The dynamic testing of soccer balls

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THE DYNAMIC TESTING OF SOCCER BALLS

by

Paul Neilson

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Loughborough University

2003
ABSTRACT

Football, or soccer, is the most popular game in the world. The Fédération Internationale de Football Association (FIFA) estimate that there are 247 million people currently involved in soccer throughout the world. In 1996 the world governing body of soccer, FIFA, launched the Denominations program to ensure the global consistency of top match soccer balls. Under the Denominations test program, a sample of balls undergo a series of testing procedures designed to ensure the manufacturing consistency of competition balls and inform the players of ball quality. The existing test procedures provide an adequate method for the assessment of ball manufacturing quality; yet do not provide any criteria for the assessment of dynamic ball performance. This study is concerned with improving the existing testing procedures, and developing new dynamic test procedures and instrumentation.

A study of elite (professional) player kicking performance was undertaken to provide data on ball launch characteristics which could then be used as a benchmark for test development. An improved method of soccer ball sphericity measurement was devised using a coordinate measuring machine that provided an entirely automated method not subject to human error and interpretation. A method of measuring out-of-balance forces within soccer balls was developed using a vertical balancing machine and the magnitude and position of out of balance forces was assessed for a range of soccer balls.

The effect of out of balance forces on dynamic ball performance was assessed in two studies. The initial ball flight characteristics and trajectories of soccer balls were investigated using a pneumatic kicking leg as a launch platform. It was shown that the magnitude and position of unbalance at impact have a significant effect on ball launch trajectory. A second study was undertaken to assess the ability of professional players to perceive unbalance within soccer balls, although no significant results were obtained. The ball performance studies identified the need for an automated system for the analysis of soccer ball flight characteristics. Consequently, an automated image analysis system for the measurement of soccer ball launch characteristics was developed. The system is capable of measuring ball velocity, elevation, spin rate and spin axis to a high degree of accuracy.
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Professor Roy Jones, for the guidance and support he has given throughout the duration of this study. His knowledge and enthusiasm has proved invaluable during the day to day running of the project.

Thanks are due to Chris Sumpter for his considerable expertise in developing the automated soccer ball performance measurement system, and to Dr David Kerr for his assistance on the image analysis aspects of the work. I would also like to thank the members of the Sports Technology Research Group for their general assistance in a range of testing activities, in particular Dan Price and Dr Jon Roberts. For technical support during the course of this study I would like to express my gratitude to Steve Carr, Nev Carpenter and Jagpal Singh.

I would like to thank adidas for supporting the project and granting access to their facilities and equipment. Dr Tim Lucas deserves special thanks for promoting the work amongst his colleagues and coordinating testing at the adidas Global Test Centre. I would also like to express my thanks to Roger Angell at BTD for granting access to their vertical balancing machine, and to the five football clubs that agreed to participate in player testing, namely: Aston Villa, Everton, Hull City, Leicester City, and Norwich City.

Finally, on a personal note I would like to express my thanks to Kate for putting up with me over the last three years, and to my mother and father for their continual support throughout my time in higher education.

Neilson, P.J. and Jones, R. (2003b). Dynamic soccer ball performance measurement. 5th World Congress of Science and Football, April 11-15; Lisbon, Portugal.


# TABLE OF CONTENTS

## CHAPTER 1

INTRODUCTION.................................................................................................................. 1

