simple (and computationally efficient) model was used to allow the high number of combinations (63), to be processed in a reasonable time.
In order to derive the contact pressure of an impact over time, the normal reaction force of the rigid plate and the contact area between the ball and plate were monitored. The normal force was divided by the contact area for each time interval, providing the contact pressure as a function of time. The results from simulations are shown for each velocity in Figure 4-12. As it can be seen, the contact pressures are of the same magnitude during the mid phase of the ball contact regardless of the inbound velocity or angle. At the start of the impacts, especially at higher speeds, initial peaks can be observed but these can be attributed to noise and discrepancies in the contact area output, i.e. no contact area being outputted, even though the reaction forces are being recorded. The reason that the pressures are at the same level throughout impact is that although the normal force increases, the area increases with a similar profile. The same is true of the decrease in force and area at the end of the impact, meaning that the resultant pressure traces approximate a square wave. Results from lower speeds, as shown in Figure 4-12(a) (5 m/s) illustrate this well.

From this it can be concluded that the contact pressures for a soccer ball impact (with reasonable deformations) will be in the range of 400 to 500 kPa, regardless of the inbound conditions. The FE data can be treated with some confidence due to the static and dynamic force measurement validation of the models carried out by Price (2005). Additionally Price (2005) has shown the ball deformations are also very similar to experimental testing, the contact areas can also be treated with confidence that they are of the right magnitude.
Figure 4-12: FE contact pressures over time for different velocity and angle combinations.
4.3.2.2 Localised

The approach taken in the previous section just looks at the magnitude of contact pressure for an impact but does not take into account whether there are any pressure variations in the contact area during an impact. In order to examine variation and to determine if pressure 'hot spots' appeared rather than a single value across the contact area two approaches were taken. Initially a FE model was created to simulate the problem before an experimental approach due to the unavailability of capable instrumentation. The FE model used was a development of the previous ball model with two layers of shell elements with anisotropic material definition used to simulate the warp and weft behaviour of the ball carcass construction. Figure 4-13 shows that the ball impacts a steel target plate which has been discretised into a refined mesh (5 x 5 mm) to output contact pressures between the outer ball surface and steel plate top surface.

![Figure 4-13: FE model setup to assess localised contact pressures](image)

Normal impacts with velocities from 5 to 35 m/s were processed as in the previous section. Additionally, oblique impacts at 15 and 45° with a velocity of 25 m/s were processed to determine if the localised pressure changed due to friction. Due to the low number of combinations, a developed model was considered more suitable to provide accurate results in the time period. Figure 4-14 and Figure 4-15 show the normal and oblique impacts respectively. The captures show ¼, ½ and ¾ of the contact time. The different velocities resulted in contact times which ranged between 8 and 10 ms. Using a typical colour map scale, reds represent high pressures through to blues which represent lower pressures.
<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Contact time (fractions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$\frac{1}{4}$</td>
</tr>
<tr>
<td>10</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>15</td>
<td>$\frac{3}{4}$</td>
</tr>
<tr>
<td>20</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>25</td>
<td>$\frac{3}{4}$</td>
</tr>
<tr>
<td>30</td>
<td>$\frac{1}{4}$</td>
</tr>
</tbody>
</table>

Figure 4-14: Normal impact contact pressure contour plots from the impact plate (all to the same contour scales)
From the normal impacts in Figure 4-14, which are all presented using the same scale, it is evident that the contact pressure remains fairly consistent across the area during the contact time. Additionally, there is no change in contact pressure from changing the inbound velocity which supports the findings from the previous section (4.3.2.1). However, at higher velocities during the initial stages of contact there are gaps in the pressure readings as shown clearly in the 30 m/s impact at $\frac{1}{4}$ contact time. Close scrutiny of the contacting surface of the ball model revealed that subtle vibrations meant that some areas of the ball were not in contact with the plate but were a millimetre or two away. It was unknown whether this phenomenon occurs in reality. Figure 4-15 shows the same output for 15 and $45^\circ$ impacts at 25 m/s. Again it can be seen there is a consistent contact pressure throughout impact and change in angle. Figure 4-14 also shows how the contact area increases with increasing velocity which agrees with the thought that the contact pressure remains constant throughout as contact area and reaction force increase and decrease together.

The validation of the contact pressures was carried out using a RSscan International footscan® 3D Gait Scientific system which consists of an array of 4096 individual piezoelectric pressure sensors in a 0.4 by 0.6 m mat. This size mat allows the system to be placed on top of a Kistler
force plate to integrate the force readings into the pressure distribution. This ensures that the pressure distributions are accurate as they originate from the z component force data.

Testing was carried out with the pressure mat laid on top of a force plate secured in the floor. The FE contact pressures were validated for the 2 m drop test (5.3 m/s normal impact) and an example of higher speed impact was carried out by throwing a ball onto the plate. The maximum recording speed of the system was 500 Hz which enabled 4 to 5 frames to be captured during contact. Additionally, the current software cannot output a colour map key to show what pressure is shown by the colours. Figure 4-16 shows the comparison for the 5 m/s impact. As can be seen, the pressure distributions look similar with no pressure hotspots or areas of non-contact between ball and surface. As the software cannot output the exact values of pressure or contact areas, the raw data was used to estimate the total pressure. This produced a range of values for the experimental pressure of 250 to 500 kPa which fits into the predicted pressures from the FE work.

![Figure 4-16: FE and experimental contact pressure distributions (not to the same scale)](image)

To supplement these results, additional impacts were carried out on two manually stitched balls with varying seam configurations at a higher velocity by throwing the ball onto the mat. Figure 4-17 shows a comparison of the Teamgeist ball which has a seamless construction compared to a 32 and 18 panel manually stitched constructions. The brief comparison clearly shows how the construction type and panel configuration can affect the contact between ball and surface. The
seams are visible on all 3 impacts with the manually stitched balls having clear areas of no contact at the interaction.

Figure 4-17: Experimental contact pressures at maximum deformation for different constructions soccer ball at a higher velocity (>5 m/s)

4.3.3 Sliding speeds

To assess the sliding speed contact condition during a soccer ball impact, two scenarios were investigated. The ball impacting the playing surface and a player’s boot were investigated to see what levels of sliding speed exist to aid the design the friction test machine.

4.3.3.1 Ball-turf

The ball impacting the turf is probably the most frequent interaction found during a game of soccer. Perhaps the most crucial interaction for performance benefits is the ball and boot interaction which is considered next. During a match a ball will bounce on the playing surface at a variety of speeds and angles. The simplest way to consider this is through an oblique impact as in the FIFA Artificial Turf tests described in section 2.2.4.2.1. Here a ball is impacted against a surface at an angle of 15° at approximately 14 m/s with no initial spin. This translates into a tangential velocity component (i.e. parallel to the impact surface) of 13.5 m/s which would indicate the sliding speed at the first point of contact. Friction between the ball and the turf would then act to slow down this sliding speed to cause topspin if sufficiently high enough. To consider all velocities and angles, a graph was produced to show what the tangential sliding
speed of an impact would be depending on the inbound velocity and angle which is shown in Figure 4-18. This was simply created by considering the initial velocity and angle to identify the initial velocity components (tangential and normal to the surface). Also it is worth noting that a ball with initial top or back spin would increase or decrease the speed respectively.

![Graph showing the sliding speeds of oblique ball impacts](image)

**Figure 4-18: Graph showing the sliding speeds of oblique ball impacts**

### 4.3.3.2 Ball-boot

To investigate the sliding speed of the ball-boot interaction, an experimental and FE approach was taken. The experimental testing was carried out at English Championship (2nd tier) football club Colchester United. Two first year professional players completed the testing. A HSV camera was attached to a custom built rig to film the player taking an instep curve kick from above. This kick type is where a player would be looking to score a goal direct from a free kick using the speed and spin of the ball to move the ball around a defensive wall and away from the goalkeeper. The HSV was the same as used for the ball launcher as described in chapter 3 and set to run at 2000 Hz. The experimental setup is shown in Figure 4-19(a). Figure 4-19(b) shows an example of the recording and (c) shows how the measurements were taken during digitisation of the images. To calculate the contact angle the ball trajectory was extended back towards the approximated heel-toe line. Ball spin and velocity were also recorded to compare to the literature. The results are shown in Table 4-1.
Table 4-1: Results from the player testing

<table>
<thead>
<tr>
<th></th>
<th>Player 1</th>
<th>Player 2</th>
<th>Total</th>
<th>Neilson (2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Velocity (m/s)</td>
<td>27.94 ± 1.6</td>
<td>25.87 ± 0.9</td>
<td>26.91 ± 1.6</td>
<td>23.42 ± 2.2</td>
</tr>
<tr>
<td>Ball Spin (RPM)</td>
<td>457.9 ± 100</td>
<td>383.8 ± 117</td>
<td>421.4 ± 105</td>
<td>474.6 ± 136</td>
</tr>
<tr>
<td>Contact Angle (°)</td>
<td>66.9 ± 1</td>
<td>64.3 ± 2</td>
<td>65.6 ± 2</td>
<td>n/a</td>
</tr>
</tbody>
</table>

As the results in Table 4-1 show, the data agrees well with the literature (Neilson 2003). From the experimental testing, player 1 achieved slightly higher spin rates and velocities. Both players’ standard deviations for spin rate were relatively high; however these values were very low for both velocity and more importantly the contact angle. The average contact angle for both players was 65.6 ± 2°. Using equations 2-2 and 2-3 (ball speed to foot speed ratio) and using a value of 1.1 from the literature the foot speed can be approximated to be 25 m/s. Therefore if the foot is simplified as a flat plate the scenario could be expressed as an oblique 25 m/s ball impact at 65°. This would indicate a tangential velocity or initial sliding speed of around 10 m/s.
Figure 4-20 shows how the FE approach was used. A model was developed using a basic adidas Roteiro ball in a simulation of the robotic kicking leg as described in chapter 3. Images in Figure 4-20(a) show a plan view of the start and end of the contact of the end-effector cylinder. The COF was set to be zero to enable the sliding speed to stay relatively constant throughout which would also be at its highest level.

Using the ball image at \( t = 0.01 \) seconds, the angle between the first point of contact (red) and the last point of contact (orange) was approximately 30°. The arc length about the end-effector cylinder was determined to be 2.4 cm. Therefore the ball can be assumed to have a contact distance of 0.024 m over 0.01 seconds thus approximating the sliding speed at 2.4 m/s. If the contact angle approach was taken as for the player testing and planar impacts, the contact angle would be 75° from a ball-cylinder offset of 4 cm. The cylinder velocity was 25 m/s which means the tangential speed will be about 6 m/s.
4.4 Design and development of the tribometer

4.4.1 Product design specification

After examining relevant literature, a product design specification was drawn up based on the elements laid out by Pugh (1991). Here follows a summary of the performance aspects.

Performance:
The test rig must be able to measure the coefficient of sliding friction between football material and a number of other material samples. The contact conditions have been investigated and the sliding speeds should ideally be in the range of 1 to 35 m/s. The contact pressures of a ball impact are equal across the contact area and are in the range of 400-500 kPa (maximum). Additionally the rig must be able to allow testing of wet samples. The rig must be stable, either through its own weight or by other means.

4.4.2 Concept design and selection

The concept design stage allowed various ideas to be put together and discussed. In the end three main concepts were chosen as the most suitable to match the contact conditions. The first two concepts involved a driven drum coming into contact with another drum or flat surface. The third involved a pendulum which comes into contact at the bottom of a swing and the swing through height is recorded. The three concepts were then marked against criteria such as ease of use, how to change material samples and whether the setup could match the soccer ball impact conditions. Each criterion was given a weighting from 1 to 3, with 3 being the most important. Each concept was then evaluated against the criterion and given a score from 1 to 4 with 4 the highest score. After considering the three concepts, the driven drum onto a flat surface provided the optimum solution.

4.4.3 Embodiment calculations

To make sure the correct components were ordered, some theoretical scenarios were chosen to enable some values to be used to select the parts. The most important part of the chosen design
was the motor which drives the drum at a constant velocity which allows for the change in torque to be monitored and therefore forces at the drum-surface interface. Using motor power and torque equations and the maximum impact forces and estimated COF of a football impact, the power rating of the motor was determined.

After using these maximum values, the torque produced would be around 360 Nm and the motor required to drive the drum at that torque would be over 110 kW which was considered too expensive for a project of this scale. The motor would have also been bulky and would have to be mounted on a complicated and expensive framework. The drum would also have to be balanced by an external contractor to prevent it vibrating and destroying the test rig. In the end the maximum motor power which could be obtained and taking into account cost and space considerations was 2.1 kW which allows a sliding speed at low COF (<1) of 5 m/s and >5 m/s at higher COF values depending on the gear ratios. One reason for this is that the maximum torque available decreases with speed. Therefore only low COFs could be tested at high sliding speeds. The motor was also controlled by an inverter which allows the monitoring of motor performance through the current feedback in the system to give speed and torque.

To apply the normal force to the surface contacting the drum, a lever approach was used. A sample tray was attached to one end of a 1 to 2 ratio lever and weights were placed at one end of the lever would provide twice the force at the sample end.

4.4.4 Test rig design and manufacture

The final design of the friction tester is shown in Figure 4-21.
4.4.4.1 Motor and Drum

The drum could have been driven by a motor which was either mounted in-line with the drum or driven via a belt or chain. It was decided that the best option was to drive the drum by a toothed belt and mount the motor parallel to the drum and axle as this method was the most economical with space. The drum has been balanced to run at the expected speeds and sample materials can be attached by using high strength double sided floor to carpet tape. To aid the attachment of the material around the drum, a 1.3 mm deep by 10 mm wide channel has been machined to allow the ends to overlap where they meet. This allows the join of the material to be as minimal as possible and should prevent the material fraying at the join. Figure 4-22 illustrates this. A standard sample of outer soccer ball panel material is approximately 1 mm thick.
4.4.4.2 Lever Arm, Tray and Pivot

It was decided that the simplest method of applying a load to the drum was by using a lever arm with a tray to hold the sample on it. A load is applied to the arm at the opposite end of the sample tray. A ratio of 2:1 was decided on for $d_1$ and $d_2$ so therefore two times the load placed on the lever would be applied to the drum due to mechanical advantage. It was also necessary for the sample tray to be accessible so the sample could be changed and a number of solutions were considered. The solution that was decided was to have a lever arm sliding through a pivot block and to have a locking pin that would secure the arm in position.

4.4.4.3 Cam and Drive System

A mechanism was needed that would load and unload the lever for a set time to prevent the sample getting too hot and micro welding occurring. It was decided the best method of achieving this would be to move the lever arm up at the loaded end, moving the sample tray away from the drum. A method using a cam driven by a small motor was developed where a micro-switch controls the motor and ensures the cam only rotates once and stops when the sample tray has been moved away from the drum. The motor can rotate at 28 RPM producing approximately 3 Nm running on a 12 V power supply.

The lever arm follows the cam’s profile via a cam follower. Where the radius of the cam is largest, the cam follower lifts the lever arm and moves the sample tray away from the drum. As the cam rotates round to where the radius of the cam is the smallest, the tray is gradually moved...
towards the drum and as the sample comes into contact with it, the cam follower no longer follows the profile of the cam.

4.4.4.4 Frame and Electrical Components

Once the working mechanism of the test rig had been finalised, a supporting frame and cage were designed to mount the test rig in. The cage protects users from mechanical trapping and abrasion hazards. The electrics have also been shielded against water to prevent electrical hazards when wet samples are used. The cage has a lockable access hatch to allow access to the samples in the sample tray and on the roller. All framework was assembled from custom lengths of Rose and Krieger 40 x 40 mm heavy duty Bocan aluminium framework.

4.4.4.5 Inverter and Feedback System

To ensure that the drum rotates at a constant, known speed, a feedback loop has been built into the system. An encoder is attached in-line to the motor shaft and the output of the encoder is fed into the motor controller. This forms a closed loop system. The encoder feeds back the speed of the motor to the controller and the controller adjusts the voltage to the motor to keep the speed constant. In the original concept, the torque was to be measured by an in-line torque transducer. However a torque transducer plus couplings were found to be too expensive at the initial design stage so an alternative method was sought. It was found that the specified Toshiba inverter was able to give an output of torque as a percentage of the motor power to a PC via an interface cable so it was decided to use this option as a starting point using (4-3) to convert to Nm.

\[
\text{Torque (Nm)} = \frac{\text{Torque(\%)} \times 2.2 \times 9550}{\text{RPM}}
\]  

[Equation 4-3]
4.5 Calibration

The calibration of the friction tester was required to validate any readings gathered by the inverter. The torque measured by the motor inverter was calibrated by two methods and the normal load and pressure was measured.

4.5.1 Torque

The inverter measures changes in torque by monitoring the power and electrical current from the motor. However, it was not known how accurate this technique of torque measurement was which would be essential for the readings taken. As the installation of a torque transducer was expensive an old fashioned approach of a Prony brake was initially used until a torque transducer became available.

4.5.1.1 Prony brake

The Prony brake was invented by Gaspard de Prony to measure torque produced by a motor or engine. The device does have a few variations but essentially applies a friction or load to the rotating shaft. For the friction tester, the shaft passing through the material drum and pulley was extended and a smooth hollow pulley attached with a taper bush. The hollow pulley was then filled with water to aid the cooling of the belt-pulley interface. An inextensible fabric based belt was placed around the smooth pulley and attached to two spring balances mounted above, as shown inset in Figure 4-23. As the belt is tighten the force increases to the desired amount. As the pulley rotates within the belt, the scales adjust to a running torque, i.e. one scale gives a decreased measurement of force whilst the other gives an increased measurement depending on the rotation direction of the pulley. This method allows the application of a known torque in the system. The torque is calculated by multiplying the radius of the smooth pulley by the difference in readings of the scales.