1.1 FIFA DENOMINATIONS PROGRAM ................................................................. 2

1.2 AN OVERVIEW OF SPORTS BALL SPECIFICATIONS ................................. 3

1.3 THE NEED FOR DYNAMIC BALL PERFORMANCE TESTING ............... 4

1.4 RESEARCH OBJECTIVES ............................................................................. 5

1.5 THESIS OUTLINE ........................................................................................... 6

## CHAPTER 2

LITERATURE REVIEW................................................................................................. 8

2.1 THE EVOLUTION OF THE SOCCER BALL .................................................. 8

2.1.1 Early Inflatable Soccer Balls .................................................................. 9

2.1.2 The Discovery of Rubber ....................................................................... 10

2.1.3 The First Soccer Rules .......................................................................... 10

2.1.4 Other Forms of Football ........................................................................ 12

2.1.5 A Period of Growth ............................................................................... 12

2.1.6 International Soccer ............................................................................... 14

2.1.7 Twentieth Century Ball Development ............................................... 14

2.1.8 The Use of Synthetic Materials in Soccer Balls .................................. 15

2.1.9 Modern Soccer Ball Construction ....................................................... 17

2.1.9.1 The Bladder ................................................................................... 17

2.1.9.2 The Stitching ................................................................................. 18

2.1.9.3 The Lining ...................................................................................... 18

2.1.9.4 The Outer Casing ......................................................................... 18

2.1.10 The Modern Game ............................................................................... 19

2.2 THE EARLY SPORTS SCIENTISTS ............................................................... 19

2.3 AERODYNAMICS ....................................................................................... 20

2.3.1 Drag Force ........................................................................................... 20

2.3.2 Reynolds Number ................................................................................ 21

2.3.3 Lift Force .............................................................................................. 23

2.3.4 Experimental Aerodynamics Studies on Spheres .............................. 25

2.3.4.1 Spinning Spheres ........................................................................ 26

2.3.5 Trajectory Analysis .............................................................................. 27

2.3.5.1 Soccer Ball Trajectory Analysis ................................................... 28

2.3.5.2 Trajectory Analysis of Other Sports Balls .................................. 29

2.4 BALL IMPACTS ............................................................................................ 30

2.4.1 Coefficient of Restitution .................................................................... 30

2.4.2 Soccer Ball Impacts .............................................................................. 31

2.4.2.1 Kicking Soccer Balls .................................................................. 31

2.4.2.2 Heading Soccer Balls .................................................................. 32

2.4.2.3 Impact Force Measurements ......................................................... 33

2.4.2.4 COR Testing ................................................................................ 34

2.4.3 Other Sports Ball Impacts .................................................................... 35

2.5 BIOMECHANICS ............................................................................................ 36
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>An Exact Method for the Sphericity Measurement of Soccer Balls</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td><strong>3.1</strong> The Need for Sphericity</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td><strong>3.1.1</strong> Soccer Ball Play Characteristics</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td><strong>3.2</strong> Existing Methods of Measurement</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td><strong>3.3</strong> Least Mean Squares Method</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td><strong>3.3.1</strong> Parameterisation of Least Mean Squares Method</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td><strong>3.4</strong> Automated Ball Sphericity Measurement Procedure</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td><strong>3.5</strong> Results</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td><strong>3.6</strong> Discussion</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td><strong>3.7</strong> Conclusion</td>
<td>58</td>
</tr>
<tr>
<td>4</td>
<td>Determination of Soccer Ball Performance Parameters</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td><strong>4.1</strong> Measurement of Ball Velocity and Spin Rate</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td><strong>4.2</strong> Participants</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td><strong>4.3</strong> Testing Procedure</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td><strong>4.4</strong> Equipment</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td><strong>4.5</strong> Flightpath Trajectory Analysis Software</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td><strong>4.6</strong> Results</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td><strong>4.7</strong> Statistical Analysis of Test Subject Data</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td><strong>4.7.1</strong> Ball Velocity Analysis</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td><strong>4.7.2</strong> Ball Spin Rate Analysis</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td><strong>4.8</strong> Discussion</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td><strong>4.9</strong> Conclusion</td>
<td>73</td>
</tr>
<tr>
<td>5</td>
<td>Measurement of Out of Balance Forces in Soccer Balls</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td><strong>5.1</strong> The Presence of Unbalance in Soccer Balls</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td><strong>5.2</strong> Unbalance Theory</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td><strong>5.2.1</strong> Static Unbalance</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td><strong>5.2.2</strong> Dynamic Unbalance</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td><strong>5.2.3</strong> Unbalance Model</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td><strong>5.3</strong> Soccer Ball Unbalance Measurement</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td><strong>5.3.1</strong> Vertical Balancing Machine</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td><strong>5.3.2</strong> Ball Fixture</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td><strong>5.3.3</strong> Fixture Calibration</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td><strong>5.4</strong> Testing Methodology</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td><strong>5.5</strong> System Evaluation</td>
<td>83</td>
</tr>
</tbody>
</table>
5.5.1 The Effect of Ball Orientation on Unbalance Measurement ............................................. 83
  5.5.1.1 Results .................................................................................................................. 84
5.5.2 The Effect of Ball Pressure on Unbalance Measurement .............................................. 86
  5.5.2.1 Results .................................................................................................................. 87
5.5.3 The Effect of Spindle Speed on Unbalance Measurement ........................................... 89
  5.5.3.1 Results .................................................................................................................. 89
5.5.4 The Effect of Additional Masses on Unbalance Measurement ...................................... 90
  5.5.4.1 Results .................................................................................................................. 91
5.5.5 Summary ..................................................................................................................... 91
5.6 UNBALANCE COMPARISON OF MAJOR BALL TYPES .................................................. 91
  5.6.1 Results ..................................................................................................................... 92
5.7 CONCLUSION ................................................................................................................. 93

CHAPTER 6 .................................................................................................................................95
THE EFFECT OF OUT OF BALANCE FORCES ON DYNAMIC BALL PERFORMANCE ........95
6.1 UNBALANCE EVALUATION OF TEST BALLS ................................................................. 95
6.2 TRAJECTORY ANALYSIS USING ROBOT KICKING LEG ............................................. 97
  6.2.1 Equipment ................................................................................................................. 98
  6.2.2 The Effect of Unbalance on Dynamic Ball Performance ........................................... 99
  6.2.3 Experimental Set Up ................................................................................................. 100
  6.2.4 Testing Procedure ...................................................................................................... 102
    6.2.4.1 Ball 2D Position Measurement Software ............................................................. 103
  6.2.5 Results ....................................................................................................................... 103
  6.2.6 Discussion ................................................................................................................... 106
    6.2.6.1 Summary .............................................................................................................. 110
6.3 THE ABILITY OF ELITE PLAYERS TO PERCEIVE BALL UNBALANCE ......................... 111
  6.3.1 Selection of Appropriate Tests .................................................................................... 111
  6.3.2 Participants ................................................................................................................ 113
  6.3.3 Testing Procedure ..................................................................................................... 113
  6.3.4 Results ....................................................................................................................... 115
  6.3.5 Statistical Analysis of Ranking Data ........................................................................ 117
    6.3.5.1 Kendall’s Coefficient of Concordance .................................................................. 118
    6.3.5.2 Wilcoxon Signed Ranks Tests ............................................................................ 118
  6.3.6 Discussion ................................................................................................................... 119
    6.3.6.1 Summary .............................................................................................................. 119
6.4 CONCLUSION ..................................................................................................................... 119