The tests were carried out at 3 loads over a range of speeds and the difference between the applied torque and measured torque is shown in Figure 4-23. A positive difference indicates that the inverter is underestimating the torque and a negative difference indicates an overestimation of
torque. As shown the readings are similar between 100-250 RPM at all loads but the inverter overestimates at low speeds and underestimates at high speeds.

Figure 4-23: How the inverter torque measurement varies with speed and load using a Prony brake technique

4.5.1.2 Torque transducer

A torque transducer was available to use on a rental schedule which enabled further calibration of the torque readings of the inverter and initial work carried out by the Prony brake. The torque transducer was rated up to 100 Nm and fitted into the current system using torsionally rigid bellows couplings which offered a high degree of misalignment compensation due to their flexible middle. For this calibration a known load could not be applied as the Prony brake system could not be mounted at the same time. Therefore two scenarios were used to gain sets of data for comparison. Using the contact conditions in the previous sections, a rotational speed of 200 RPM was used to test boot-ball materials and 600 RPM (maximum allowed) to test Astroturf-ball materials. These speeds of the drum represent close matches to the sliding speeds encountered for each material combination. The normal load was restricted to one weight which created a normal force of 90 N at the material interface. Figure 4-24 shows the results from the testing. Three ball materials were used in wet and dry conditions on either the K-Leather or Astroturf. Each contact was repeated five times to gain an average.
Figure 4-24: (a) Shows example torque readings and (b) shows a summary of the results
Figure 4-24(a) shows examples of the traces at the two speeds. For the 200 RPM (which equates to a sliding speed of approximately 2-3 m/s) the torque traces for the inverter and torque transducer are very similar at both the high and low frictional conditions created by the dry and wet situations. The torque transducer offers a higher sampling frequency than the inverter. The inverter operates at 4-5 Hz whereas the torque transducer is nearer 40 Hz. For the higher speed condition the inverter is underestimating the torque. The speed of the drum was monitored to detect any changes during contact but these were less than 5% even at the high speeds.

Figure 4-24(b) summarises the calibration to show the comparison between torque transducer and inverter averages. As seen, the 200 RPM speed shows good correlation even if the sampling frequency is much lower for the inverter but at higher speeds there are significant differences between the two measurements. The underestimation of the torque readings at higher speeds above 250 RPM confirms the Prony brake approach.

4.5.2 Normal load

The normal load used to calculate the COF for the torque transducer calibration was estimated by assessing the weights acting at different positions on the lever to bring the surfaces in and out of contact. With one 7.5 kg weight added to the opposite end, a normal reaction force of 90 N could be achieved at the interface. The force could be increased as more weight was added to the weight stack end although the motor to drive the cam system could not operate more than one weight.

4.5.3 Contact area and pressure

The contact pressure was estimated by placing a strip of pressure sensitive ink paper and applying the normal force without the drum rotating. The area was approximated to be 0.001 m² (0.1 by 0.01 m). One weight as used created a contact pressure of 90 kPa. If the cam motor was to be upgraded, a contact pressure of 400-500 kPa could be achieved by using 4-5 weights.
4.6 Summary

This chapter has described the design and development of a friction tester for soccer materials. The contact conditions were examined to help in the development process where it was found that sliding speeds could reach up to 35 m/s and average contact pressures of 400 to 500 kPa were experienced. After analysing existing friction testing machines for sports ball and other industries the contact conditions were needed to be modelled accurately. A block on rig approach was chosen where the torque was monitored to assess the frictional forces. Calibration has shown that the motor inverter on its own cannot accurately measure torque at all speeds and loads. With an upgraded cam motor the contact time could be reduced from 1 second and move larger weights. This would benefit the system by shortening the contact time and more exactly simulating the intended contact pressures.
5 The effect of adding a surface texture to a soccer ball

5.1 Chapter overview

The surface of a soccer ball varies from manufacturer to manufacturer where improvements to the control, aerodynamics, hydrodynamics and ball perception are sought. These ball characteristics are not considered in FIFA’s Laws of the Game and the FIFA Quality Concept. Therefore the only regulation concerning ball factors outside of the rules is whether the match referee (or FIFA) decide that it may cause a danger to the players. It is apparent that there is little published literature surrounding the effect of a surface texture on dynamic ball performance. In order to design a ball with improved performance consistency between dry and wet, the effect of varying the outer ball surface texture needs to be considered.

The three major companies who have previously added a texture to a soccer ball are Nike, Mitre and Puma. The Puma Shudoh soccer ball is perhaps the most unique as it has adopted the golf ball dimple concept, perhaps seeking the same benefits of the dimples on the golf ball with respect to flight range. The Nike Total Aerow 90 soccer ball, currently in use for the 2005-2007 English Premiership League seasons, has a texture in the form of microscopic channels giving the ball a cloth like feel. According to marketing information from the manufacturer, aerodynamic performance benefits rather than grip improvement was sought by this innovation. The Mitre ball describes its micro texture will have benefits to goalkeepers although no test results are mentioned.

5.2 Oblique Impacts

A series of experimental tests were carried out using the LU STRG ball launcher to create game relative ball velocities for a series of impacts on a planar and cylindrical surface. These impacts
were performed in order to assess whether adding a surface texture to a soccer ball created any significant changes in rebound behaviour between dry and wet conditions.

5.2.1 Testing Protocol

The ball launcher was set up as explained in chapter 3 with the HSV camera set up perpendicular the ball trajectory. As well as the flat planar surface of the target plate, a steel cylinder was attached to achieve an impact on a different shape e.g. a goal post. Both the planar and cylindrical forms had materials attached to give a realistic contact pairing as seen during a game. The majority of the testing was carried out using a Kangaroo Leather (K-Leather) but also a carpet style Astro-Turf and goalkeeper glove palm latex foam. These materials were attached to the target plate as described in section 3.2.1 and as illustrated in Figure 3-3. The balls used were of the 2006 adidas Teamgeist construction with the standard smooth surface finish and also varying textures. The only differences between the balls are the surface textures as shown in Figure 5-1.

![Figure 5-1: The ball textures used in the experimental testing](image-url)
The ball launcher was set up to achieve 25 m/s ball velocities ($V_{in}$) towards the plate or cylinder which in turn were positioned or rotated to achieve varying inbound impact angles ($\theta_{in}$, as shown in Figure 5-2(a)). The valve of the ball was positioned to face the camera, so the axis of spin should nearly always be through the valve-counterbalance. To overcome ball variability, 5 repeats were taken for each condition which was created by specifying 5 equally spaced points around the equator of the ball if the valve-counterbalance axis acts as the pole. A wet condition was created by using a spray bottle to cover the surface equally. For the wet impacts, the surface was dried between water applications to ensure the same amount of water was applied for each impact. Several water spray bottles were compared to ensure that the bottle chosen had the most uniform characteristics.

The 5 repeat tests for each condition also accounted for any differences in ball deformation caused by the inner carcass as described in section 5.5. The metrics taken were the outbound spin rates, rebound angle ($\theta_{out}$) and oblique COR ($V_{out}/V_{in}$). Additionally for the planar impacts, the surface pace was taken which is simply the COR of just the horizontal velocity components. Figure 5-2 shows which metrics were taken for each scenario. The metrics chosen for this study were those that would be noticeable to a player during a game. The speed, angle and spin of a bouncing ball are what a player would notice most.

![Figure 5-2: (a) Shows the metrics for the planar impacts and (b) shows the metrics for the cylindrical impacts](image)

### 5.2.2 Results

The results section presents the data from low and high speed impacts on a planar surface and high speed impacts onto a cylindrical surface.
5.2.2.1 Planar Impacts

5.2.2.1.1 High Speed (25 m/s)

The data from the testing onto a flat planar surface covered by a K-Leather surface are shown in this section. Figure 5-3 shows the rebound spin rate for a textured and standard ball in wet and dry conditions at a range of angles at 25 m/s. The ball launcher produced a consistent inbound velocity of 25.23 ± 0.8 m/s from a sample of 40 trials. Figure 5-3 shows the dry impacts for both the standard and textured ball to be very similar in terms of spin rate. Both followed a linear trend with the highest spin at the shallow angles and the lowest spin near a normal impact. The correlation of coefficients for these two sets of data were very high, 0.97 and 0.96 for the textured and standard ball respectively for dry impacts. The wet impacts showed a different trend. In general for both ball types in the wet, there was minimal spin at shallow angles which then increased to around 600 RPM and then dropped back to near zero as the angle tended towards a normal impact. Between 15 to 50° the impacts in the wet showed some differences between the textured and standard ball. The textured ball showed a more consistent spread of spin rate data at each angle whereas the standard ball had greater directional deviation. Additionally at 50° the biggest difference is seen. In general the spin rate of the textured ball in the wet was found to be the same as it was in the dry. The spin rates of the standard ball in wet and dry did not match until the inbound angle increased to 60°. The point at which the spin of a wet impact is the same as the spin of dry impact is perhaps an important feature of determining differences between ball types. After 60° all of the impacts from both balls, wet or dry followed the same trend as the spin decreases.

The trend of the measured performance of wet impacts matching those of dry impacts at certain angles is also shown in the following graphs. In Figure 5-4, the surface pace is shown and as would be expected, high spin rates would indicate lower surface pace values. For example at 15° where the greatest difference between wet and dry impacts was found, a dry impact had a rating of approximately 0.55, (i.e. 55% of its initial tangential velocity was conserved) whereas a wet impact was found to have nearer 0.95. Where the spin rates converge in Figure 5-3 at approximately 60°, so do the surface pace values.
Figure 5-5 shows the outbound angle and all ball and condition combinations show very strong linear correlation coefficients (all >0.98). Again as with the first two graphs, the dry and wet impacts converge with a similar trend and values at an inbound angle of 60°. At 15° the difference between a wet and dry impact rebound angle is approximately 10°. There are no noticeable differences between a textured and standard ball with respect to the rebound metrics.

Figure 5-6 shows the COR from the magnitude of the velocities before and after impact. Here the results are mainly affected by the loss of conservation of tangential velocity as shown in the surface pace graph. The largest differences between wet and dry are seen at shallow angles where the surface pace has the greatest influence. Again the values converge at angles of 60° or more.

To illustrate some of these findings Figure 5-7 shows still images from the video captures on the left hand side for two angles ((a) 15° and (b) 60°). This shows how the rebound behaviour of the same ball can be very different between dry and wet conditions at shallow angles but similar at steeper angles. On the right hand side some simple digitisation of the rebound is shown, indicating the trajectory, speed and spin. The images show the dry impacts with red outlines and wet impacts with blue outlines. A composite image of a series of digitised frames of a wet and dry impact for both angles is then shown at the bottom of these images for comparison. This allows the visual differences of the graphical results to be seen. The 15° impacts show clearly how the speed, angle and spin are all affected by the wet condition. In a dry condition, the ball was observed to slow down significantly, increasing the rebound height and undergoing approximately ¼ of a revolution as compared to a wet impact where the ball was observed to slide throughout impact causing minimal deceleration. Additionally as the ball did not grip the surface sufficiently to cause rolling, the rebound height was lower and the tangential velocity was maintained. Compare this to the second example at 60° where the frictional condition was changed but the rebound characteristics were very similar in terms of speed, angle and spin as shown in the composite digitised image.

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Figure 5-3: Scatter graph showing the outbound spin rate

Figure 5-4: Scatter graph showing the surface pace
Figure 5-5: Scatter graph showing the rebound angle

Figure 5-6: Scatter graph showing the overall COR
Figure 5-7: Video captures and digitised images to illustrate rebound characteristics from a planar surface.
To determine whether the texture type caused differences in results, the data for the diamond and Propeller textures were added to the results with the Fujiama texture used in the first part. Figure 5-8 and Figure 5-9 show the spin rate results for a 25 m/s impact at 15° and 45° respectively. Additionally, an artificial turf carpet and foam based material from the palm of goalkeeper gloves were also used to see how the rebound characteristics were affected. From Figure 5-8, it can be seen that the ball texture type and surface material have little influence on the spin rate. From these shallow impacts it can be determined that the wet/dry condition has more of an effect than any other factor. Figure 5-9 shows the spin rates at 45°. Here it is seen that the dry results for all combinations are very similar but in the wet condition differences can be observed between textures (especially on the leather surface). The Astro-turf produced higher spin rates in the wet than the leather as the water lies on the surface on the leather whereas on the turf it was able to drain to the base of the fibres. Both graphs are set to the same scale to illustrate the differences in the magnitude of spin between a 15 and 45° scenario.

![Figure 5-8: Scatter graph showing the spin rate from 25 m/s at 15° impacts for ball textures and surfaces](image-url)
5.2.2.1.2 Low Speed

The low speed testing was carried out using a vacuum controlled ball drop test mechanism. This mechanism held the ball via a vacuum at the specified drop height which allowed the controlled drop of the ball for recording the impact with the HSV. The same target plate as used in section 5.2.1 was used allowing impacts at the same range of angles. Again, only the spin rate results are presented as these showed the differences between ball texture, surface and condition combinations.

Figure 5-10 shows the results for the 15° impacts at approximately 5 m/s. The vacuum controlled ball drop test mechanism also ensured that the drop height was always the same resulting in the same impact velocity. Here it can be seen that the lower velocity resulted in spin rates approximately 1000 RPM less than those measured in the previous higher speed tests. As with the high speed tests at 15°, the surface wet/dry condition was found to have the greatest influence with the target surface type the next most significant. In terms of putting the factors in order of significance, the ball texture type was found to be the lowest.
The results for a 45° impact are shown in Figure 5-11. Here it can be seen that the wet and dry spin rates were found to be very similar for all combinations except for the standard ball where a reduction in spin in the wet condition was observed. The spin rate was found to be reduced from 200 RPM to 100 RPM although the standard deviation was found to be doubled. To show this difference for a smooth ball and standard ball on the leather surface, the video captures are shown in Figure 5-12. As with the analysis for the high speed tests, the digitised images have been grouped together for a wet and dry impact for each texture to show the effect of the presence a texture against the absence of a texture. The ball in the example had the Propeller texture and shows little or no difference between wet and dry conditions. The standard ball however shows how both the spin and angle change.

![Figure 5-10: Scatter graph showing the spin rate from 5 m/s at 15° impacts for ball textures and surfaces](image-url)
Figure 5-11: Scatter graph showing the spin rate from 5 m/s at 45° impacts for ball textures and surfaces.

Figure 5-12: Video captures for the standard and textured balls for a 5 m/s impact at 45° digitisation to show the dry to wet differences.
5.2.2.2 Cylindrical Results

The impacts on to a cylindrical surface were carried out in the same manner as the high speed impacts on the flat planar target in section 5.2.2.1.1. As the inbound angle was difficult to predict, the cylinder was positioned in different positions to gain impacts from very shallow, glancing impacts before being adjusted gradually to obtain near normal impacts. The inbound angle was then measured from the HSV. The shallowest angle achieved was about 25° and the testing produced an even spread of data across the range up to 80°.

Figure 5-13 plots the spin rate as a function of the inbound angle. It can be seen that the dry spin rates for both textured and standard balls were found to be low at glancing impacts but increased sharply to a peak of 1400 RPM at 40°. From 30° to 40° the spin increased by almost 1000 RPM, indicating that the spin generated was very sensitive to changes in angle. The spin rates then decrease linearly towards zero as the impact angle approached the normal. The wet impacts followed a similar trend but with much lower levels of spin. The spin was measured to increase from near zero up to a peak of 600 RPM where the results were found to converge with the dry condition levels of spin. The wet impacts were observed to decrease in a similar fashion to the dry condition. This trend of the wet and dry impact results converging at higher contact angles was similar to that seen in the planar impacts. Examining the differences between a standard and a textured ball, it can be concluded that the results were similar in the dry but the textured ball produced slightly higher and more consistent levels of spin in the wet.

Figure 5-14 shows the resultant rebound angles. The rebound angle was calculated differently to the planar impacts as the outbound angle was measured from the inbound trajectory of the ball rather than the surface. Therefore a 0° angle would indicate the ball rebounded in the same direction as it approached, a 90° impact would bounce perpendicularly to the original trajectory and 180° would indicate that the ball continued in a straight line. The graph shows that at shallow angles the dry and wet impacts are similar but then separate as the angle increases and then they converge again at the steeper angles.

Figure 5-15 shows the velocity ratio of the impacts. The trends of the data are the opposite of the spin rate. For example in the dry condition for both balls, a sharp decrease was observed as the
angle was increased from 20°, with a minima observed at 40° before increasing. The wet impacts from the shallow angles up to 60° maintain velocity as the ball slips across the cylinder and therefore have a higher COR. As with the previous graphs, the wet and dry values are close at glancing impacts but then separate until a maximum at 40° and then converge at 60°.

Figure 5-16 shows two examples of the wet and dry conditions at two angles; (a) 40° which shows the largest differences and (b) 70° to show how the impacts are similar. Each angle shows a textured ball in the dry and wet conditions in video captures then as before as a collection of digitised images. Again each angle is summarised as a composite digitised image with the wet and dry trajectories plotted. For the 40° impact, large differences were seen in the rebound characteristics whereas the speed, spin and angle were much more similar in the 70° example.

![Figure 5-13: Scatter graph showing the outbound spin rate](image-url)
Figure 5-14: Scatter graph showing the rebound angle

Figure 5-15: Scatter graph showing the overall COR
Figure 5-16: Video captures and digitised images to illustrate rebound characteristics from a cylindrical surface
5.2.3 Discussion

The experimental testing has revealed some interesting trends for a soccer ball in wet and dry conditions depending on its texture. The following discussion is presented which relate these results to a game scenario and the energy transfer of an impact.

Initially the results are compared to a game scenario. When a player takes a free-kick in which they apply spin, the player will angle their foot accordingly. From the previous chapter the players tested recorded a contact angle for an instep swerve kick of $65.6 \pm 2^\circ$. Even though the geometry of the foot has not been exactly matched in the testing, the planar and cylindrical surfaces should give some indication on how the contact conditions affect ball performance in terms of velocity, spin and angle. The high speed impacts are in the velocity range achieved by players taking the spin kicks so at the $65^\circ$ inbound angle a comparison can be made between the ball impacts and player’s kick. In all the results for the planar and cylindrical outbound metrics, there was a convergence of the wet and dry data as the inbound angle increased. This point was about the 60-70° range for both. Therefore it could be concluded that whatever the frictional condition at the interaction, i.e. texture or environmental condition, the overriding factor was the contact angle. If the player struck the ball correctly it would not matter what the wet/dry condition was or the type of surface texture used. However if the dry to wet consistency was improved, the convergence of data between would occur at a lower angle meaning that there would be more scope for error from the player point of view in how the boot contacts the ball.

To assess the ball impact from a different perspective, Figure 5-17 summarises the energy transfer for an oblique impact with no initial spin. Ignoring gravity, the inbound ball will have the kinetic energy from its translation velocity and no rotational energy. After impact the energy will be conserved or converted into other forms. These are translational velocity, rotation and others, including heat and sound. For a low frictional condition, the velocity component after impact will be high as seen in the results, the surface pace is near 100% for shallow impacts and the spin rate is low. In high frictional conditions, more spin is produced and more tangential velocity is lost causing more energy to be transferred as a rotational component.
\[
\frac{1}{2} m v_1^2 + \frac{1}{2} I \omega_1^2 = \frac{1}{2} m v_2^2 + \frac{1}{2} I \omega_2^2 + \text{loss}
\]

Figure 5-17: An energy analysis of a ball impact

5.3 Robotic Kicking Leg

5.3.1 Test Setup

Chapter 3 outlined the typical test set up for the robotic leg testing. As this test was to assess the effect of adding a texture to a soccer ball, the equipment setup was left constant throughout. The ball centre-cylinder centre offset was set to 4 cm to achieve spin rates of around 300 + RPM with a ball velocity of 25 ms\(^{-1}\). These values were chosen to recreate what players achieve when they take direct free-kicks from outside the penalty area, Nielson (2003). This was found by carrying out an initial study as described in section 5.3.2. The target was placed 18 m from the direction of a straight kick then moved perpendicularly to accommodate the lateral shift in ball direction which was approximately 5 m.

As with the testing carried out with the ball launcher, a standard smooth ball and textured ball were used to complete the tests with the robotic leg. Figure 5-18 shows the two types. The textured ball was called Flags as the texture consisted of an array of striped and crossed Flags. Each ‘flag’ was approximately 5 mm by 5 mm and 0.2 mm high. The balls are referred to as Standard and Flags throughout this work.
The leg speed was set to its maximum and through initial testing the leg velocity was shown to have a very high consistency. This was monitored by measuring the time taken for the leg to pass through a laser gate positioned normal to the motion of the swing. Even during the testing it was still monitored to ensure that any significant changes in velocity were identified and kicks repeated if necessary. To ensure a statistical validity of the data, 6 points around the equator of the ball were chosen to be impacted with the valve acting as the ‘North Pole’, with three repeats on each point. The valve was placed at the top (with the counterbalance at the bottom) to minimise the effect on spin rate caused by any out of balance or localised changes in stiffness present in the ball (Price 2005 and Nielson 2003). A laser positioning system was used to enable the ball to be placed on the tee in exactly the same orientation for each kick, as seen in Figure 5-19. The laser also helped align the equator of the ball horizontally and allowed the chosen contact point to be aligned with the cylinder. Six points around the ball were chosen to mitigate any differences in deformation behaviour caused by the anisotropic nature of the weft and weave of the carcass panels as described by Price (2005). As also seen in Figure 5-19, a yellow spot was placed to the left which was used as the spin reference point. The same laser positioning system was also used to position the target as also seen in the background of Figure 5-19.

Figure 5-18: The Standard smooth ball (a) and the textured ball 'Flags' (b)
Four surfaces were used on the kicking foot to gain more information on the effect of the texture, as results for one material may have been surface specific and were unlikely to be representative of all boot materials. The plain aluminium cylinder (with no material) was used as the reference surface and three boot upper materials were compared; a kangaroo leather (natural), a leather synthetic (PU) and a rubber based material (RLT). These materials either have been or are likely to be used in soccer footwear products in the future. Testing was carried out in wet and dry conditions and a spray bottle was used to consistently and easily create a wet environment. Both the ball surface to be contacted and the cylinder were each sprayed twice for each kick.

5.3.2 The effect of changing the ball-cylinder offset

To determine the correct ball placement on the tee and the ball-cylinder offset, a study was carried out to see the effect of changing the offset from 0 cm (i.e. a straight kick) through to a 5 cm offset (see Figure 3-10(a)). The aim was to choose an offset that created similar spin rate levels and velocities to those of a free-kick style curve kick as described in section 4.3.3.2.
For this study, a single ball was used, with 5 repeats for each offset in a dry condition. To assess the impact of the change in offset, the ball velocity, spin rate and launch angle were measured. As compared to Figure 3-9, the camera was positioned perpendicular to the trajectory of a straight kick and the impact location target only 10 m away. The HSV field of view covered the initial launch from the impact of the leg and to record one full revolution of the ball. The initial ball trajectory was used to measure the ball velocity (using the time frame and distance using the ball diameter as a scale factor) and the launch angle from the horizontal. The remaining ball trajectory allowed the measurement of spin. For the smaller offsets, lower levels of spin were seen so only ½ a revolution was used for assessment. A second marker was placed diametrically opposite the original marker to allow this.

Figure 5-20(a) shows how the ball spin rate is affected by changing the offset. As it can be seen, changing offset from 2 to 5 cm causes a direct change in spin rate. Each additional centimetre increases the spin rate by approximately 50 rpm. There is no data for 0 and 1 cm due to the resultant low ball rotation making it very difficult to determine ¼ or even a ⅛ ball revolution required to calculate the spin. Above 3 cm, at least 1 full revolution was seen for every kick. The 4 and 5 cm spin rates fall within the average ± 1 SD of Nielson’s (2003) player data, (475 ± 136 RPM).

Figure 5-20(b) shows how the ball launch velocity changes with offset distance. As the offset increased, the ball moved further away from the camera so only the velocity in the perpendicular direction could be determined. The velocity was found to stay relatively constant from a straight kick (0 cm) through to a 4 cm offset at approximately 25 m/s. At 5 cm the velocity was found to decrease slightly as more rotational energy is applied to the ball. All offset velocities fall within the range found be Nielson (23.5 ± 2 m/s)

Figure 5-20(c) shows how changing the offset affects the launch angle. As the ball is moved further away from the cylinder centre, the less likely the leg is to strike the ball below the equator and more so the side of the ball causing a lower launch. Additionally at 5 cm the SD of the data is much larger than the previous smaller offsets which may indicate that the results are less repeatable.
Figure 5-20(d) shows how the offsets affect the flight repeatability of the ball trajectory. This is of interest for setting up the target for the actual testing and making sure the trajectory replicated a real life free kick. At 0cm the ball was found to impact slightly to the right of a straight kick but only by one ball diameter, i.e. 0.2 m over the 10 m distance. By adding 1 cm offsets, the ball trajectory is moved by 1 m at the target distance for each cm.

After considering the data collected, it was decided to use a 4 cm offset due to the reduction in velocity and launch angle seen at 5 cm. The ball velocity and spin rate data at 4 cm fit within the player testing data collected by Nielson (2003), therefore this set up for the robotic leg would in theory replicate a free-kick/instep curve kick for a player.
(a) The effect of changing the ball-cylinder offset on spin rate

(b) The effect of changing the ball-cylinder offset on ball launch angle

(c) The effect of changing the ball-cylinder offset on ball launch angle consistency

(d) The effect of changing the ball-cylinder offset on ball flight consistency

Figure 5-20
5.3.3 Robotic leg kicking

5.3.3.1 Spin

The 288 kicks for the experiment were analysed as described in chapter 3. The data for the spin rates are grouped by material type and presented by ball texture type with wet and dry condition denoted by blue and orange colours respectively in Figure 5-21.

![Figure 5-21: Scatter graph of the spin rate raw data comparing the materials and ball textures](image)

As it can be seen for the first two columns of each material, there is very little change between wet and dry for the 'Flags' texture ball. Additionally the dry performance between the Flags and Standard is very similar. The major repeating observation for each material is the wide variation in spin rates for the Standard ball in the wet compared to the other groups of data. The wet variation of data for the Standard ball is over four times as much as the Flags in both wet and
dry, and the Standard in the dry. The pattern is practically identical for all the surfaces. The Flags in wet and dry and the Standard in the dry have a range of approximately 50 RPM whereas the Standard reaches a range of around 200 RPM across the surfaces. Additionally the spin rate decreases significantly in the wet for the Standard ball while the Flags ball in the wet maintains a spin rate somewhere near the overall mean.

5.3.3.2 Flight Consistency

The flight consistency is plotted as an average point in x and y with ±1 standard deviation error bar added to provide some indication of significance to the data. Each average point is based on 18 kicks which gives a good level of statistical validity. Figure 5-22 show the plots of each ball in the dry and wet for the four surfaces. The horizontal distance is measured from the position of a straight kick as shown in Figure 3-9.

For the consistency plots a picture of the target is scaled and placed behind the graph to give an indication of the real life result, (the target is 3.16 m by 2 m). As seen all four surfaces provide varying results. The results from the K-leather showed some significant differences between the average points and favour the results seen in the spin rate data. The K-leather results show that the Flags in wet and dry and the Standard in the dry have a similar accuracy position whereas the Standard in the wet has an increase in x position and a decrease in height. Figure 5-23 shows a composite image of the HSV recording used to calculate spin rate but also shows clearly the trajectory differences in the wet between a texture and standard ball.

From these data it can be concluded that the spin rate data do not automatically replicate what is seen in the accuracy data. For example, the 3 boot upper materials produced very similar spin rate data patterns but gave 3 varying flight consistency plots. The consistency therefore is dependent on the launch angles (how far the ball slips around the cylinder), the resultant spin rate, launch velocity and then the aerodynamic effects. To see how much lateral deviation (i.e. an increase in X) is due to the aerodynamic effects a trajectory simulator, using typical soccer ball drag and lift coefficients, was used. The trajectory simulator forms part of the software used by the soccer ball launch condition acquisition system, QuinSpin.

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Figure 5-24 shows how the lateral swerve distance increases with spin rate for a kick over 10 m and over 20 m. From the spin rate data, the average value was approximately 300 RPM resulting in a lateral swerve distance of 1.4 m for a kick of around 20 m in range. It can be seen that the longer the kick the more of an effect the spin rate has on the swerve distance. For the ranges shown for 10 and 20 m, an increase from 200 to 500 RPM gives a difference in swerve of 0.22 m and 0.91 m respectively for the ranges. Therefore the difference for 10 m is only a ball diameter for the spin range whereas over 20 m the difference is over 4 ball diameters.
Figure 5-22: Graphs illustrating the accuracy plots of the two textured balls split into carcass positions, all the same scale.
Figure 5-23: Composite images showing the ball trajectory of (a) a textured ball and (b) a standard smooth ball after a wet contact kick.

Figure 5-24: Graph showing the effect of ball spin rate on the swerve distance for two ranges of kick.
5.3.3.3 Wet to dry consistency

Throughout the initial robotic leg testing a means of comparing both the spin rate and accuracy data was developed. The differences between wet and dry average positions and spin were calculated and then plotted as a scatter graph as shown in Figure 5-25.

![Figure 5-25: Scatter graph showing the differences in spin and in position between wet and dry conditions](image)

The error bars were created by combining the standard deviations of two samples by calculating the square root of the sum of the squares of the standard deviation for wet and dry results. The difference in position was the magnitude of wet and dry X and Y coordinates. Therefore when plotted, the closer the consistency position to (0, 0) the higher consistency between wet and dry performance in terms of spin and direction. This is emphasised on the graph by the curved lines. However the error bars show that there were few significant differences between the samples. The Flags for the three boot upper materials exhibited the more consistent spin performance but the variation in material also gave some differences between wet and dry accuracy. For example the K-Leather exhibited very good consistency for both spin and accuracy but the PU synthetic leather also had very good spin consistency but poor accuracy consistency. The Standard ball texture had relatively higher differences for all three materials in terms of both spin and accuracy.
5.4 Friction testing

5.4.1 Initial results from developed friction tester

As presented in the previous chapter, the COF results from the friction test device are shown in Figure 4-24(b). Here it can be seen that higher COF values were found in the dry conditions when compared to the wet conditions. For the boot leather and Astroturf the sliding speeds were chosen to simulate as closely as possible the actual impact sliding speeds.

For the lower sliding speed for the boot leather no significant differences were found between ball materials in the dry although significant differences were found in the wet. Wet conditions were difficult to achieve with regards to consistency as each contact changed the levels of moisture at the interface. However due to the see-saw motion of the sample plate on the lever the water tended to be replenished at the contact area although this was not entirely consistent. To gain a consistent set of contacts the same amount of water was applied for each ball material and the torque readings were observed to ensure these remained relatively consistent over the 5 contacts. For the wet condition, the Diamond texture produced noticeably higher COF values than the Fujiama texture and the Standard smooth finish.

Significant differences were found between textures in the dry contacts with the Standard having the highest COF of approximately 1.2 followed by the Diamond at 0.95 then the Fujiama at 0.65. The standard and Diamond error bars representing one standard deviation did overlap. However in the wet the COF values were much lower at 0.2 but no differences between textures could be seen.

5.4.2 Relating friction tests to impacts

For the friction test results to be compared to actual impacts, the sliding speeds needed to be of a similar value. However due to the lack of torque in the cam motor, the contact pressure was restricted to just under 1 MPa. For the boot leather material, the experimental impact testing conditions considered were the low speed impacts at 45° (5.2.2.1.2 and Figure 5-11) and the robotic leg testing (section 5.3.3). The dry COF values for all ball types from the friction tester
were relatively equal which compares similarly to the experimental ball testing where spin rates were of a similar level for all ball types. The friction test results also revealed differences between some textured balls and the Standard ball in the wet condition. The Diamond COF results were very close to having no significant difference between dry and wet for the friction tests which were similar to the experimental angled impact spin rates.

5.5 Effect of the carcass anisotropy on spin rates

5.5.1 Role of the carcass
The role of the carcass is to provide an internal structure for the foam based outer panels to be adhered to. The carcass, as described in the literature for adidas' new generation soccer balls, the Roteiro (2004) and the Teamgeist (2006) consists of 2 layers of woven polyester/cotton fabric. These two layers are adhered to one another, with the fibre direction orientated at right angles to the other layer. This composite layer is then impregnated with latex which then encases the bladder and valve system.

5.5.2 Known effects of the carcass
As Price (2005) discovered, the carcass provides the basis for the deformation behaviour of the new generation balls. The way the 12 pentagon shaped panels are arranged can have a significant effect on ball behaviour which includes COR, deformation in the normal and tangential directions and contact time. For a normal impact of the carcass with no outer panels at 33.7 ms\(^{-1}\) and with the carcass rotated through various degrees the contact time produces a range of approximately 1 ms and the COR ranges from 0.75 to 0.9. Therefore the same carcass impacted at different orientations can provide significant changes in ball behaviour. This is due to the anisotropic properties of the woven panels distorting differently during impact. Some orientations created a stiff response whereas others created a soft response. Another observation was the generation of spin from a normal impact of the carcass due to the shearing that occurred during the deformation. Spin rates were seen to reach 600 RPM (10 rev.s\(^{-1}\)). The carcass and outer panels
were created in FE and validated to show high levels of similarity in both qualitative deformation shapes and quantitative rebound data.

5.5.3 Robotic leg testing – experimental case study of carcass effects

5.5.3.1 Experimental data manipulation
To begin to analyse the ball spin rates and accuracy data in terms of how the carcass may affect it, the orientation of the carcass within the Standard and Flags balls must be determined. For the new generation balls, the valve is always positioned in the same carcass panel, identifiable from the exterior graphics. Additionally all the carcasses are assembled identically, giving the same combination of material anisotropy around the 12 carcass panels. The only unknown is the orientation of the carcass which can be rotated at any angle about its valve. The valve pentagon is always in the same position but this then gives 5 different rotational orientations to which the carcass might be positioned.

To see how the two balls varied, the balls were cut in half for comparison. Next the 6 impact positions of the two balls on the outer panels were determined on the inside of the carcasses. The positions were then matched to determine whether any impact points around the outside of the ball correlated with respect to the orientation of the carcass.