CHAPTER 7 ..................................................................................................................................121
AUTOMATED SOCCER BALL PERFORMANCE MEASUREMENT SYSTEM ......................121
7.1 INTRODUCTION ............................................................................................................... 121
7.2 BACKGROUND ............................................................................................................... 122
  7.2.1 Flightpath System ....................................................................................................... 122
  7.2.2 Spindot System ......................................................................................................... 123
7.3 SOCCER BALL MEASUREMENT SYSTEM CONCEPT ............................................... 123
  7.3.1 Pattern Identification Criteria .................................................................................... 124
  7.3.2 Genetic Algorithm ...................................................................................................... 125
  7.3.3 Spin Measurement .................................................................................................... 126
LIST OF FIGURES

CHAPTER 2
Figure 2.1 - 18 panel soccer ball
Figure 2.2 - 32 panel soccer ball
Figure 2.3 - Exploded view of soccer ball constituent parts (Soccer Ball World, 2003)
Figure 2.4 - Transition from laminar to turbulent airflow (adapted from Metha and Pallis, 2001)
Figure 2.5 - The Magnus effect caused by asymmetric boundary layer separation (adapted from Wesson, 2002)
Figure 2.6 - Leg movement in a typical soccer kick (adapted from Wesson, 2002)

CHAPTER 3
Figure 3.1 - An example of a constant diameter lobed shape (Hume, 1968)
Figure 3.2 - Ball sphericity measurement on CMM
Figure 3.3 - 2D representation of a LMS approximation to a sphere (adapted from Dagnall, 1976)
Figure 3.4 - Box plot of sphericity by ball type
Figure 3.5 - Box plot of average diameter by ball type

CHAPTER 4
Figure 4.1 - Unbranded test balls with added circumferential markings
Figure 4.2 - NAC high-speed camera with additional floodlighting
Figure 4.3 - Creation of composite image for digitising
Figure 4.4 - Flightpath analysis software
Figure 4.5 - Box plot of ball velocity data
Figure 4.6 - Box plot of ball spin rate data

CHAPTER 5
Figure 5.1 - System with static unbalance
Figure 5.2 - System with dynamic unbalance
Figure 5.3 - Representation of unbalance in soccer balls
Figure 5.4 - Schematic diagram of BTD vertical balancing machine
Figure 5.5 - Comparison of square wave pulse and vibration response peaks in order to generate unbalance angular orientation
Figure 5.6 - Diagram of fixture mounted to spindle and used to secure ball in position
Figure 5.7 - Fixture calibration on BTD vertical balancing machine
Figure 5.8 - Diagram of calibration process
Figure 5.9 - Unbalance measurements obtained at a range of ball orientations
Figure 5.10 - Boxplot of ball unbalance by ball orientation
Figure 5.11 - Prediction of unbalance magnitude for a range of ball orientations
Figure 5.12 - Box plot of ball unbalance for the adidas Finale at a range of inflation pressures
Figure 5.13 - Box plot of ball unbalance for the Puma Shudoh at a range of inflation pressures
Figure 5.14 - Ball unbalance measurement at a range of spindle speeds
Figure 5.15 - Boxplot of ball unbalance by major ball type

CHAPTER 6
Figure 6.1 - Additional masses added to balls around valve
Figure 6.2 - Boxplot of unbalance by additional mass value
Figure 6.3 - Schematic diagram of pneumatic kicking leg
Figure 6.4 - Spherical end effector attached to kicking leg
Figure 6.5 - Schematic diagram of launch instrumentation
Figure 6.6 - Target screen featuring grid for digitising
Figure 6.7 - Average impact positions for the adidas Fevernova ball
Figure 6.8 - Average impact positions for the unbalanced ball
Figure 6.9 - Calculation of variance for ball impact positions
Figure 6.10 - Effect of off-centre impacts on ball impact variance
Figure 6.11 - Combined impact dispersion of test balls on target
Figure 6.12 - Long passing test at Aston Villa FC