5.5.3.2 Ball carcass layouts
The comparison of carcasses and the photos of the two balls are shown in Figure 5-26(a) and (b). In the picture the valve acts as the north pole and the lines seen show the equator of the ball and the relative positions of the 6 impact points; A1, A2, B, C, D and E. Each impact point along the equator falls at a point of a pentagon from either the top half of the ball or the bottom. As previously mentioned, the carcass can lie within the outer panels in 5 orientations. Figure 5-27(a) simplifies the problem by plotting the impact points of the two balls on one diagram. As it can be seen, the Flags points are one position anticlockwise (i.e. 72°) offset from the Standard ball impact points. The blue lines on the diagram illustrate the principle material direction from inside the carcass which aided the comparison of the two balls. Then with the points plotted on a
carcass diagram, the matching pairs between the two balls could be identified, as shown in Figure 5-27(b). Therefore there are 4 identical carcass impact points to compare the spin generation and accuracy for the two textures, which now takes into account the carcass deformation behaviour.

(a)

(b)

Figure 5-26: Photos showing (a) the Standard ball cut in half and (b) the Flags ball, with the equator line shown passing through the impact points and panels
Figure 5-27: Carcass diagram (a) compares the impact locations of the two ball and (b) indicates the matching pairs of points.
Additionally from the four matching pairs of points, the type of carcass deformation could be predicted by assessing the panel fibre orientations of the deforming panels. Figure 5-28 illustrates the location of the panels that are likely to influence the deformation behaviour. The angles of the fibre orientation are determined by describing the angle by the vertical (shown as a thick red dotted line). The panel interactions show that there are two identical sets of pairs, position 1 and 3. In theory these two positions should give a similar ball behaviour which would then lead to similar spin rates and accuracy. The solid red horizontal line indicates the ball equator.

![Panel Interactions](image)

**Figure 5-28: Illustration describing the interaction of deforming panels during an impact and the material angles crested with respect to the vertical**

5.5.3.3 Revised results

5.5.3.3.1 Spin rate

Through identification of the carcass positions, the data from section 5.3.3.1 were adjusted to show how the carcass might influence the results. As a result of only having 4 pairs, the data were cut from 18 to 12 data points, or 4 sets of 3. Figure 5-29 shows the spin rate data. As before the pattern remained that the Flags in dry and wet and the Standard in the dry produced very similar spreads of data. However, it could be argued that the gap between the Standard data in the dry and wet was greater as the spread of data was slightly less than before. The results from the 3 boot upper materials were more apparent whereas the cylinder data was less so. With reference to the carcass positions there does seem to be a pattern emerging for the boot materials. From the graph, for the Flags in the dry and wet and the Standard in the dry, position 3 (red dots)
impact location gives the highest spin rates. For the same position the Standard in the wet gives the lowest spin values. For the *Flags* alone in the wet and dry for the boot materials, positions 1 (blue) and 3 (red) give the highest spin. These are the two with the same panel interactions as described in section 5.5.3.2.

![Figure 5-29: Graph showing the spin rate data separated by colour into carcass positions](image)

Regarding the spread of data, the smallest range was approximately 50 RPM for one ball in one condition, i.e. the *Flags* texture in the dry with RLT boot upper material. The largest spread of data was found for the K-Leather and the Standard ball in the wet which was almost 200 RPM, 4 times as much as the smallest for the boot materials.

With these revised data, a between subjects factorial ANOVA was used to determine what was the significant factor for these spin rate results. The analysis shows (from Figure 5-30) that the only effect with no significant differences was the material on the cylinder, $F(3,176) = 1.49,$
\[ p = 0.219, \text{ using a 95\% confidence. All other main effects and interactions produced significant differences beyond the 0.001 (99.9\%) level. To examine the differences more closely to determine which were significant, the mean values were plotted as main effects and interactions. The main effects showed that the \textit{Flags} ball had significantly higher spin rates than the standard ball regardless of condition and material. Also the dry condition produced significantly higher spin rates than the wet condition. From this analysis, it can be concluded, using the 'F' value as an indicator, that the most significant effect was the wet/dry condition with the ball type the next important. The material of the kicking cylinder had no significant effect on spin rate on its own but when in an interaction with the condition the material it has a small influence.} \]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Source} & \text{Type III Sum of Squares} & \text{df} & \text{Mean Square} & \text{F} & \text{Sig.} \\
\hline
\text{Corrected Model} & 654962.998 \text{a} & 15 & 43656.200 & 48.361 & .000 \\
\text{Intercept} & 17756824.6 & 1 & 17756824.76 & 19666.940 & .000 \\
\text{Material} & 4093.320 & 3 & 1345.107 & 1.490 & .219 \\
\text{Ball} & 152831.627 & 1 & 152831.627 & 169.272 & .000 \\
\text{Condition} & 194536.046 & 1 & 194536.046 & 215.462 & .000 \\
\text{Material \* Ball} & 18199.071 & 3 & 6066.367 & 6.719 & .000 \\
\text{Material \* Condition} & 122180.302 & 3 & 40726.767 & 45.106 & .000 \\
\text{Ball \* Condition} & 112387.711 & 1 & 112387.711 & 124.477 & .000 \\
\text{Material \* Ball \* Condition} & 50792.919 & 3 & 16930.973 & 18.752 & .000 \\
\text{Error} & 156906.322 & 176 & 902.877 & & \\
\text{Total} & 18570884.1 & 192 & & & \\
\text{Corrected Total} & 813869.320 & 191 & & & \\
\hline
\end{array}
\]

\text{a. R Squared = .805 (Adjusted R Squared = .788)}

\text{Figure 5-30: ANOVA of the revised spin rate results}

\text{5.5.3.3.2 Flight Consistency}

Figure 5-31(a) to (d) show the revised accuracy plots for the experiment for the dry condition to assess if the carcass had any effect. The coloured dots represent the positions of individual kicks as an average of 3 kicks would give misleading information. The position colours are the same for the spin graph and the \textit{Flags} and Standard ball are represented by triangle and circle indicators respectively. The first observation is that the K-Leather data show less variability than the other three whilst the cylinder data showed the greatest spread. Since the kick was over 18 m (perpendicular distance) and around 20 m from the tee to the impact position on the target, the combination of differences in spin causing variations in the magnitude of swerve (see Figure 5-24) and initial launch angle would have contributed towards the accuracy.
Figure 5-31: Graphs illustrating the accuracy plots of the two textured balls split into carcass positions, all the same scale
5.6 Discussion

The data conclusively shows that adding a textured surface to the ball has been found to increase the consistency of the spin rates between wet and dry conditions. Additionally when the effect of the carcass was included, the spin rate data exhibited a similar pattern indicating that the effect of the texture was more significant than the effect of the carcass between wet and dry conditions. The accuracy was slightly more difficult to analyse as it was a function of several factors which may have disguised which factor was dominant, such as the effect of spin rate on aerodynamic swerve distance. For example a ball which slipped on contact with the cylinder is likely to have created a wider release angle causing a greater lateral displacement distance but with a lower spin rate. Alternatively a ball which gripped the cylinder causing a higher spin rate is likely to have moved more during the trajectory producing a greater displacement. From Figure 5-4, a change of 100 RPM in spin rate causes a 0.5 m change in swerve distance over 20 m.

The study also assessed how the internal structure of a ball may have influenced the ball’s behaviour and the effect on results. The carcass of the ball, which has a high degree of anisotropy, has been known to create asymmetrical deformation shapes for normal impacts but until this study the effect of these deformations on spin generation was unknown. From the experimental data the effect of the carcass was noticeable. The smallest range of data was approximately 50 RPM for the 6 impact positions which could indicate that this might be the effect of the carcass. Additionally, the impact position around the ball was a potential source of error. Figure 5-29, shows that for the Standard ball in the wet, there were groups of positions producing more spin, e.g. positions 2 and 4 produced more spin than positions 1 and 3. Figure 5-28 shows the panel interactions that occurred and coincidentally, positions 1 and 3 had matching angles. This could indicate that the stresses seen in the deforming area were related to spin generation. Additionally if only one point was chosen, the range of data collected would not be representative of the true range of data for several points around the equator. The Flags ball had positions 1 and 3 producing the highest spin for both wet and dry however for the Standard ball, these positions produced the highest spin in the dry but the lowest in the wet. Therefore the way the ball slips against the cylinder in the wet must be more significant for the Standard ball than the Flags ball.
The effect of a texture is also commonly used to increase grip with automobile tyres. In the dry, slicks are used as this creates the greatest area of contact between the road and the tyre. However in the wet the slick tyres are more prone to aquaplaning as a film of water cannot be broken. The tread of tyres with the blocks and circumferential lines allow the water film to be broken and drained behind the tyre respectively. It might be expected that the Standard and Flags ball would perform similarly in the dry but the textured Flags ball should perform more consistently in the wet which is exactly what the spin rate data showed for all materials. With the addition of a boot material to the cylinder, the Flags ball was twice as consistent as the Standard ball.

To supplement the carcass aspect of the study, a HSV camera was setup next to the robotic leg to inspect any changes in deformation shapes of another Standard ball. Figure 5-32 shows the deformation shapes of a separate Standard ball at 5 equally spaced points around the equator with the valve acting as the equator. The cylinder is set up to be impacted at 4 cm offset as comparable to the study to see if there were any visual qualitative observations. Points D and E show some signs of asymmetrical deformation as indicated where there seems to be some unusual shapes. The remainder of the results exhibited fairly similar shapes but these shapes are not as clear as the ones seen by Price (2005) for normal impacts on to a planar target plate using the ball launcher.

![Figure 5-32: HSV images at max deformation of a Standard ball at 5 equally spaced points around the ball equator for 4cm offset](image-url)
5.7 Summary

This chapter describes the experimental testing carried to determine the effects on ball performance due to changing the frictional properties at the ball-surface interaction. Results have been presented for a ball impacting two surfaces and being kicked with a boot leather surface at representative ball speeds. The results have shown the significant influence of how a wet interface can affect ball rebound characteristics. The kicking tests carried out by the robotic leg, which allows consistent repeatable kicks, has shown the positive effect of adding a texture to a soccer ball. This has been substantiated through the ANOVA of the spin rates for the standard and textured ball.

As this chapter describes a series of experiments it is important to take in to account that the results described are a function of the test setup rather than the ball itself. The experimental setups were designed to match game realistic conditions which would mean that any effects observed are relative and not just applicable to the lab tests.

The results gathered have been used to validate FE friction models which are presented in Chapter 6.
6 Finite element modelling of soccer ball impacts and friction models

6.1 Chapter overview

This chapter examines the FE friction modelling capabilities of Abaqus by using a soccer ball impact as a case study. Three types of impacts are considered, two where a moving ball is impacted against different stationary objects and a third where a stationary ball is "kicked" by a moving object. The FE model results are compared to the experimental data from the previous chapter in order to form conclusions about the suitability of a FE friction model.

6.2 Finite element setup

6.2.1 Overview

The aim of this area of investigation was to carry out a FE study into the effects of friction in a soccer ball impact. This topic has been investigated previously by Asai et al (2004) for soccer kicking and Kanda (2004) for a tennis ball impact. However these two studies did not attempt to validate the simulated results obtained when the values of the COF were adjusted in FE. The experimental data collected and presented in the previous chapter provide the validation for the FE investigation carried out in this chapter. The planar and cylindrical high speed (25 m/s) ball impacts were replicated in the FE environment at the range of angles used experimentally.

6.2.2 Models used

The wide range of FE models created and validated by Price (2005) enabled a choice to be made between basic models and more developed models involving material orientations of the carcass layer. Typically a basic model which incorporated a single layer of shell elements impacting either a planar or cylindrical analytical rigid surface would take around 2 hours to complete on a single processor. A developed model with the anisotropic material orientations of the carcass
would take nearer 10 hours to complete. Since the study involved a high number of simulations, which totalled over 230 to complete the investigation, a decision was made to use the basic model of the adidas Teamgeist ball as used in the experimental testing. Additionally, the basic model was assigned isotropic material properties which meant that the orientation of the ball had no bearing on the impact characteristics. Figure 6-1 shows the model setups used.

![Figure 6-1: The FE setups used for a planar impact (left) and a cylindrical impact (right)](image)

### 6.2.3 Boundary conditions

The basic model consisted of a single layer of shell elements that represented two layers of the ball construction; the panels with the carcass material backing and the bladder. A node set that encompassed all of the ball nodes was used to control the inbound conditions of the ball towards the impact surface. Before the ball could be moved, the inflation and holding stages were first completed. The ball was inflated to the pressure used in the experimental testing which was 0.9 bar. This value represented the middle of the range specified by adidas and the FIFA ball quality standards. To inflate the ball to this value, hydrostatic fluid elements were used as surface elements on the inside surface of the shell elements to create a cavity. These fluid elements shared the same nodes as the shell elements representing the ball materials. To apply pressure a cavity reference node was coupled to the fluid elements. The quantity of compressible fluid (i.e. air) was controlled by specifying the fluid flux function which applied a flow rate of fluid. The correct ball pressure of 0.9 bar was obtained by specifying the mass flow rate over the step time. To equalise the stresses and strains involved in inflating the ball which changed the geometry in a relatively quick time, a hold step of 0.05 ms was included at the end.
Once inflated, the ball was subjected to the boundary conditions used to define the ball impact velocities. The node set that has all of the ball nodes was assigned a velocity of 25 m/s. To change the angle of approach for the planar impacts, the 25 m/s magnitude value was resolved into two orthogonal components in the normal and tangential directions to the surface. Since the ball needed an initial velocity, these boundary conditions were applied over a very short time period before the ball came into contact with the surface. A final step was then used to analyse the impact of the freely moving ball onto the rigid surfaces, which were constrained in all degrees of freedom (encastre).

6.2.4 Friction application

The aim of this investigation was to assess the effects of friction for a soccer ball impact using FE. Abaqus can apply the COF in a variety of friction models and there are three main models within its environment. These are based on the classical isotropic Coulomb friction model and are:

- A single COF value which can either be constant or defined in terms of contact pressure, slip rate and/or surface temperature,
- Values for the kinetic and static COF which can be defined in terms of smooth transition with an exponential curve,
- An anisotropic extension of the simple Coulomb friction model

Since it was not known through previous studies or literature which friction model is best suited to a soccer ball impact, the basic single value constant COF Coulomb friction model was chosen to provide varying levels of friction for the simulated impacts. This model simply related the maximum allowable frictional or shear stress across two interacting surfaces to the contact pressure between the contacting bodies, Abaqus (2007). The single value of the COF provided the limit to how much shear stress could be carried at the interface before sliding occurred. Shear stress values below this level meant that sticking occurred between the two surfaces. The Coulomb friction model defined this critical shear stress, \( \tau_{\text{crit}} \), at which sliding of the surfaces starts as a fraction of the contact pressure, \( p \), between the surfaces (\( \tau_{\text{crit}} = \mu p \)). This fraction was more commonly known as the COF or \( \mu \). Abaqus calculated when the two surfaces were slipping
or sticking which could be shown as in Figure 6-2. More complex friction models are available in Abaqus and are described in the documentation, (Abaqus 2007).

Since Abaqus/Explicit was used to complete the analysis, the frictional constraints were imposed by the kinematic method, which defined how the model applied the sticking constraints at the interface. The value of the force required to enforce sticking at a node was first calculated using the mass associated with the node, the distance the node had slipped and the time increment. If the shear stress at the node calculated using this force was less than \( \tau_{\text{crit}} \), the node was considered to be sticking as shown in Figure 6-2. Consequently this force was applied to each surface in opposing directions. On the other hand if the shear stress exceeded \( \tau_{\text{crit}} \) the surfaces were slipping and the force corresponding to \( \tau_{\text{crit}} \) was applied. This resulted in acceleration corrections tangential to the surface at the slave node (in this case the ball nodes) against the analytically rigid surface. The alternative option for enforcing the frictional constraints would have been the penalty method, which is a less stringent version of the kinematic method. An example of where this would have been appropriate would be when two rigid surfaces are in contact.

A range of COF values were chosen to validate the model, for both the planar and cylindrical surfaces a COF from 0 to 1 in 0.1 steps and from 1 to 4 in 0.5 steps to give array of rebound values for the ball model. These values would then be mapped on to the experimental data to examine their correlation. Then if further refinement of the COF values were required these
models would be run. Additionally the inbound angle was chosen to increase initially in 10° steps however where sudden changes in the outbound measure occurred then intermediate angles were chosen to refine the curve.

6.2.5 Analysis

Once the Abaqus simulations were completed the processor outputs a database file which contained the visualisation and data requests in the history and field outputs. A standard analysis technique was developed in order to create an efficient process from opening the output database file to an analysis calculation template created in Microsoft Excel. The results required from the simulations were the same as the metrics used in the experimental testing as described in the previous chapter. This enabled the FE results to be validated and/or compared against the experimental. The velocity of the ball after impact was measured using a predetermined node set consisting of a single node on the outside of the ball. If the impact was observed perpendicular to the motion of the ball, the node would always appear to be in the centre of the ball and coincided with the axis of spin. This node set was used to output the velocities in the tangential and normal directions (as a history output) and the values were taken at the end of the analysis to ensure the ball had returned to its original shape. The two velocity vectors could then be used to calculate the velocity magnitude as well as the rebound angle. The ball spin could not be directly output from Abaqus. To calculate the ball spin, two nodes at the top and bottom of the ball, which were diametrically opposite, were probed from the deformed shape animation at two instances in time after impact. The node position coordinates were used to define a line across the ball by which the angle could be measured. The change in angle of this line from the two time instances, typically 0.005 seconds apart, gave the spin in degrees per second. This technique was similar to the one used for the experimental data collection.

The data collection was made more efficient by creating a report text file of the velocities and ball node coordinate positions for a series of simulation which then could be imported into Excel. An analysis equation template was then used to calculate the required metrics in the correct units.
6.3 Validation of ball-plate impacts

This section presents the results from the FE analysis. The results from the high speed planar and cylindrical impacts are shown. Additionally the high speed planar impacts are also presented in video captures to emphasise certain aspects of the results.

6.3.1 Planar

The planar results show the data for the rebound spin rate, rebound angle and overall COR. Each metric is first presented as a series of COF curves across the range of angles to show how adjusting the COF was found to affect the rebound characteristic and then are matched to the experimental data for a standard and textured soccer ball in the wet and dry conditions. The matching COF values were chosen from the spin rate data then applied across the other two metrics for comparison.

Figure 6-3 shows the FE COF curves in terms of spin rate over the range of inbound angles. At steeper angles, the effect of friction was found to have a reduced effect on spin rate. The largest differences between spin rates were found at shallow angles with the COF curves converging to a similar value as the angle increases towards the normal. Additionally each COF value has an optimum angle to produce its maximum spin. From these curves, it was determined that both sets of experimental ball impact data in the dry matched the simulation completed with a COF of 0.8. In the wet, the textured ball matched the simulation run with a COF of 0.15 and the standard ball the simulation run with a COF of 0.08. This is shown in Figure 6-4. Not only do the FE COF curves accurately predict the values of spin produced experimentally but also the trends in spin rate found across the range of angles used.

Figure 6-5 shows the rebound angles for each of the FE simulations of different COF values. At very steep or very shallow inbound angles, a change in COF was found to have less of an effect than at the mid range inbound angles. For example at inbound angles of 50 or 60° the range of outbound angles was almost 20° whereas at either 10 or 80° the range was nearer 5°.
Figure 6-7 shows the overall COR for the range of FE COF (see section 5.2.1 for description). In this case low COF values were found to generate higher COR values at shallow angles as more tangential velocity was conserved. Higher COF values at shallow angles caused only 60% of velocity to be conserved as compared to almost 100% at low COF values. Again as with the spin rates, the COF curves were found to converge and followed a similar trend as the inbound angle was increased towards the normal.

Figure 6-6 and Figure 6-8 plot the results of the experimental testing against the three COF value curves that were found to be best fitting from the spin rate results. Again, good agreement can be seen between the results. There is no clear difference between the wet results for the two ball types but the FE simulation does not show a clear difference either.
Figure 6-3: Graph showing the spin rates for the FE COF curves (planar impact at 25 m/s at varying angles)

Figure 6-4: Graph showing the FE COF curves that match the experimental test data for spin rates
Figure 6-5: Graph showing the rebound angle for the FE COF curves (25 m/s at varying angles)

Figure 6-6: Graph showing the FE COF curves that match the experimental test data for rebound angles
Figure 6-7: Graph showing the overall COR for the FE COF curves (25 m/s at varying angles)

Figure 6-8: Graph showing the FE COF curves that match the experimental test data for the overall COR
6.3.2 Impacts against a cylindrical object

As with the planar results in the previous section, the FE results were first presented as a series of curves, each representing a different COF. The best fitting curves were determined from a comparison of the spin rate data. These are then compared against the simulated results from the remaining two metrics. The spin rate FE COF curves are plotted in Figure 6-9. Similar to the planar data, each individual COF value was found to have an optimum inbound angle for its maximum spin. Generally, although at different levels of spin, each COF curve revealed a low spin rate at shallow angles which then increased as the inbound angle increased to a maximum before decreasing as the angle approached the normal. Once the spin rate had peaked, all the COF values were found to follow a similar gradient and trend as seen in previous data.

To match the experimental data, a value was chosen for both ball types in the dry and separate values to represent the differences shown in the wet condition between the standard and textured ball as seen in Figure 6-10. These FE COF values were determined to be lower than the values determined for the planar impacts which may suggest that the geometry of the impact surface plays an effect. However the COF curves chosen were also found to match the values and trends of the experimental data, even the sharp increase of spin in the dry data which was observed at angles from 30 to 40°. Although the FE curve perhaps underestimated the spin rate slightly after this peak. At most this difference was found to be around 20%.

Figure 6-11 and Figure 6-13 show the FE COF curves for the rebound angle and overall COR for the cylindrical surface. Figure 6-12 and Figure 6-14 then show the FE COF values as taken from the spin rate graph. For the rebound angle the FE COF values chosen again reflect the experimental results. For the wet FE COF values, even though these indicate differences in spin, they also show small differences in rebound angle as it can be seen between the experimental wet results. The overall COR data can also be predicted by the chosen COF values including the drop in COR of the dry experimental data.
Figure 6-9: Graph showing the spin rates for the FE COF curves (cylindrical at 25 m/s at varying angles)

Figure 6-10: Graph showing the FE COF curves that match the experimental test data for the spin rates
Figure 6-11: Graph showing the rebound angle for the FE COF curves (cylindrical at 25 m/s at varying angles)

Figure 6-12: Graph showing the FE COF curves that match the experimental test data for the rebound angles
Figure 6-13: Graph showing the overall COR for the FE COF curves (cylindrical at 25 m/s at varying angles)

Figure 6-14: Graph showing the FE COF curves that match the experimental test data for the overall COR
6.3.3 Video recordings

As examined in Figure 5-7 for the experimental data from the previous chapter, the FE visualisations were compared to the experimental video captures to illustrate the influence the COF had on ball rebound characteristics. A large effect was found at shallow angles but this was not present at steeper inbound angles. These are presented in Figure 6-15 on the following page. Although the initial orientations of the balls did not exactly match in the comparison, the rotation of this line with time (spin rate) was accurately predicted by the FE model. For the same COF values a large difference in spin and velocity was seen at 15° but at 60° the differences were minimal. This represented the convergence point seen in the graphs between low and high frictional conditions as the inbound angle increased.
15° impact – large differences between dry and wet

60° Impact – similar rebound characteristics between dry and wet

Figure 6-15: Video captures to illustrate high and low COF conditions in FE and experimental
6.4 Validation of ball-foot impacts

6.4.1 Introduction

This section examines the role of friction during a kick. As with the previous part of the chapter, a basic ball model was used in a similar setup as the experimental testing carried out in chapter 5. A cylinder of the same size as the robotic leg end-effector was modelled as an analytical rigid body as with the planar and cylindrical impacts. To create the rotation, a rigid body reference point was positioned at the pivot location of the leg rotation used to control the motion of the body. The body was then constrained in all degrees of freedom except the rotation axis. An angular velocity of 15.6 rad/s was applied to the reference point causing the cylinder to rotate with a tangential velocity of approximately 14 m/s, the same as that measured experimentally from the robotic leg. The basic Teamgeist ball model was positioned accordingly to create the 4 cm ball-cylinder offset reported in the testing in the previous chapter. As before, the single value COF was adjusted from 0 to 1 in 0.1 steps and 1 to 4 in 0.5 steps. Where maximum and/or minimum peaks occurred in the metric output, the COF was refined for more precision.

6.4.2 Metrics

The main metric required from this analysis was the overall spin rate to compare to the experimental data collected. As mentioned earlier the spin rate was not a direct output from Abaqus and in this scenario was found to be significantly more complex to measure. In the planar and cylindrical FE impacts the spin rate measurement could be simplified to a 2D problem where the spin axis was assumed to be always in the same orientation. However in the robotic kicking leg situation, the spin rate axis was more difficult to predict. It was discovered the spin axis of the ball after being kicked (experimentally and in FE) had components of top and side spin. Therefore a new approach was required to measure the magnitude of spin. The chosen method was to use the individual velocity magnitude values of each ball node over time. Figure 6-16 illustrates the process. Image (a) shows a ball during flight with the contours indicating the velocity. As the ball is spinning and translating, the net velocity of nodes on one side of the ball was greater than the translational velocity due to the direction of the spin. The velocity of the nodes on the other side was lower than the translational velocity. The example shows the
velocity vectors across the ball. The red and blue arrows indicate the sides of the ball going with and against the spin. The whole ball speed can be calculated by averaging these maximum and minimum velocity values. Image (c) shows the velocity of over 2000 nodes plotted against time. The maximum and minimum values in (a) correspond to the values in (c). The spin can then be determined by finding the difference between the maximum (or minimum) speed and whole ball speed which represents a tangential velocity from the ball centre, as shown in image (b). Using the ball radius the tangential velocity can be converted to an angular velocity in rad/s and then RPM.

![Diagram illustrating velocity components](image)

**Figure 6-16:** Diagram illustrating (a) the velocity magnitudes of parts of the ball in flight, (b) the relative velocity components and (c) the field output of each nodes velocity.

Although the spin rate was the only measure taken during the experimental testing, three other measures were collected during the FE analysis; ball velocity and the two trajectory angles. The ball velocity was found using the method described above. The trajectory consisted of the elevation and deviation angles as shown in Figure 6-17. The deviation angle ($\theta_d$) described the two dimensional angle the ball trajectory made with the vector representing a theoretical straight kick, obtained by extending the motion of the cylinder. The elevation angle ($\theta_e$) was the angle the ball trajectory made with the horizontal.
6.4.3 Results

The results of the FE analysis of the robotic kicking leg are shown in Figure 6-18. As it can be seen, the COF had little effect on the metrics when it is set to be greater 1.0. Graph (a) shows how the COF between the cylinder surface and ball affected the spin rate. The spin rate increased sharply from COF(0) to COF(0.1) to form an initial peak at 240 RPM. The spin rate then dropped to 200 RPM at COF(0.2) but then increased again and remained constant at 250 RPM at COF(1.0). Interestingly, spin was generated at zero friction. This was possible due the cylinder impacting at an offset to the ball's centre of mass causing a moment. The velocity in graph (b), showed a similar trend but without the initial peak. The lowest ball velocity of 24 m/s was found with a COF of 0 which then increased to 24.5 m/s with a COF of 0.5 where it again remained constant. The elevation angle in graph (c) exhibited the same trend of the velocity but the values ranged from the lowest of 10.6° at COF(0) to 13° at COF(>1). The deviation angle in graph (d) experienced a sudden decrease initially from 22.5° to 16.8° at COF(0.1), followed by a small increase at COF(0.2) then a gradual decrease to a plateau at 16.2° at COF(>1). This range from the initial value represented a decrease of nearly 40%. From these results the COF had a larger effect on spin rate and deviation angle from a COF in the range 0 to 1 than the velocity or elevation angle.

Figure 6-17: The deviation angle (left) and the elevation angle (right)
Figure 6-18: Graphs showing the FE analysis results for (a) the spin rate, (b) the ball velocity, (c) the elevation angle and (d) the deviation.
The spin rate data gathered from the FE analysis (Figure 6-18a) was compared to the experimental data. Agreement was not found between the maximum spin rates found in the experimental testing and the FE simulations. The average for all the dry spin rates was $331.9 \pm 29$ RPM and in the wet it was $281.4 \pm 70$ RPM. Comparisons revealed that the FE results only represented the wet condition data spread.

6.5 Game scenario – the cross bar impact

6.5.1 Introduction
Although the results presented so far in this chapter have provided a basis for analysis and validation of simple impact scenarios, the ball is likely to encounter many more complex interactions in a game situation. As an example this section attempts to use the data collected to predict whether a ball hitting a cross-bar of the goal framework after a shot at goal would bounce into the goal or out.

6.5.2 Analysis
To examine the influence of friction in this scenario, the results from the cylindrical high speed impacts were considered. Figure 6-19 depicts a schematic diagram of the results. The ball was projected at $25 \text{ m/s}$ with no initial spin on an upward trajectory $5^\circ$ below the horizontal and impacted against the cylinder making a $60^\circ$ contact angle. The cylinder used to mimic the cross-bar in the testing was $9.2 \text{ cm}$ in diameter, in accordance with the Laws of the Game where FIFA stipulate that the goal posts must not be more than $12 \text{ cm}$ in diameter (FIFA 2005). The distance from the bottom edge of the cylinder to the ground must be $2.44 \text{ m}$. The goal line must not be more than $12 \text{ cm}$ wide. As it can be seen in Figure 6-19, the rebound angle was found to vary by $28.8^\circ$ due to the change in friction. This equates to a ground distance of $1.29 \text{ m}$ (or just less than 6 ball diameters). For the ball velocity used, a non-uniform change in angular rebound was found with uniform increases in COF.

On a dry day (the COF would be for example $0.3$ and above) and this would be where the ball would be more likely to bounce near the line. On a wet day (the COF would be $<0.3$) and would more likely to land further behind the line. It could be concluded that a ball hitting the cross bar
on a dry day will have more chance of rebounding near the line than on a wet day where the cross-bar and ground would have very low COFs.

Figure 6-19: The cross-bar scenario setup and resultant ball directions

6.6 Effect of carcass anisotropy – finite element study

6.6.1 Introduction

Section 5.5 examined the influence of the adidas Teamgeist carcass construction on the spin rates generated during a kicking situation using the experimental results from the robotic leg testing. The two types of ball used were dissected to identify similar impact locations with respect to the orientation of the carcass. It was found that 4 identical impact locations around the carcass occurred and these were considered for comparison. The spin rate data was then manipulated to plot the spin rates as a function of carcass position. It was found that the positions had different effects on spin for wet and dry conditions. For example a position which had consistently the highest spin of the positions in dry conditions had the lowest spin of the positions for wet
conditions. This section attempts to use the more advanced ball model with the anisotropic material data incorporated into the carcass layer to examine whether the FE method could be used to predict this behaviour.

6.6.2 Carcass layout

In Figures 6-20(b) and Figure 6-21(b) shows the numbering systems used in the carcass construction where panels 2 and 12 are the valve and counterbalance panels (not shown). The image for the planar impact shows the ball impacting at panel 11. The image for the robotic kicking leg contact shows a panel 4 impact.

6.6.3 Planar impacts

Impacts at 25 m/s and 45° to the planar surface were setup in FE using the 10 carcass positions. The angle and velocity were chosen to cause significant ball deformation rather than a glancing shallow impact. The results are shown in Figure 6-20(a). The COF was set to 0.5 to create the comparison.

As it can be seen the orientation of the carcass within the outer panel structure has an effect on spin rate. The range of data is 56.1 RPM which is a 7% increase from the minimum to maximum value. The carcass orientation also has an effect on the rebound angle and overall COR. The average rebound angle is 55.6° and the range is 6.7° which is an increase of 12.7% from minimum to maximum. The overall COR has an average of 0.75 with a range of 0.09 which is an increase of 12.8% from minimum to maximum.
Figure 6-20: The FE spin rates as a function of carcass impact orientation at 25 m/s at 45° (a) and the carcass impact positions within the ball (b)

6.6.4 Robotic Kicking Leg

This section presents the FE and experimental data generated from impacting the carcass in various locations with the robotic leg.

6.6.4.1 Spin rates

As with the planar impacts, the robotic leg kicking impacts are presented as a function of the carcass panel which comes into contact with the surface first and are shown in Figure 6-21(a). In the dry condition (i.e. a COF of 0.5) the range of spin was simulated to be approximately 40 RPM. The wet condition (in this case frictionless or a COF of 0) also produced a similar range but at much lower spin values. There was no relationship found between the high and low COF spin rates orders.
One of the findings from Chapter 5 was that trends occurred between positions. For example, the highest spin producing position was not the highest in the low spin producing conditions. The FE analysis was then used to investigate this trend. By examining the ball carcasses and the FE carcass model, the corresponding panels for the 4 positions were determined. Similarities in spin patterns between the FE and experimental were found for the simulated ‘dry’ and ‘wet’ conditions as found in Figure 5-29.

6.6.4.2 Launch angles and velocities

Even though no experimental data was collected for the trajectory angles and ball velocity, the data provided a useful insight into how the friction of an impact may affect ball performance in a kick scenario. Table 6-1 shows the FE data for all of the panels at a high and low frictional condition. Also added is the average, standard deviation and range of the data to show how the orientation was found to vary the ball flight. Interestingly, the spin rate appeared to be the only metric that was significantly affected. The two trajectory angles which describe the balls flight
only had a maximum standard deviation of 0.3°. Similarly, the ball velocity had a low standard deviation with a maximum of 0.1 m/s.

<table>
<thead>
<tr>
<th></th>
<th>Velocity (m/s)</th>
<th>Elevation (°)</th>
<th>Deviation (°)</th>
<th>Spin Rate (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>24.8</td>
<td>13.8</td>
<td>24.6</td>
<td>228.9</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.1</td>
<td>0.31</td>
<td>0.20</td>
<td>10.2</td>
</tr>
<tr>
<td>Range</td>
<td>0.3</td>
<td>0.8</td>
<td>0.7</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 6-1: Showing the FE velocity, trajectory angles and spin rates at COF(0.5) (red) and COF(0) (blue)

6.7 The application of the coefficient of friction in Abaqus

Abaqus allows the user to set the level of friction between two surfaces which in the case of this study was the single constant value COF. However it is not known whether the FE solver applies this COF continually throughout the impact. Therefore an investigation was undertaken to establish whether the intended COF was actually produced during a soccer ball impact by considering the normal and tangential reaction forces generated in the history output. Figure 6-22 shows the COF values calculated by dividing the tangential reaction force by the normal force over time. The key on the bottom right shows what the intended COF value was. Graph (a) shows the results for a 20° impact angle at 25 m/s. For this angle, generally all the intended COFs were achieved except throughout the impact with the exception of those periods when the impact involved the reversal of the frictional force as the intended force can not be applied in the opposite direction. For values of COF above 1, the frictional force reverses twice.
Figure 6-22: Graphs of the actual recorded FE COF values during a soccer ball impact at 25 m/s.
6.8  Force plate testing

6.8.1  Setup

To supplement this testing, the impact plate reaction forces were validated to see if the correct magnitude of normal and tangential force were produced. Price (2005) carried out a validation procedure on the models using both a quasi-static and dynamic approach for a series of normal impacts and concluded that the FE models produced results in the correct ranges. The dynamic testing was carried out by projecting a ball onto a force plate at different velocities.