CHAPTER 7

Figure 7.1 - SpinDot ball spin measurement system
Figure 7.2 - Reference frame used to calculate 3D ball transformation for a unique pattern match
Figure 7.3 - Munsell colour cylinder HSI colour model
Figure 7.4 - The colour spectrum
Figure 7.5 - Prototype ball #1 featuring arbitrary arrangement of red, green, blue, black and white coloured panels
Figure 7.6 - Indoor image of prototype ball #1 obtained using NAC 500 high speed camera
Figure 7.7 - HSI histogram obtained for central green panel
Figure 7.8 - Image segmentation by thresholding of the blue panels within IPP
Figure 7.9 - Calculation of blue panel centroid coordinates within IPP
Figure 7.10 - Prototype ball #2 featuring unique arrangement of red, yellow, green, blue and white coloured panels
Figure 7.11 - Exploded view of panel colour assignment derived from genetic algorithm
Figure 7.12 - Indoor image of prototype ball #2 obtained using NAC 500 high speed camera
Figure 7.13 - Sequence of images of prototype ball #2 obtained using Canon XM1 digital camera
Figure 7.14 - 1st ball image undergoing arithmetic image ‘differencing (absolute)’ operation in order to identify ball location within the image frame
Figure 7.15 - Automatic identification of ball location within image frame
Figure 7.16 - Measurement settings required for detection and measurement of circular objects
Figure 7.17 - Determination of a unique ‘pattern match’ using spin analysis tool (developed by Chris Sumpter)
Figure 7.18 - Determination of spin axis using spin analysis tool (developed by Chris Sumpter)
Figure 7.19 - Sequence of outdoor images of prototype ball #2 obtained using Canon XM1 digital camera
Figure 7.20 - Binary image illustrating the problem caused by a non-static background during automatic identification of ball location
Figure 7.21 - Modified automatic identification of ball location in order to reduce the effect of background movement
Figure 7.22 - UG model of coloured ball used to assess spin measurement accuracy
Figure 7.23 - Prototype image capture unit mounted on tripod with specially manufactured coloured soccer ball
Figure 7.24 - Ball impact location relative to camera unit required for normal assessment of reasonable velocity kicks
Figure 7.25 - Results displayed from a typical capture obtained using the prototype system
Figure 7.26 - Unsuccessful calculation of spin rate due to close proximity of ball to flash units
Figure 7.27 - Unsuccessful determination of ball location indoors due to poor ball illumination at a distance of 3m from the camera lens
Figure 7.28 - Unsuccessful determination of ball location outdoors due to poor ball illumination at a distance of 3m from the camera lens
Figure 7.29 - Identification of specific kicking zones for 3 ball velocity ranges
Figure 7.30 - Pair of sequential images obtained in an indoor sports hall containing reflective surfaces within the image frame
Figure 7.31 - Binary image illustrating failure to recognise ball as circular due to presence of reflective surfaces within the image frame
Figure 7.32 - Pair of sequential images obtained indoors containing ball shadow projected on background
Figure 7.33 - Binary image illustrating ball location inaccuracy due to presence of shadow on background
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
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<tr>
<td>AOI</td>
<td>Area of interest</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer aided design</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer aided engineering</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge coupled device</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinate measuring machine</td>
</tr>
<tr>
<td>COR</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>FA</td>
<td>Football Association</td>
</tr>
<tr>
<td>FC</td>
<td>Football club</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FIFA</td>
<td>Fédération Internationale de Football Association</td>
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<tr>
<td>HSI</td>
<td>Hue saturation intensity</td>
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<tr>
<td>IMS</td>
<td>International matchball standard</td>
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<td>IPP</td>
<td>Image pro plus</td>
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<tr>
<td>ITF</td>
<td>International Tennis Federation</td>
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<tr>
<td>LMS</td>
<td>Least mean square</td>
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<tr>
<td>MDU</td>
<td>Machine Drive Unit</td>
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<tr>
<td>PU</td>
<td>Polurethane</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>RFU</td>
<td>Rugby Football Union</td>
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<tr>
<td>RGB</td>
<td>Red green blue</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>SDK</td>
<td>Software development kit</td>
</tr>
<tr>
<td>TTP</td>
<td>Touch trigger probe</td>
</tr>
<tr>
<td>UG</td>
<td>Unigraphics</td>
</tr>
<tr>
<td>USGA</td>
<td>United States Golf Association</td>
</tr>
<tr>
<td>VHS</td>
<td>Video home system</td>
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\[ \theta \] \hspace{1cm} Angle of rotation  
\[ \rho \] \hspace{1cm} Density of air  
\[ \gamma \] \hspace{1cm} Kinematic viscosity  
\[ \varphi \] \hspace{1cm} \Phi \text{ (spin axis angle)}  
\[ \psi \] \hspace{1cm} \Psi \text{ (spin axis angle)}
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</thead>
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<td>Three-dimensional</td>
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<td>$Li$</td>
<td>The $i^{th}$ data point in the set $L$</td>
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<td>$L_{acc}$</td>
<td>Luminance</td>
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<tr>
<td>$m_b$</td>
<td>Mass of ball</td>
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<tr>
<td>$M$</td>
<td>Mass of leg and foot</td>
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<td>$m/s$</td>
<td>Metres per second</td>
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<tr>
<td>$p_{si}$</td>
<td>Pounds per square inch</td>
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<td>Cartesian coordinate direction</td>
</tr>
</tbody>
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CHAPTER 1

INTRODUCTION

The application of engineering techniques to the design and development of sports equipment has increased considerably over recent years. This is largely due to the increased participation in sport at all levels, allied to the financial gain that this brings to the various equipment manufacturers. In the UK it is estimated that participation in sport amongst the adult population has increased from 39% in 1977 (Taylor, 1998) to 70% in 1999 (TSIF, 2001). This rise in participation has boosted equipment sales and increased competitiveness within the industry. The quest for innovative products within the sports equipment industry is crucial in order to give companies a significant advantage over their competitors.

The purpose of innovation in sports equipment design is to aid and enhance the performance of the athlete. These developments frequently take the form of increased power, velocity, stability or accuracy. However, there is a balance required between the need to continually improve equipment through innovation and the potential effect that these changes can have on the ethics and principles of the game. The various governing bodies are responsible for ensuring that equipment development does not have an adverse effect on the sport. In addition the media has considerable influence over sport because of the income it generates for governing bodies and equipment developments have also to be considered for their effect on media income.

Football, or soccer, is the most popular game in the world. The Fédération Internationale de Football Association (FIFA) estimate that there are 247 million people currently involved in soccer throughout the world. There are approximately 305,000 registered clubs, with 1,550,000 teams. At the highest level it is estimated that there are 127,000 (male and female) professional players worldwide (Stamm and Lamprecht, 2000). In the UK soccer is the most popular spectator sport with 36% of the population regularly watching games in person or on television (MIG, 2002).
In 1996 the world governing body of soccer, FIFA, launched the Denominations program to ensure the global consistency of top match soccer balls. Balls undergo a series of testing procedures that ensure consistency of top competition balls and inform the players of ball quality. The existing test procedures provide an adequate method for the assessment of ball manufacturing quality yet do not provide any criteria for the assessment of dynamic ball performance. This study is concerned with improving the existing testing procedures, together with developing new dynamic test methods and instrumentation.

1.1 FIFA DENOMINATIONS PROGRAM

The FIFA Denominations program was introduced on January 1st, 1996 to ensure the global consistency of top match soccer balls. All matches played under the auspices of FIFA, or the six confederations, must only use balls that have passed official FIFA test procedures. Ball testing is currently carried out by EMPA, the Swiss federal test laboratories, based in St. Gallen, Switzerland. There are two designations of FIFA endorsed balls, ‘FIFA Inspected’ and the more prestigious ‘FIFA Approved’. There is also a third designation technically equal to “FIFA Inspected” called International Matchball Standard (IMS), although the IMS designation does not allow the use of the official FIFA logo on the balls. In order to qualify for the ‘FIFA Inspected’ designation ball manufacturers must provide EMPA with 7 balls on which 6 common tests are carried out. The six tests comprise: - weight, circumference, sphericity, pressure, rebound and water absorption.

Having passed all 6 tests the manufacturers are able to use the ‘FIFA Inspected’ hallmark, or the International Matchball Standard ‘IMS’ standard hallmark. In order to receive the more prestigious ‘FIFA Approved’ hallmark, manufacturers firstly need to submit ten balls for testing as opposed to seven. Secondly the balls must pass the original 6 tests at a higher level as well as passing a seventh test on shape and size retention. Table 1.1 gives an overview of the FIFA test criteria for outdoor soccer balls.
<table>
<thead>
<tr>
<th>Test</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Each ball is weighed three times in a sealed cabinet. Balls should weigh between 410 - 450 grams for FIFA Inspected, 420 - 445 grams for FIFA Approved.</td>
</tr>
<tr>
<td>Circumference</td>
<td>The diameter of the ball is measured at 10 different points and the mean average circumference calculated. FIFA inspected balls should measure from 68.0 - 70.0 cm, FIFA Approved balls from 68.5 - 69.5 cm.</td>
</tr>
<tr>
<td>Sphericity</td>
<td>The diameter of the ball is measured at 16 points and the mean average calculated. The difference between the highest and lowest diameter must be no more than a specified percentage of the mean diameter: 2% for FIFA Inspected, 1.5% for FIFA Approved.</td>
</tr>
<tr>
<td>Pressure</td>
<td>The ball is inflated to a pressure of 100 kPa (1.0 bar) and in 72 hours must lose no more than 25% of air pressure for FIFA Inspected, 20% for FIFA Approved.</td>
</tr>
<tr>
<td>Rebound</td>
<td>The ball is dropped 10 times onto a steel panel from a height of two metres. FIFA Inspected balls must bounce between 115 - 165 cm, FIFA Approved balls between 120 - 165 cm. The difference between lowest and highest bounce must be no more than 10 cm in both cases.</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>The ball is turned and squeezed in a tank filled with water 2cm high 250 times. For FIFA Inspected balls the water uptake should be no more than 15% of the balls initial weight, FIFA Approved 10%.</td>
</tr>
<tr>
<td>Shape &amp; Size Retention</td>
<td>The ball is fired 2000 times onto a steel panel at a speed of approximately 13.89 m/s (50km/h), from a distance of 2.5m. The seams and air valves must be undamaged, and the loss of pressure, or deviation in the ball's circumference and roundness, must be minimal.</td>
</tr>
</tbody>
</table>

Table 1.1 - Overview of FIFA test procedures for outdoor soccer balls (FIFA, 2003a)

On January 1st 2000 the FIFA test program was expanded to include indoor soccer balls. The tests employed for the assessment of indoor balls are the same as for outdoor balls with the exception of one test. The water absorption test is redundant for indoor play and is replaced by a ball balance test. To test for unbalance a ball is rolled down an inclined slope onto a table with predetermined rolling direction. The angle of ball roll deviation against the original direction is then measured. The ball specifications ensure that indoor balls are smaller, lighter and exhibit significantly lower rebound characteristics in comparison with outdoor balls. Indoor balls can attain 'FIFA Inspected' and 'FIFA Approved' status in the same way as outdoor balls (FIFA, 2003a). Full details of the indoor and outdoor FIFA testing criteria are given in Appendix 2.

1.2 AN OVERVIEW OF SPORTS BALL SPECIFICATIONS

The majority of ball sports use spherical balls, with the exception of rugby, American football, Australian Rules football, bowls and "curling"; the rest of the major ball sports
played worldwide all use spherical balls. Today, the most popular sports in the world are ball sports and these can be either team games such as association football (soccer) or individual games such as golf. The common denominator for all these sports is the essential piece of equipment without which the game cannot be played, the ball itself.

All major ball sports state ball specifications within the rules of the game. Table 1.2 shows ball weight, circumference and pressure specifications for the major ball sports.