For this part of testing, a portable soccer ball launching device manufactured by Jugs was used. This machine was of a simple construction consisting of two counter rotating horizontally mounted tyres. The tyres and motors were supported by a frame which can be transported on a set of wheels. The force plate was mounted into the floor to minimise any vibrations of the system which may interfere with the signal. The short duration of a ball impact causes the plate to vibrate near its natural frequency which causes noise in the force signal, (Davies 2005). The Jugs machine can achieve velocities of up to 80 m/s but the range of angles is limited if the ball is projected downwards. Therefore a velocity of 22 m/s at angles of 15 and 30° to the floor was used as a case study. Figure 6-23 shows the setup and a composite HSV image of a typical impact. HSV operating at 4000 Hz set up perpendicular to the ball motion was used to record the ball inbound and rebound measures. An adidas Roteiro ball was used which was similar to the Teamgeist but with a standard 32 panel configuration instead of 14.

![Figure 6-23: Schematic diagram of the setup (left) and a composite image from the HSV recording (right)](image)
6.8.2 Force plate data to predict ball performance

As discovered in the first part of this chapter, it was found that a single COF value was able to predict the ball rebound performance across a range of angles at a single velocity. Therefore if a ball was impacted onto a force plate to obtain an average COF value, this could be used to input into the FE model and predict the ball performance for other angles. To obtain a single COF value from the experimental impacts, the reaction forces were first restricted to just the compression phase and then plotted as a scatter graph. The raw data points were plotted with the normal force on the x-axis and the tangential force on the y-axis so that the gradient would be the COF. The compression phase was chosen so that the COF remained positive throughout and avoided the friction force reversal. From this the gradient of the data points, which intercepts at \((0, 0)\), is 0.7. This value is the average COF that was used in the FE simulations.

As an adidas Roteiro ball was used, the basic FE ball model was changed to represent this and the inbound conditions from the experimental force plate impacts were replicated. To analyse whether this COF value in FE replicated the experimental data, the spin rate, angle and overall COR were used as metrics plus using the FE generated reaction forces as a comparison. The experimental ball rebound metrics were recorded from the HSV.

Figure 6-24 shows the FE force and COF data overlaid on the experimental data. The calculated COF of 0.7 accurately predicted the tangential forces in terms of magnitude and trend. The FE simulation predicted that the friction force would reverse for the 30° impact but not the 15° which was consistent with the experimental findings. Since the normal reaction forces were validated by Price (2005) it could be assumed that the tangential forces and subsequently ball performance would also be representative of the experimental if the COF value was correct. Figure 6-25 shows the FE and experimental results comparison in terms of spin rate, rebound angle and overall COR for both the angles. The results show that the simulations show excellent agreement to the experimental for all three metrics. The force plate method of obtaining a COF for a ball-surface pairing seems, for this initial study, an accurate way of predicting ball performance. The results show that if the correct forces can be produced then the ball rebound behaviour will be accurately predicted. This was true even at shallow angles created by the Jugs machine where the COF has a large influence on spin, angle and velocity.
Figure 6-24: A comparison of the FE and experimental reaction forces and COF values during an impact, (left hand side: 22 m/s at 15°, and right hand side: 22 m/s at 30°)
Figure 6-25: Graphs showing the experimental and FE data in terms of 
(a) spin rate, (b) rebound angle and (c) the overall COR

6.9 Summary

This chapter has presented the FE friction modelling capabilities of Abaqus by using a soccer ball impact as a comparison. The results have shown that a single value COF can be used in most instances to accurately predict ball performance across a range of angles at one velocity. However, FE analysis obviously cannot predict the spread of data caused by the inconsistency of a wet condition. One of the main findings from Chapter 5 was the ability of a ball texture to minimise the inconsistency of a wet condition. The results have been applied to a game scenario where it was found that friction between the ball and cross-bar could be the difference between a goal or not. A method to predict ball rebound behaviour using a force plate to acquire a COF for FE simulations proved successful.
7 Finite element modelling of soccer ball surface textures

7.1 Chapter overview
After examining the experimental effect of adding a texture to a soccer ball and investigating the effects of friction at the ball-surface interface using a FE approach, a more in depth analysis of the performance of these textures was required. This chapter describes the process of modelling the performance of a texture on a soccer ball. The method chosen was to use a FE approach to simulate what happens to a surface texture under realistic pressures. Firstly the existing FE soccer ball model was developed to include solid elements for the outer panels which allowed isolated boundary conditions of localised panel deformation at the contact area to be applied to a sub model of the texture geometry. The fluid structure interaction possibilities available are then investigated to determine their suitability for simulating water flow between the texture and another surface.

7.2 Manufacture and materials
7.2.1 Outer panel materials
The construction of the new generation of adidas soccer balls', such as Roteiro and Teamgeist is described in the Section 2.2.2. Their carcass construction is identical and the balls use similar materials to create a composite outer panel material. The outer panels, which are thermoformed onto the carcass construction, consist of two foam layers, the underlying softer material is an ethylene-propylene-diene-monomer (EPDM) (2.9 mm thick) which is covered by a higher density PU foam (1 mm thick). The outer PU foam layer consists of a solid PU foam and transparent PU film for applying artwork and is backed by a plain-woven fabric. For simplicity the outer panels are considered to be two layers, the softer EPDM foam and the tougher outer PU layer. The softness of the EPDM material allows compliance between the ball and the other surface whereas the outer PU foam is resistant to water and wear. Other applications of the
EPDM foam are mouse-mats and foam grips for hand tools. The surfaces of both balls can be considered as smooth, Figure 7-1 illustrates the composition of layers of the outer panels.

![Figure 7-1: Outer panel construction highlighting the micro structure of the outer PU layer](image)

### 7.2.2 Texture manufacture

The textures created for the soccer ball used in the previous sections were manufactured using a release paper method. Here the outer PU material is formed on the release paper which has a predefined inverse pattern of the intended texture. The inverse of the texture is firstly transferred to a steel roll by a CNC (computer numerical control) machine which is then heat embossed onto the release paper. The PU material is then knife coated on to the release paper until the texture cavities are filled without any air traps. Further PU coatings can then be applied depending on the final use of the materials. Once all of the thermoplastics are cured or vulcanised, the release paper can be removed. Release papers can be reused up to several times depending on their material quality, adidas (2008). In Figure 7-1 the profile of the texture can be seen in the waviness at the very top of the microscope image.
7.3 Surface measurement techniques

This section describes how a surface texture was assessed and measured using qualitative and quantitative methods.

7.3.1 Qualitative

To understand the topography of the surface texture on a soccer ball the first stage is to inspect the pattern and geometry visually. This can be aided with an optical microscope to help understand the way the type, sequence and frequency of the pattern. Here the features can be identified which are to be measured in the next stage. Figure 7-2 shows four examples of ball surfaces.

![Figure 7-2: Optical microscope images of (a) Nike Total Aerow 90 combed grooves, (b) pimples, (c) Puma Shudoh dimple and (d) adidas Feverova decorative print](image)

7.3.2 Quantitative

During this research, two approaches were employed to gain quantitative data about a surface texture. The first was a laser scanner to obtain two and three dimensional point data from prototype or production products and the second was through the use of computer aided design (CAD) drawings. Examples of these can be seen in Figure 7-3. The laser scan data which creates an x, y, z set of coordinate points can be analysed using the procedures described in section 2.3.3.
7.4 Outer panel material data

In order to model the surface textures on the soccer ball, quantitative data representing the compressibility of the foams was required. FE material models based on this information can then be described and fitted based on this experimental data.

7.4.1 Experimental

To measure the response of the outer panel foams, uniaxial compression data were gathered and analysed from previous testing carried out by the STRG. The compression data was carried out on the two main components of the outer panels; the outer PU and the EPDM foam, individually. Additional testing was carried out on the composite panel. Individually, since the materials are relatively thin for a compression test, multiple samples were bonded together to create thicker test pieces. The outer PU was placed in layers of three to create a disc 3.2 mm thick. The EPDM foam was bonded together in two layers to create a disc 5.3 mm thick. A uniaxial compression test machine was used with a strain rate of 1000 mm/min. Figure 7-4 shows the compression stress-strain curves obtained for the three materials. As it can be seen, the EPDM foam exhibits a soft response as compared to the outer PU. This was approximately 10 times softer at a strain of 0.5. The stiffness of the composite outer panel was found to be mid-way between the two
components. Although below a strain of 20%, the softer material was found to dominate the deformation response.

![Nominal Strain vs. Nominal Stress graph](image)

**Figure 7-4: Experimental uniaxial compression data for the components of the outer panels**

### 7.4.2 Abaqus foam material models

Abaqus was the chosen solver for this research and two main material models for modelling nonlinear elastic materials were available.

#### 7.4.2.1 Hyperfoam

The Hyperfoam model is used to represent elastomeric foams where the material behaviour is isotropic and nonlinear. It allows for very large volumetric changes and can deform elastically to strains of 90% in compression, Abaqus (2007). The Abaqus documentation also describes the mechanics of foam in compression which can be distinguished in three stages:

1) At small strains (<5%) the foam deforms in a linear elastic manner due to the cell wall bending,
2) The deformation then plateaus at a constant stress caused by buckling of the cell walls. For a closed cell, as with the materials used, the enclosed gas pressure and membrane stretch increase the level and slope of the plateau.

3) A region of densification then occurs where the cell walls crush together resulting in a rapid increase of compressive stress. Ultimate compressive nominal strains can reach 70 to 90%. (Abaqus 2007).

These typical features of a compression stress-strain curve were identified previously in the outer panel material testing in Figure 7-4. Uniaxial test data is the minimum requirement to start to fit the material models within Abaqus with the user to input a constant poisons ratio (υ) if required. Typically for foam compression, the υ is 0.3 which then decreases to near zero for stages 2 and 3 where the buckling of the cell walls occurs causing little to no lateral expansion.

The Hyperfoam model can be adjusted to fit the experimental data by changing the strain energy potential. The strain energy potentials define the strain energy stored in the material per unit of reference volume (as in the initial configuration) as a function of the strain at that point in the material, Abaqus (2007). The inclusion of test data allows Abaqus to calculate the coefficients required to represent the material.

7.4.2.2 Hyperelastic

The Hyperelastic material model was designed to represent rubber like materials at finite strains and provides a general strain energy potential to describe the material behaviour for nearly incompressible materials, Abaqus (2007). In contrast to the Hyperfoam model, the Hyperelastic model provides several forms of the strain energy potential which are of particular use for the modelling of incompressible rubber materials. For this section of the research, where the compression of foams was the primary interest, it was appropriate to use the Hyperfoam model. The stress-strain curves of the experimental testing also justify the use of the Hyperfoam model as these match the characteristics described for a typical compression curve.
7.4.3 Fitting material models

The Hyperfoam material model was used to fit the experimental uniaxial compression data. The Hyperfoam model can be compared against the experimental data by varying the order of the strain energy potential from 1 to 6. As Abaqus does not support material model fitting application for the Hyperfoam option, a simple model of the compression test was used to assess the suitability of the strain energy potentials. The force and displacement history outputs were used to form a stress-strain curve. The results of this matching procedure for the outer and foam components can be seen in Figure 7-5. As shown the strain energy potentials do not have a large influence on the shape of the curves for this set of data. Any of the strain energy potentials could be use for the softer foam whereas for the outer PU a potential of 2 or more provides an accurate fit to the data. These models were used to provide the material information of the compression testing of the textures.

Figure 7-5: Graphs of the experimental data (a) and the Hyperfoam model at strain energy potentials (1-4) (b)
7.5 Developing a soccer ball finite element model to include solid elements

7.5.1 Approach taken

This section describes the process used to assess the performance of a surface texture for a soccer ball during a typical impact. A soccer ball model with one layer of shell elements representing all of the material layers contains over 2000 nodes, equally spaced at approximately 1 cm. Since a texture is on average 0.1 mm in height and in most cases the features are of the order of a few millimetres wide, applying a geometric texture across the ball would result in an estimated 350 million elements. Therefore it was decided to create a sub-model of the texture using boundary conditions (BC) determined from the whole ball model. In order to establish the BC the levels of deformation through the thickness of the panel were found for a typical ball impact. Simply using the contact pressure of an impact as determined in previous sections would not be an entirely accurate BC as the interaction of the panel with the air pressure of the ball on one side and the rigid surface on the outside would not be represented. From a true representation of the compression, a BC was then applied to a small sample of panel representing the topography of the texture and the two main foam layers to gather data about the contact.

7.5.2 Converting a shell to solid element based ball model

7.5.2.1 First development

The first task was to obtain the boundary conditions from the whole ball to apply to the sub-model. The existing soccer ball models created by Price (2005) were based around the use of shell element representing a theoretical through thickness of the panels and carcass. Shell elements were chosen for these models due to their computational efficiency for modelling long and thin structures where the deformation of the outer panels was thought to be negligible as compared to the strains experienced along the length of the materials. The ball model chosen to develop was the closest match to the adidas Teamgeist and was within 5% of the experimental data. This model consisted of two layers of shell elements tied together with the outer layer representing the outer panel construction and the inside layer, the carcass and bladder. This enabled the outer panel construction to be isolated for further development. The application of
solid elements in the outer panels allowed the localised deformation of the compression to be estimated for an impact.

The first approach adopted was to use solid elements sandwiched between the existing carcass layer and a thinner version of the existing outer panels shell layer (Model A). It was hoped that the solid elements would represent the compression data whereas the thin shell layer of the outer panels would give the longitudinal tension data as before. Figure 7-6 illustrates this development. To create the solid elements Abaqus has an edit mesh facility. The first step involved using the existing outer panels shell mesh and extruding outwards the panel thickness using one element. In this process the original shell mesh was deleted. The new shell layer on the outer was created by sharing the nodes of the newly created solid layer which meant that the layers would not have to be tied together.

Model ‘A’ was set up to impact a planar rigid plate at a normal angle at 25 m/s to enable a comparison. The velocity was chosen such that significant deformation occurred (ball diameter compression to 70% of original in the impact normal direction). The original shell model was also simulated at this velocity for comparison. The models were compared using the COR, contact time and the two orthogonal cross-sectional dimensions of the ball at maximum deformation. These were the metrics used for the majority of the development of the models by
Price (2005). The solid elements used a Hyperfoam model based on the whole panel compression tests. The thin top shell layer used the existing Hyperelastic material model for the tension mode of the outer panels. Figure 7-7(a) shows the deformation measures and the results of the impacts are shown in (b). A suitable model would result in values almost identical to the original. The COR values were found to be similar whereas the deformation measures (5%) and contact time (12%) were less similar. This was due to the fact that the beta damping value used for the model which controlled the energy losses was the same as for the original shell model. The beta damping is a stiffness proportional value which is related to the total strain rate, Abaqus (2007). The contact time and deformation were dependent on the stiffness of the material which was too soft causing larger tangential and normal deformation and a longer contact time. To supplement model ‘A’, the same model was run using 2 and 4 elements through the panel thickness (Figure 7-7(c)), although this made no difference to the results or artificial energies as seen for other ball models (Cordingley, 2002). The simple compression FE tests used to determine the strain energy potentials was also used to determine if the number of elements through the thickness had a significant effect, however it was seen that this did not influence the results.

Figure 7-7: Showing (a) the deformation metrics, (b) the model comparison and (c) the elements through the thickness of the panels

From these results and visualisations, the softer material of the solid elements appeared to be dominating the extension material model data of the Hyperelastic outer shell elements. Therefore the extension data of the Hyperfoam model was predicted by Abaqus from the compression data which had a significantly softer response that the Hyperelastic material. To illustrate this, a
tension and compression material test was carried out in FE for the outer panel Hyperfoam material and the results plotted against the tension experimental data to see how the Hyperfoam performed in extension. The results of this can be seen in Figure 7-8. As shown the nature of the Hyperfoam curve causes a very soft response initially before an exponentially increasing stress value. The Hyperfoam model is a very good match for the compression data but the transition to tension causes the soft response. This problem led to the second development of the model which is described below.

![Stress-strain graph of the Hyperfoam model as compared to the experimental material test data](image)

**Figure 7-8: Stress-strain graph of the Hyperfoam model as compared to the experimental material test data**

### 7.5.2.2 Second development

With the problem of the material models identified, a new approach was required. A single material model was needed to represent the complete range of strains required and to take into account the discontinuity between compression and tension. The expected strain in extension was calculated to be up to 20% whereas the compression of the panel was not known. The material data for the extension of the EPDM foam and outer PU are plotted on the same stress-strain graph as the compression data as shown in Figure 7-9. As seen the EPDM foam is very sensitive to changes in stress as compared to the outer PU material. As described in the previous section the Hyperfoam material model when created using compression data alone provides a poor fit to the extension data. Even with the extension data added, the material model fit is good for the compression but has the same characteristics as the model shown in Figure 7-8 where the extension data is severely underestimated. As these were two separate tests (but at similar test speeds) this was expected. To smooth the data at this point a novel method was adopted. As the
Hyperfoam material model uses strain energy potentials which are loosely based on a polynomial curve, the raw experimental data was used to fit a polynomial trendline in Excel, using a suitable power to fit a curve with the intercept set to (0, 0). This is shown in Figure 7-9(b).