<table>
<thead>
<tr>
<th>Sport</th>
<th>Circumference (cm)</th>
<th>Weight (grams)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soccer</td>
<td>68 - 70</td>
<td>410 - 450</td>
<td>69 - 103</td>
</tr>
<tr>
<td>Rugby Union</td>
<td>58 - 62 &amp; 76 - 79</td>
<td>400 - 440</td>
<td>66 - 69</td>
</tr>
<tr>
<td>Tennis</td>
<td>20 - 21</td>
<td>56.7 - 58.5</td>
<td>*</td>
</tr>
<tr>
<td>Golf</td>
<td>&gt;13.5</td>
<td>&gt;45.6</td>
<td>NA</td>
</tr>
<tr>
<td>Netball</td>
<td>69 - 71</td>
<td>400 - 450</td>
<td>59 - 108</td>
</tr>
<tr>
<td>Volleyball</td>
<td>66 - 67</td>
<td>260 - 280</td>
<td>29 - 32</td>
</tr>
<tr>
<td>Cricket</td>
<td>22.4 - 22.9</td>
<td>156 - 163</td>
<td>NA</td>
</tr>
<tr>
<td>Water Polo</td>
<td>68 - 71</td>
<td>400 - 450</td>
<td>83 - 90</td>
</tr>
<tr>
<td>American Football</td>
<td>53 - 54 &amp; 71 - 72</td>
<td>397 - 425</td>
<td>86 - 93</td>
</tr>
<tr>
<td>Basketball</td>
<td>75 - 78</td>
<td>567 - 650</td>
<td>**</td>
</tr>
<tr>
<td>Squash</td>
<td>17.9</td>
<td>&gt;43</td>
<td>***</td>
</tr>
<tr>
<td>Baseball</td>
<td>23 - 23.5</td>
<td>142 - 149</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 1.2 - Ball specifications from major sports

* No specific pressure specification in Tennis.

** Basketballs should be inflated to a pressure such that when it is dropped onto the playing surface from a height of 1.8m measured from the bottom of the ball, it will rebound to a height, measured to the top of the ball, of not less than about 1.2m nor more than about 1.4m.

*** Squash balls do not have any recommended pressure. However, they should rebound to a height of not more than 1.15m when dropped from a height of 2.5m at a temperature of 25 degrees Celsius.

1.3 THE NEED FOR DYNAMIC BALL PERFORMANCE TESTING

The FIFA Denominations program was introduced with the objective of improving the global consistency of top match soccer balls. The existing FIFA test criteria encompass a series of tests that provide a basic assessment of ball manufacturing quality. However, at present there are no dynamic tests employed by FIFA that relate to how a ball performs in a
game situation. Although the FIFA rebound test could be considered a dynamic test, the use of a 2m guided free fall drop test means that ball velocity at impact is relatively low and not comparable to velocities that occur in a game situation.

In order to ensure that innovation in soccer ball design and advances in materials technology do not have a detrimental effect on the game of soccer, it may be necessary to introduce limiting ball performance standards. If no restrictions are imposed on soccer ball performance there is a danger that the game could significantly change from its tradition and lose its attraction to spectators. This could have implications for the health of the game as the media generates much of the clubs income through television contracts and merchandising. A notable example of the adverse effect of technology development in sport is that of tennis. Advances in racket technology have changed the nature of the modern game, which is often criticised for being too fast and too reliant on the serve, although the ITF have considered racket power measurements. The introduction of dynamic ball standards by FIFA would limit the effect of developments in ball technology on the game, therefore maintaining the principles and ethics of the sport for future generations to enjoy.

1.4 RESEARCH OBJECTIVES

This study aims to develop new dynamic test methods and instrumentation that could provide improved regulation of ball performance characteristics. The establishment of a dynamic ball performance test program should encompass a number of key ball performance factors. Essentially these performance factors can be split into 2 groups: flight characteristics and impact characteristics. Ball flight characteristics encompass aerodynamic forces, ball velocity and ball spin rate. Ball impact characteristics include coefficient of restitution (COR), frictional interaction and mechanical characteristics (vibration, moment of inertia, stiffness). Due to time constraints it is not possible for a comprehensive set of test procedures to be developed that encompass all aspects of soccer ball performance, this study will focus on the assessment of ball characteristics which effect launch conditions.

Soccer ball manufacturing methods have improved significantly over recent years. Balls are now manufactured entirely from consistent thickness synthetic materials, ensuring excellent water resistance and durability qualities. The introduction of the ‘FIFA Inspected’ and ‘FIFA Approved’ hallmarks has been successful in standardising balls in terms of a number of static measurements. However, manufacturing inconsistencies such as poor sphericity and ball out-of-balance are common defects that can occur during soccer ball production. The accuracy of the existing sphericity measurement procedure carried out by
FIFA is debatable, and sphericity can have a detrimental effect on ball roll and flight properties. Ball unbalance has been identified as a possible cause of inconsistent ball flight performance due to uneven mass distribution. The problem of unbalance within soccer balls and the associated effect on ball performance requires evaluation and standardisation.

In order to simulate ball velocities and spin rates that are likely to occur in a game situation in dynamic tests, it is necessary to obtain data on the kicking abilities of elite players. The ball velocity and spin rate data obtained from an evaluation of elite players could be used as a benchmark for the development of dynamic test standards. The ability to accurately measure soccer ball flight performance parameters is essential for the development of dynamic test criteria, and to assess the effect of manufacturing inconsistencies such as poor sphericity and ball out of balance. A system capable of obtaining accurate measurements of ball velocity, and spin rate, if used in conjunction with a consistent ball launch platform, would allow accurate dynamic comparison of different ball types and constructions, as well as the establishment of ball velocity and spin standards.

Contemporary media coverage of soccer now includes more live television coverage of matches than ever before. The increased media coverage and the money this generates have led to an increased interest in the game amongst spectators particularly at the highest level (FIFA, 2002). When a spectacular free kick goal is scored in an important game the goal will be replayed numerous times in countries throughout the world, yet few people will understand the scientific principles required to explain the balls performance. This study will also endeavour to increase the scientific knowledge on soccer ball performance.

1.5 THESIS OUTLINE

This thesis reports the work carried out on the development of dynamic test criteria for improving soccer ball performance evaluation. It comprises nine subsequent chapters, encompassing five major studies. The outline of the thesis is as follows:

Chapter 2 reviews the current literature associated with the performance of a range of spherical and non-spherical sports balls and other projectiles. The review examines previous work published on the majority of major ball sports including golf, tennis, basketball, baseball, rugby, American football, Australian Rules football, cricket and in particular soccer. The chapter comprises a number of sub-sections concerned with work published on aerodynamics, ball impacts, biomechanics, computational modelling and ball launch and tracking systems.
Chapter 3 describes the development of an automated method of measuring the sphericity of a soccer ball using a coordinate measuring machine (CMM). The results from the CMM method are compared to results obtained from the existing FIFA method.

Chapter 4 presents the results of a series of tests carried out using a group of elite soccer players to determine soccer ball performance parameters. The range of ball velocities and spin rates achievable by elite players are reported.

Chapter 5 investigates the presence of out of balance forces within top class soccer balls. A method of using a vertical balancing machine to assess the position and magnitude of unbalanced forces present within soccer balls is described and evaluated.

Chapter 6 investigates the effect of out of balance forces on dynamic ball performance. The effect of ball unbalance, orientation and strike point on initial ball launch characteristics and trajectory is assessed using a pneumatic kicking leg launch platform. Furthermore, the ability of elite players to perceive unbalance in soccer balls is reported.

Chapter 7 describes the development of an automated image analysis system, developed to provide accurate launch data on soccer ball velocity, launch elevation, spin axis and spin rate. The system development is documented from the concept stage to the evaluation of a prototype system.

Chapter 8 discusses possibilities that have emerged for further work, and Chapter 9 presents the conclusions of this research study.
CHAPTER 2

LITERATURE REVIEW

This chapter summarises previous work carried out on the dynamic performance of sports balls. Testing procedures for sports balls are largely transferable across a range of different sports, as the fundamental performance characteristics are often similar. Consequently, this literature review includes work published on the majority of major ball sports including golf, tennis, basketball, baseball, rugby, American football, Australian Rules football, cricket and in particular soccer. The published scientific literature concerned with sports equipment has increased significantly over recent years, helping to improve the scientific understanding of sport balls. This review encompasses published literature on the history of the soccer ball, the early sports scientists, aerodynamics, ball trajectory models, ball impacts, the biomechanics of kicking, computational modelling and ball tracking systems.

2.1 THE EVOLUTION OF THE SOCCER BALL

Ball sports have been in existence in primitive form for thousands of years. Evidence from many ancient societies - Chinese, Greek, Mayan, Roman and Egyptian reveal that kicking games were played as a leisure activity. The Chinese of the Han Dynasty called it 'tsu chu', the Japanese called it 'askemari', the Aztecs 'tlachtli', the Greeks 'episkyros', and the Romans 'harpastum' (Buder, 1991). Balls were often not spherical and goals took several forms including bamboo shoots, curtain holes and rings on a wall. According to Murray (1994) the Chinese kicking game of tsu chu was played as long ago as 2500 BC and this is generally regarded as the earliest football reference. However, as there were so many ancient cultures that participated in kicking games, it is extremely difficult to determine exactly where and when football began. According to Morris (1981) the oldest playing balls in the world that exist today are from ancient Egypt. The balls were red, green and yellow in colour and consisted of an outer layer of linen stuffed with cut reed or straw. Due to the fragility of these balls they would not have been suitable for kicking games, but more likely simple rolling and catching games.
Early forms of football existed in many European countries long before the game was officially recognised. Early games in England involved mass participants taking part in violent struggles across towns and countryside. Few rules were employed and some of the balls used in these games were enormous by modern standards. Perhaps the world's first form of 'organised football' was that of calico, first played in Florence, Italy around 1530. The game is historically significant as it was played as a show of defiance whilst the city of Florence was under siege. To this day, every June, two teams of twenty-seven players recreate the original contest in Florence dressed in medieval costume (Harris, 1972). In medieval times balls were made from an outer material of leather filled with cork shavings, although it would not have been practical to perform kicks with balls of this type. Similarly, inflated animal bladders were also used as balls in simple games, although they were always susceptible to puncture and not suitable for kicking.