Figure 7-9: Showing the combined experimental material test data and the polynomial smoothing method

As shown the polynomial trendline method can provide a smooth transition between the compression and tension material data sets whilst also closely matching the data. The polynomial trendline equation was used to create a table of stress-strain values to be used for the Hyperfoam material model. A simple FE material model test proved that the new Hyperfoam model accurately matched the experimental test data in both modes of deformation as shown in Figure 7-10.
These new material models for the separate layers were then used to create the second development, (Model B). The benefits of using both materials would allow the isolation of different levels of deformation in the layers as they have very different stress-strain responses. The construction of Model 'B' is shown in Figure 7-11. From the original shell model, the outer panel elements are extruded outwards by 2.9 mm (1 element thick) and then 1 mm (1 element thick) which created the EPDM foam and outer PU layers respectively. The original outer panel shell elements were deleted and the two solid layers share nodes between layers to eliminate the use of a tie constraint.

Figure 7-10: Results of the polynomial trendline method for material modelling

Figure 7-11: Diagram illustrating the final development of the solid element ball model
As with the first model developed, the new solid model was impacted against a rigid plate at 25 m/s. The metric comparisons can be seen in Figure 7-12(a). It can be seen that the new model compares favourably to the original shell model with all metrics within 3%. This equates to about 2 mm in terms of deformation, 0.2 ms difference in contact time and 0.016 in COR. Also the benefits of the two separate layers can be seen in Figure 7-12(b) and (c) where the differences in stress values at maximum deformation and during inflation can be seen. However on closer inspection, the behaviour of the foam during impact revealed distortions during the impact on the inside surface. The softer EPDM foam distorts due to hourglassing of the mesh which in part is due to the coarseness of the mesh. The distortion was not present for the stiffer outer PU layer. These distortions are shown in Figure 7-13(a).

<table>
<thead>
<tr>
<th>(a) Metric comparison</th>
<th>COR % out</th>
<th>Contact Time % out</th>
<th>Tangential Def. % out</th>
<th>Normal Def. % out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Shell Model</td>
<td>0.814</td>
<td>0.007311</td>
<td>0.243</td>
<td>0.154</td>
</tr>
<tr>
<td>Two Hyperfoam Layers - Outer and Foam</td>
<td>0.830</td>
<td>2.02</td>
<td>0.00753</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Figure 7-12: Metric comparison of the new model plus images showing the differences between the two outer panel layers

The reduced integration brick elements (C3D8R) that have been used to model the solid foam materials of the ball are susceptible to exhibiting hourglass modes. This is where the stiffness of the element is effectively zero as a change in the shape of the element does not always result in a change in length, or relative angle, of the integration lines, (Gibbs 2006 and Cordingley 2002).
To control this behaviour Abaqus can apply a number of controls. As the ball models are run in Explicit, Abaqus sets the default section control to the “integral viscoelastic approach”. This method “generates more resistance to hourglass forces early in the analysis step where sudden dynamic loading is likely” however this has little influence on the distortion seen in Figure 7-13(a). This was due to this method being unavailable for Hyperfoam and Hyperelastic materials. The method that produced the best results was the Kelvin viscoelastic approach using the pure stiffness form. This acts to maintain a normal resistance to hourglassing throughout the simulation. Abaqus recommends this approach for reduced-integration elements in transient dynamic simulations of which this soccer ball impact is an example. In addition the stiffness control can be adjusted by specifying a displacement hourglass scaling factor. The results of changing this factor in relation to the ball panel hourglass shapes and metrics are shown in Figure 7-13(a) and (b) respectively. The increase in this factor decreases the hourglass modes but has a detrimental effect on the COR and contact time in particular. An hourglass factor of 20 provides a trade-off in terms of model performance and realistic deformation shapes to identify localised loading characteristics for the sub-modelling which is now described.

<table>
<thead>
<tr>
<th>Original Shell Model</th>
<th>COR</th>
<th>Contact Time</th>
<th>Tangential Def.</th>
<th>Normal Def.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.814</td>
<td>0.007311</td>
<td>0.243</td>
<td>0.154</td>
</tr>
<tr>
<td>Solid Model 2</td>
<td>0.650</td>
<td>2.0</td>
<td>0.00753</td>
<td>3.0</td>
</tr>
<tr>
<td>HG1</td>
<td>0.843</td>
<td>3.6</td>
<td>0.00746</td>
<td>2.0</td>
</tr>
<tr>
<td>HG5</td>
<td>0.858</td>
<td>5.4</td>
<td>0.00725</td>
<td>-0.8</td>
</tr>
<tr>
<td>HG10</td>
<td>0.861</td>
<td>5.9</td>
<td>0.00712</td>
<td>-2.6</td>
</tr>
<tr>
<td>HG20</td>
<td>0.867</td>
<td>6.6</td>
<td>0.00697</td>
<td>-4.7</td>
</tr>
<tr>
<td>HG50</td>
<td>0.862</td>
<td>5.9</td>
<td>0.0067</td>
<td>-8.4</td>
</tr>
</tbody>
</table>

Figure 7-13: The effect of adding and changing the levels of hourglass controls for foam deformation
7.5.3 Texture Sub-modelling

This section describes the process of using the solid element ball model to identify localised panel compressions in order to generate boundary conditions which can be applied to a sub-model for the analysis of textures.

7.5.3.1 Determining the boundary conditions

A small section of panel with a texture applied to the outer PU surface formed the basis of the sub-model. The base surface of the EPDM foam was constrained in all degrees of freedom (encastre) whilst an analytical rigid planar surface was to be driven by a predetermined time-displacement curve to compress the surface. The model developed in the previous section was used to simulate a normal impact at a range of velocities with the panel thickness throughout contact monitored. Figure 7-14(a) illustrates this measurement from the simulations. The results in Figure 7-14(b) revealed that the panel thickness over the contact time was symmetrical with a sharp decrease in the first 0.001 seconds to 0.5 mm then a slower compression over the next 0.004 seconds to a total compression of an average 0.6 mm. The change in velocity did not have a large effect on the total deformation. From these results, a simple time-displacement curve was established to represent the compression of the panel to be used for a sub-model as shown in Figure 7-14(c). A displacement driven analytical rigid surface was identified as being the most efficient method of recreating this localised deformation. As the inertial effects were not of interest, the sub-model was simulated in Abaqus/Standard. Initial models of a small sample being compressed produced similar results both quasi-statically and explicitly. However the quasi-static approach produced the best contact outputs with regards to noise in the ratio of artificial to internal energy and the reaction forces.
Nodes used to monitor the change in distance during an impact
- They are located vertically in line with the rigid surface at the base of the ball

![Diagram](image)

Figure 7-14: Measuring the compression of the outer panels throughout the ball contact at different ball impact velocities (b) led to the development of a typical panel compression curve (c)

### 7.5.3.2 FE soccer ball texture generation

A wide range of soccer balls with different textures but with same construction and materials were available from the industrial collaborator. It was decided to use these manufactured textures to provide the basis of the sub-modelling technique. The textures chosen were those that were easy to replicate within a FE model, i.e. those that had a simple geometric shape that could be instanced several times to reproduce the texture. Complex shapes and random patterns were omitted. Figure 7-15 shows the process of generating the FE models of the textures. Instead of using scanned point cloud data to generate the surface, the texture was simplified to aid the meshing and model creation. The other benefit of this method was that if a dimension needed to be changed, i.e. shape height, Abaqus would automatically update the instanced parts on the panel with the new dimension and re-mesh. The CAD data and laser scans also provided the correct instancing patterns and dimensions. The sub-models were meshed using C3D8R elements. Since the compression of the material was of interest, the Hyperfoam material models were based on only the compression material test data.
7.5.3.3 Contact areas

The main metric to compare the texture’s performance under realistic loading conditions was the contact area. The boundary conditions used were those determined in the previous section. As the different textures varied in size and spacing, each texture was assigned a different size panel to create a good representation of the pattern. For example the Flags texture was the largest and required a panel 0.04 x 0.04 m., whilst the Diamond texture was smaller and needed only a 0.009 x 0.008 m panel to create an accurate representation. As the panels were different sizes the contact area expressed in m² would not allow for a valid comparison. Consequently the percentage contact area was used. Figure 7-16 shows the percentage contact area over the loading time with the final contact areas shown below the graph.

Figure 7-15: The generation procedure for producing the FE sub-models of the different textures
Figure 7-16: Graph showing the percentage contact area over time (top) and the final compression contour plot showing areas in contact (blue) and out of contact (white)

7.5.3.4 Analysis of contact areas

From Figure 7-16 it can be seen that each texture has an individual contact area trend during loading. The ends of the curves represent the mid point of an impact. As would be expected the Standard smooth ball outer creates a 100% contact area throughout. The other textures vary from final contact areas of 52 to 86%. Perhaps the most critical phase of establishing ball grip would be the initial period of contact, for example the first 10% of the contact time, i.e. 0.001 seconds. During this phase the Flags texture reaches 55% immediately whereas the others reach this value at the end of the first 0.001 seconds. The important question that arises is: what is the optimum contact area?
It is obvious that the optimal contact area in a match situation will depend on the environmental conditions and the other contacting surface. However to simplify the analysis the other surface was considered to be analytically rigid allowing the ball texture to be isolated for comparison. For a dry condition the optimum contact area could be assumed to be 100%. The area here is the true area of contact rather than the nominal area. The same theory applies to automobile tyres where racing slicks are chosen for dry tracks for maximum traction. However, similarly to the tyres comparison, any moisture between the surfaces would mean that the risk of hydroplaning increases thus decreasing the adhesion component of friction to almost zero and reducing the deformation factor. Therefore a treaded tyre, as described in the literature, allows the moisture to be channelled away leaving the raised tread blocks to come into contact with the road. However in dry conditions, treaded tyres are susceptible to high rates of wear due to frictional heating plus the treaded areas mean that the true area of contact is much reduced. Therefore a compromise racing tyre is an intermediate which has features of high grip and tread for channelling low amounts of water. Since professional soccer is typically played on pitches that are watered just before kick-off there is generally going to be an element of moisture for a ball-surface interaction (Mooney and Baker, 2000). Therefore a ball texture is likely to be more of an improvement than hindrance to performance.

The textures modelled show a wide range of trends with the *Flags* having consistent contact area throughout around 55% compared to the increasing area of the *Fujiama* which increases to 86% by the midpoint of a ball impact. From the experimental ball impacts no significant differences were found between textures but a difference was found between a textured ball and a Standard ball when wet impacts were considered. Perhaps the most significant results occurred for the robotic leg testing between dry and wet conditions for the Standard and *Flags* ball. Here the textured ball performed similarly in the dry but maintained spin rate and consistency in the wet as compared to a Standard ball.

Not only is contact area important but also are the free volumes created by the depths of textures. All textures were 0.1 mm high except the *Flags* which was 0.2 mm. Therefore the *Flags* texture created deeper free volumes than the others. The ability of a deformed texture to channel water away from the apparent contact area is determined by both the free volumes and the pattern of
areas out of contact. Figure 7-16 shows the final areas of contact to help illustrate this. The two highest contact areas (Fujiama and Propeller) create isolated pockets whereas the two lowest (Flags and Diamond) create channels similar to tyre treads. It is also worth noting that in the first 0.001 seconds the Fujiama and Propeller also create channels but under the maximum loading these are minimised to just pockets. Therefore an optimum texture would have a high as possible contact area for dry conditions but create clear channels for moisture dispersion. On a slightly larger scale, the influences of seam patterns and size would also have an influence. As seen in the experimental impact testing, at steep inbound angles, the surface water was found to collect at the seams, which offer a less restricted path away from the contact zone. It is reasoned that the quicker the water can be moved to the seams the better the grip between ball and the other surface. The micro texture on a soccer ball should aid this process.

7.5.3.5 Predicting new texture performance

As mentioned in the previous sections, the modelling of the textures was carried out entirely in Abaqus software from the CAD generation to meshing to job analysis. This enabled the texture geometries to be easily altered and re-meshed for a unit and then the single unit being instanced over the panel. Therefore subtle changes to a texture can be made and an input file created quickly to start to predict the performance of new designs. To trial this technique, the Fujiama texture was doubled in height to compare to the original texture. Figure 7-17 shows the difference in percentage contact area by doubling the height of the Fujiama texture under realistic loading conditions.
7.5.4 Experimental validation attempt

The accuracy of the Hyperfoam FE model to predict foam deformation provided some confidence in the results of the compression of the textures. This section describes a simple experimental technique which was undertaken to validate the contact area results. Three initial techniques were trialled to assess their suitability for the application. The most significant obstacle to carrying out this investigation was caused by the small scale of the textures under investigation. This meant that electronic pressure sensors and pressure sensitive ink paper could not be used due to their inadequate resolution. A suitable method was developed which used image processing techniques. The sample of panel was compressed between two small polycarbonate plates to the approximate panel compressed height (3mm) as shown in Figure 7-18(a). Recording an image of the deformed texture through the transparent polycarbonate plate then allowed the contacting and non-contacting areas to be identified from their greyscale values, caused by each area’s different light reflecting properties. The images were then processed in Image Pro Plus to threshold by an appropriate greyscale value to create a binary image. A histogram was then used to count the number of black and white pixels to create a percentage contact area. Figure 7-19 shows the final contact area comparison between the FE analysis and experimental. Also included are selections of other textures which have not been modelled in
FE. As shown the experimental technique gave a good approximation to the FE except for the Fujiama texture where the FE was found to overestimate the value.

Figure 7-18: The image processing method to determine the texture contact area experimentally

Figure 7-19: Results comparison for the FE and experimental contact areas
7.6 Abaqus hydrodynamic/fluid modelling capabilities

7.6.1 Equation of state material model

Abaqus has the capability to model fluid-structure interactions (FSI) in dynamic loading situations. Currently the main applications of this modelling are sloshing and inertial loading effects such as water bottles being dropped or water moving in a tank. This FSI technique is not a full computational fluid dynamic (CFD) approach but can accurately simulate certain applications (Abaqus, 2007)

The model involves modelling a solid body as an incompressible and inviscid fluid to represent the structural response of a fluid. The material model, available in Abaqus/Explicit only, is an Equation of State (EOS). This material model provides a volumetric strength of a hydrodynamic material as a function of density and internal energy (Abaqus, 2007). Deviatoric strength of the material can be considered separately if viscous behaviour is needed. The material is modelled as a solid deformable body using hexahedral elements and an automated adaptive meshing regime.

The adaptive meshing involves the elements and nodes automatically adjusting their positions to either maintain the initial mesh grading or increase the number of elements in areas of high concave curvature.

Water is typically modelled using a linear EOS controlled by the Navier-Stokes equation of fluid motion. Additionally the laminar flow follows the Navier-Poisson law of a Newtonian fluid (i.e. similar to water). The linear EOS is of the Hugoniot form \( (U_s - U_p) \) from the Mie-Grünesien equations. The Hugoniot curve is based on the unique relationship between pressure and volume as derived from the bulk viscosity, deviatoric stress tensor and the deviatoric part of the strain rate. Full equations and derivations can be found in the Abaqus Analysis Users Manual (2007).

Simply put, the linear relationship can be described as:

\[
U_s = c_0 + sU_p
\]  

[Equation 7-1]

Where \( c_0 \) and \( s \) define the linear relationship between the linear shock velocity, \( U_s \), and the particle velocity, \( U_p \). In Abaqus, water can be defined by a density (983.204 kg/m\(^3\)) and a wave
speed (45.85 m/s). This wave speed corresponds to a bulk modulus of 2.07 MPa, three orders of magnitude less than the actual bulk modulus of water, 2.07 GPa. This was needed to avoid an overly stiff reaction so the internal forces arising due to the deviatoric response of the material should be kept several orders of magnitude below the forces arising due to the volumetric response. The shear viscosity was chosen as $8.9 \times 10^{-4}$ Pa.s. The values for water have been taken from example analyses in the Abaqus documentation as there is little information on these simulations.

7.6.2 Combining texture and water

This section describes the experimentation of the Abaqus hydrodynamic material models and what their possibilities.

7.6.2.1 Preliminary Investigation

The first stage of experimentation involved simulating the response capability of the material model. As the material model was to be used in compression, two scenarios were setup involving a solid deformable block of water surrounded by an analytical rigid box to constrain it. The first investigation was aimed at determining how the material responded to a sudden indentation at a similar speed and time to a soccer ball impact. Here a rigid revolved body of an indenter was displaced quickly down and held into the block of material as is shown in Figure 7-20(a). It can be seen how the sudden indentation started to propagate a wave and a rise in water level. The second example was to involve some tangential motion. Again a revolved rigid body was indented a small amount into a block of water and was displaced quickly across the surface. This is shown in Figure 7-20(b). Here a bow wave was formed at the leading face of the indenter.
7.6.2.2 Textures and water

After the initial application of the EOS material model it was then applied to the soccer ball panel compression testing. The EOS was unable to model free flow behaviours such as splashing or surface tension as it was more suited to a structural response. As seen the model was able to deform significantly but it did not act in the same way as say the smooth hydrodynamic particles used in other FE software such as Radioss. This is where small particles can be linked together to act like a fluid but also can separate and mimic splashing. If a small block of water was placed between the panel textures surface and the rigid plate, the block would simply deform to a flat object until the mesh distorted. To overcome this, the water block was split into one layer of 10 by 10 smaller blocks. The general contact condition was used with no friction to allow these water blocks to slide against one another and apart if required without having to specify contact pairs. As analytical rigid surfaces could not be used in the general contact formulation and this was replaced by a solid steel block to allow the top surface to be included in the contact.

Figure 7-21 shows the key images from this simulation. Image (a) shows the model setup with the panel above a steel plate with a layer of water (100 blocks). Images (b) illustrate the sequence of the compression until the elements distort to failure. The views taken are of a model cut in half to see through the middle of the interaction. Finally in (c) are two images to create a comparison between a smooth and textured surface from the same time through a compression. As seen the smooth surface created a circular spread of water blocks with the panel spread
equally across. Contrary to this result, was the spread created by the texture surface. Here the water blocks were disrupted and dispersed in different directions creating holes in the water layer. In this case it was more likely for the panel to come into contact with the other surface more quickly than the smooth surface.

Mesh distortion and computational times were found to be the big disadvantages of this modelling scenario. To avoid mesh distortions various element section controls were used to minimise the mesh tangling but none had an effect on this loading scenario. The best result was achieved by adding an artificial stiffness to the water. The EOS material model was found to be a computationally costly analysis as compared to a smooth hydrodynamic particles approach. In summary the EOS model is not suited to this type of analysis.
Figure 7-21: Images showing (a) the model setup, (b) an example of the panel compression with water and (c) the final spread of the water blocks for a smooth and textured panel surface.
7.6.3 Future FSI possibilities

The other feasible routes for investigating the FSI between a soccer ball panel and a surface of interest would be to couple Abaqus to a CFD solver. Due to the time scales involved to learn and set this up it was not deemed feasible and further work should be carried out in this area. Due for release in early 2008, a new version of Abaqus (6.7-EF) will have a fully incorporated multiphysics capability which will mean the solver will be able to complete full FSI and CFD based applications. It is based on an Eulerian-Lagrangian approach to model simple fluids interacting with structural models created in Abaqus. However the software technical staff believe that the short time period of a ball impact and scale of the current soccer ball textures are too small to use for this approach. Therefore sacrifices would have to be made in relation to scaling up the geometry and time for the specific compression problem analysed in this chapter. Initial examples produced by Abaqus show that the software will be suited to tyre hydroplaning examples. However there is a lack of validation in the literature for the shapes and flows of the fluids produced by CFD/FSI solvers. Caution should therefore be used when using these solutions and validation should be a primary task of any future work in this area. The approach taken in this chapter has created a method to show how free volumes and spaces can be created by changing the features of a micro surface texture. Therefore it is perhaps in the best interests of soccer ball designers and developers to concentrate on designing free volumes and how features seen in tyre tread design can be used to create different water dispersal.

7.7 Summary

To analyse the performance of soccer ball micro textures an existing FE soccer ball model has been developed to determine localised loading conditions on the outer panels during an impact. The development involved changing the outer panels from shell to solid elements to predict the panel compression during an impact. Foam material models were created to simulate the two main layers of the soccer ball outer panels. Existing soccer ball textures were generated by reverse engineering and existing CAD data to apply to a sub-model of a part an outer panel to which the localised loading was applied. Contact areas were compared and an experimental validation attempt showed a good approximation. A FSI approach was then evaluated which involved the EOS material model, unfortunately the software proved to be inadequate for this complex interaction.
8 Conclusions

8.1 Chapter Overview

The final chapter of this thesis attempts to summarise and draw conclusions from the research carried out. Firstly a discussion of the main findings is presented which then leads on to the areas of future work which have arisen from the findings. The research questions posed in the first chapter are then answered to conclude the thesis.

8.2 Discussion

8.2.1 Friction testing and contact conditions

A friction tester was developed through the initial work in an attempt to replicate the complex operating conditions in which a soccer ball impact occurs. The contact conditions were characterised by the sliding speed, contact pressure and environment. The friction tester was developed to test flat samples of materials rather than the whole ball, which would enable the testing of materials before a manufacturer was required to commit to the expensive tooling and manufacturing costs associated with the construction of a whole ball. The coefficient of friction was derived from a measurement of the torque made from the rotating drum when it came in to contact with the sample plate operated by a lever based system.

The contact conditions were subsequently quantified and it is anticipated that these will provide important information for future investigations into the interaction of soccer surfaces. The contact pressures were found to be relatively consistent and independent of the inbound conditions (speed and angle) at a contact pressure of approximately 400-500 kPa. This was due to the normal reaction force increasing and decreasing, proportionately to the contact area. Further investigations into the outer panel foam compression during an impact were reported in chapter 7. It was found that the outer panels may not experience such pressures as the inflation of the ball may help compensate the total external contact pressure.
Friction at the interface of two interacting surfaces is arguably one of the most difficult parameters to measure in engineering with reference to a specific application. It can be easy to create relative comparisons between material pairs with apparatus that is readily available but it will not provide accurate friction measurements specific to a real life system. The fidelity of models and simulations run in FE that involve contact are highly dependent on the quality of the friction parameters assigned. Some material pairs may provide the optimum friction condition in one set of contact conditions but may exhibit radically different behaviour at others. Currently, the best method of deciding material pairs is through trial and error where materials are placed in the actual system and the performance monitored. It was concluded that the best method for deciding on a soccer ball surface texture remains to physically carry out experimental impacts to compare materials.

8.2.2 Experimental ball impacts

The addition of a texture to the outer surface of a soccer ball was one way of changing the frictional interaction and was examined in dry and wet conditions against different surfaces, at different inbound angles. From the tests it could be seen that the wet and dry condition had the most significant influence on the ball rebound behaviour in terms of velocity, spin and angle. The contact angle at a set speed was also very significant. The ball texture was found to produce no significant difference in the dry but slight performance enhancements in the wet in terms of consistency. The lower speed drop tests on to an angled planar surface produced significant differences between a textured ball and a standard smooth ball in the wet. At a contact angle of 45° and using the average values, the standard ball produced 55% less spin, a 9% lower rebound angle and was 10% quicker (COR) than a typical textured ball in the wet condition. These metrics are all indicators of increased slip. The textured balls all performed similarly in both dry and wet.

The Robotic Leg was used to analyse the effect of a texture during a free kick scenario. The robotic kicking leg produced a consistent kicking action to a ball placed at an offset to the swinging motion to create a spinning ball. The results showed that no matter what the kicking leg cylinder material, the textured ball produced similar spin rates in the wet as compared to in
the dry condition. The *Standard* smooth ball experienced a drop in spin and an increase in spread of data. The textured ball maintained a similar spread of data. An ANOVA proved significant differences existed for the condition and ball type. Again the contact angle proved an important factor as a change in 1 cm in the kicking leg cylinder-ball offset can cause an increase (or decrease) of 100 RPM in spin. Finally, for future ball impact studies based on the carcass substructure of thermally bonded soccer balls the carcass effect must be taken into account by multiple impacts around the ball and/or by identifying the orientation.

### 8.2.3 FE friction capabilities and ball impacts

Considering just the FE results, it can be seen that the COF does have a large effect on velocity, angle and spin of an impact. Additionally the change of inbound angle, which changes the sliding speed of an impact, has a significant influence on the rebound metrics. This was further illustrated by using the cylindrical impacts to simulate the effect of changing the properties of interaction between a ball and the cross-bar. The scenario considered showed that by changing the friction from 0 to 1 caused a rebound angle difference of 29°, corresponding to a ground distance of 1.3 m. Therefore the wetness of the cross-bar could be a significant factor in whether a goal is scored when the ball impacts below the horizontal of the centre of the bar.

Varying the friction was found to cause large differences at shallow angles but as the angle was increased, all COF values converged to a similar trend and value. Adding a texture to a soccer ball caused this convergence to change between wet and dry conditions by comparison to a standard smooth ball. From the player testing of free-kicks, contact angles were found to be approximately 65° and at this value, the positioning of the foot was considered likely to be the dominant factor in the interaction. However the texture may increase the consistency and increase the range of error for foot positioning.

Using a force plate to obtain an average COF for an impact proved a successful way of determining a value to be used in the FE models where spin, angle and velocity were accurately predicted at relatively shallow angles. As it was determined that a single value COF can accurately predict ball rebound behaviour a method can be used to predict the ball across the
remainder of the desired contact angles. A single ball impact on to a force plate to gain an initial COF can be used to plug into the FE model to predict the ball rebound behaviour across a range of contact angles at the required velocity. The challenge for future designers and manufacturers therefore, is to find materials and/or textures that can take advantage of the effect friction can have on ball impacts to improve ball performance.

8.2.4 Texture modelling and performance

To supplement the experimental and computational analysis of the soccer ball impact, the texture was sub-modelled in Abaqus. The existing shell element soccer ball model was developed to include solid elements to predict the levels of through-pane thickness deformation. These levels were then used as the boundary conditions for a sub-model of a small sample of out panel. This technique provided a method to compare texture performance under realistic loading conditions in terms of contact area. The debate then logically followed as to what the optimum contact area would be. Obviously a 100% contact area would provide the optimum grip in dry conditions but would be detrimental in wet conditions. A heavily textured ball would reduce contact area and therefore experience a reduction in grip in the dry as well be subject to greater degrees of wear. The contact area is not the only important factor; the depths and profiles of the ‘tread’ are also significant as they provide free spaces for moisture to collect. The texture ball used for the robotic leg testing had a relatively large texture compared to others and was twice the height (0.2 mm) which may have contributed to its consistent performance between dry and wet in terms of spin rates and flight consistency. The area of interactions which was not considered was the pattern and geometry of the ball seams. The texture on the panels may enable the moisture to be directed to the seam positions more quickly than a smooth ball and break up a layer of moisture. The current manufacturing processes used to create the soccer ball surface textures typically permit a maximum texture depth of 0.15 - 0.2 mm. Therefore as the depth of textures is restricted, the design of the texture geometry is the key to improving surface interactions.

Initial FSI attempts have shown the complex nature of the compression of moisture between a ball and surface. The short time period combined with the small geometry may mean that many FSI systems may not be able to predict this scenario. In order to gain useful information from
FSI simulation, the compression would have to be scaled up and slowed down. However, this is likely to be detrimental to the accuracy of the prediction. Another drawback is the lack of straightforward techniques available to validate FSI simulations, meaning at this time FSI remains an area where further investigation is required.

8.2.5 Limitations

The main factor that has limited the conclusions that can be drawn from this research was found to be the large number of parameters that affected the impact and contact behaviour between the ball and surface. Due to time constraints only one velocity could be fully investigated across a range of angles with the velocity chosen being of a typical instep swerve kick where spin is applied. Other factors are the type of surface geometry, material type, levels of moisture, ball construction type and number of panels.

8.3 Recommendations for future work

8.3.1 Further FE modelling of soccer balls

From the initial development of modelling the construction and materials of the adidas soccer balls carried out by Price (2005) to the modelling work of the surface interactions reported in this thesis, the development and use of the models have been extensive. Since it is now known how the ball responds to rigid surfaces at different angles and friction, work can begin to model the other surfaces involved. These could include boot upper materials, goalkeeper glove palm foams and artificial pitches to see how varying the material properties of these affect the whole interaction. The effect of asymmetrical soccer boot lacing and grip areas could be investigated.

If the ball surface texture is modified for improvement to surface interactions then other consequences of this need to be investigated. In particular how the surface texture affects the overall aerodynamics of the ball during flight and potential skin abrasion for player during ball-skin contact.
8.3.2 FSI of sports equipment

The quickly developing nature of hydrodynamic simulation software has excellent potential to permit the modelling and prediction of moisture movement in sports equipment. This could range from ball-surface impacts such as tennis, golf and rugby through to ground interactions of the tread patterns of athletic footwear.

8.3.3 Contact pressure

Although a small piece of experimental testing in the development of a friction tester for soccer materials, the work associated with establishing the contact pressure stimulated various future possibilities. The higher velocity impacts on the pressure mat revealed how the seams of different types of ball constructions might be detected. This suggests the potential of this technique to investigate ball impacts and running shoes to see how textures, treads and seams perform in real time contacts. The measurement of soccer ball contact pressures could be of particular interest in the area of head injuries where the long-term effects of heading a soccer ball are investigated. As improvements in contact pressure measurement systems are made, with particular reference to sampling rates and pixel size, this would benefit not only soccer ball impacts but any short duration contact in sport.

8.4 Research questions

This section revisits the initial questions put forward in the introduction to conclude the research carried out in the thesis.

1) Is it possible to quantify the friction between a soccer ball and a surface of interest and relate this to impacts experienced in play?

    The measurement of friction between two surfaces has been shown to be a very complex interaction which is amplified with the testing of deformable materials such as polymers. It was found in the research that the friction is a property of a system of the two surfaces, materials, environment and contact conditions. Many existing friction testing devices do not model real life
systems and are only used because they are available to use. The data taken from a tribometer are only valid for that machine so the set up is paramount to gaining accurate COF results. Therefore a new tribometer or friction tester was developed to accommodate soccer materials and attempted to match the complex contact conditions such as high sliding speeds, high pressures and short duration contacts in different environmental conditions. The design can achieve the correct pressures and sliding speeds although to fully achieve the higher loads and speeds, more expensive motors would be required. Initial testing provided some interesting results indicating the dry to wet performance of different textures of soccer balls on leather.

An alternate approach was the reverse engineering of the COF using the single constant value and comparing to experimental impacts. This approach proved very successful and the trends and values of the rebound metrics for oblique impacts on different geometries were accurately represented. From this study it could also be seen how friction plays a role in soccer ball impacts and kicking. At shallow angles of impact the COF was found to be the dominant variable whereas at steeper angles the impact angle was the dominant factor. Interestingly many ball and surface combinations (boot leathers, artificial turf and goalkeeper glove materials) produced similar rebound metrics in the dry conditions but the performance varied only in the wet. The FE COF study concluded that for planar impacts when the COF was approximately 1 and above, the rebound metrics were similar. Additionally for the Robotic Leg simulations, there was little change in spin rates above a COF of 0.6. The key to future designs is matching the dry values in wet conditions which the surface texture of a soccer ball attempts to do, with some success. To conclude, the challenge is to select a certain number of scenarios that can be measured, quantified and understood such that a wider understanding can be developed.

2) How does varying the surface contact conditions, i.e. surface texture, affect the dynamic performance and consistency of a soccer ball?

The manufacture of soccer balls with varying surface textures with the same underlying construction and materials enabled the texture performance to be isolated. The main comparison completed in this research was whether a surface texture was better than a smooth finish. From the experimental work the benefit of having a surface texture was established. The oblique impacts at high speeds showed that the use of texture had little effect in the dry but a positive
effect in the wet. The spin rate data showed that the values were more consistent through a lower spread of data and converged to the dry condition spin rates at a shallower inbound angle. The low speed angled drop tests produced significant results at the 45° inbound angle on boot leather, as compared to a textured ball which performed similarly in dry and wet, the standard smooth ball had 55% lower spin in the wet. The rebound angle was 9% shallower and was 10% quicker indicating an increased level of slip. The spread of data was also higher for the standard ball. For robotic leg kicking, the significant ANOVA condition was the ball type and dry/wet condition rather than the boot material type. The scatter graph of spin rates clearly shows the benefit of having a textured soccer ball. The textured ball has similar averages and standard deviations in the dry and wet whereas the standard ball has a drop in spin and increase of standard deviation in the wet as compared to the dry. The standard and textured balls performed equally in the dry showing that the texture was not detrimental to the contact.

The experimental impacts were then compared to FE COF results for further analysis. The results presented show how the COF affected a soccer ball impact with experimental data for comparison. Previous research, such as the work carried out by Asai et al (2004) did not validate any of the FE simulations to show the effect of changing the COF. This research has shown that the COF has more of an effect for shallow angle impacts whereas the contact angle is more critical at steeper angles. As described the convergence of dry and wet rebound metrics as the contact angle increases from shallow to steep can be subtlety affected by surface texture. For a player taking a free-kick where spin, power and accuracy are required, the contact angle is a crucial variable. However a surface texture may allow for some error in foot orientation to create the same ball launch metric between dry and wet conditions as well as maintaining a high level of consistency.

3) Is it possible to design a soccer ball to perform equally well and consistently in wet and dry conditions?

   The answer to this research question is not definitive. Some of the experimental results suggests that it is possible and some not. This is due to the wide range of surfaces and conditions the soccer ball interacts with during a game. This aspect of engineering is still being developed
even for the automobile industry where there has been considerable investment in tyre technology, on wet tracks the lap times are still significantly slower than in the dry. Adding a surface texture to a soccer ball definitely causes a positive outcome towards closing the gap between dry and wet performance as seen with previous smooth ball. Positive results were seen with the robotic leg in particular but for the oblique impacts only at certain angles, speeds and surfaces. The area where the surface texture has little of no effect is at shallow angles especially at high speeds. The artificial turf used in the testing showed no differences between textures at low speeds. However since the contact angle is relatively steep when a player contacts a ball, the texture only has to change the rebound metrics slightly to achieve equal and consistent performance.

Chapter 7 reported an assessment of the performance of textures in relation to their design using a FE sub-model with realistic localised loading conditions. The percentage contact area is perhaps the key design factor which relates to dry and wet performance. A low contact area may help in the wet but would be disadvantageous in the dry indicating perhaps that an optimum contact area is required. The best design would involve a high contact area but where there are free spaces the volumes would need to be deep. The oblique impact testing showed the role that seams play in the initial contact pressure study, the optimum outer surface for a soccer ball would need a combination of seams and texture. The underlying material and construction also has to play a role. The tyre industry shows that dropping the pressure or using softer rubbers increases the grip. This relates to the deformation component of the deformable material friction when in hydrodynamic conditions the adhesive component is zero. However softer materials could be subject to higher levels of wear than tougher durable materials. Therefore to design a ball that performs equally well and consistently in dry and wet conditions the topography (texture and seams) along with the material properties would need to be considered. This research will provide an essential background to future soccer product development where surface interactions are of concern.
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