2.1.1 EARLY INFLATABLE SOCCER BALLS

By the early 19th century boot and shoemakers introduced leather casing around the inflated animal bladder, thus protecting the bladder from puncture. The casing usually took the form of eighteen brown leather strips (in a cubic pattern of six arrangements of three panels), joined together at the poles by a central disc or button. The panels were hand stitched together inside out using five-ply hemp thread until just one seam remained. The panel casing would then be reversed and the bladder inserted through the open seam. The bladder would then be manually inflated by means of a clay pipe. Kippen (2002) gives evidence that some workers contracted lung diseases from blowing up many hundreds of animal bladders. Once the bladder had been inflated the open seam which was usually around 15cm long would be closed and held in place with thick laces.

There were a number of problems associated with the soccer balls manufactured in the early 19th century. Firstly, due to the use of irregular shaped animal bladders the balls were far from spherical and were usually in fact, plum shaped. The panels were manufactured from cowhide leather, and the balls would often vary in quality depending on which part of the cow had been used. Panel thickness would not be uniform around the ball, and ball performance would suffer as a result. In wet conditions the leather casing would absorb large amounts of water significantly increasing the weight of the ball. Consequently this made kicking, and in particular heading the ball difficult and painful, and players would often try and improve the water resistance qualities of balls by applying dubbin to the ball exterior surfaces. Although this made a slight improvement it did not stop the ball from taking on water and the presence of buttons at each end of the ball could be the cause of painful injury.
should a player be unfortunate enough to head the ball with a button incident on the forehead. The same could also be said if a player headed the ball with the thick laces incident on the forehead and according to Shillcock (1997), accidents to the eyes of the players caused by poorly inserted laces were common.

2.1.2 THE DISCOVERY OF RUBBER

The discovery and subsequent use of rubber as a new bladder material was a major development in soccer ball manufacture. Christopher Columbus's second voyage to the Americas had taken place at the end of the 15th century and the European explorers had observed local people playing ball games with a ball made from the gum of a tree. Indeed, because of the availability and elastic properties of rubber, a popular ball sport known as 'tlachtli' had existed in Central America since around 500 BC. Several hundred years passed after Columbus's discovery before rubber was first manufactured in Europe. Charles Goodyear had first patented vulcanised rubber in 1836 and the subsequent discovery of the correct solvent for raw rubber enabled the manufacture of rubber sheet material. According to Kippen (2002) the first rubber inflatable bladder was produced in 1862 by HJ Lindon, and these soon superseded the use of animal bladders. The overall ball shape is dependent on the bladder, therefore the superior sphericity of the early rubber bladders presented a significant improvement over animal bladders.

The discovery of rubber was crucial to the development of the modern game of soccer and as rubber manufacturing developed in the 19th century, soccer also expanded. The development of thin but strong bladders created the first European soccer ball that would bounce and behave consistently when kicked, allowing for a more skilful and appealing game to players and spectators alike. Clearly therefore, the rate of development of soccer has been dependent on the discovery of suitable equipment materials.

2.1.3 THE FIRST SOCCER RULES

After successive governments had tried and failed to suppress football from taking place in early 19th century England, the Highway Act of 1834 finally made street football illegal forcing the game to take on a more civilised nature in order to survive. With the advent of the Industrial Revolution and the major reductions in leisure time that this brought about for the working man, the "mob football" originally popularised by the working classes began to flourish in a more restrained form in the English public school system. Football soon became well established in public schools and universities by the mid 19th century, although there was little uniformity, with each establishment playing to their own set of rules and the home side
usually choosing the playing ball (Green, 1953). Clearly, unification of the various rules sets in use was essential for the game to progress.

There are four sets of laws that can be said to have made a significant contribution to the development of the rules now used in modern soccer: Cambridge (1846), Sheffield (1857), Uppingham (1862) and the Football Association (FA) (1863). At a meeting of the fledgling Football Association in 1863 it was agreed that the majority of members wished to outlaw kicking, tripping and carrying of the ball, and the advocates of the Rugby football style were forced to leave. The game of football was therefore split into two codes with new definitive sets of rules agreed for each. Rugby football allowed the handling and carrying of the ball, and association football (or soccer), banned the use of the hands (Soar, 1986). None of the early rule sets specified any dimensions or materials for the ball. According to Green (1953) the first soccer ball size specification was given in March 1866, before the first ever representative game between the Football Association and the Sheffield Association when it was specified that a ‘Lillywhite’s No. 5’ ball should be used. Interestingly, the size 5 designation still signifies the standard regulation sized soccer ball 130 years later. The respective modern day specifications for size 3, 4, and 5 balls are summarised in Table 2.1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Circumference (cm)</th>
<th>Weight (grams)</th>
<th>Age Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size 3</td>
<td>58.5 - 61</td>
<td>310 - 340</td>
<td>Under 8</td>
</tr>
<tr>
<td>Size 4</td>
<td>63.5 - 66</td>
<td>350 - 390</td>
<td>8 to 12</td>
</tr>
<tr>
<td>Size 5</td>
<td>68 - 70</td>
<td>410 - 450</td>
<td>13 and older</td>
</tr>
</tbody>
</table>

Table 2.1 - Soccer ball size specifications

In February 1872 Chequers FC moved a resolution that stated:

‘That a fixed size be appointed by the committee for the Association Football...’

The FA committee agreed to consider the matter in September 1872 and generally the consensus of opinion favoured the Lillywhite’s No. 5, however the final decision was deferred until the average measurements of the ball had been ascertained. In October 1872 the FA standardised the ball size as Rule 10 of the Association Rules and Rule 5 of the Challenge Cup Rules, stating:
That the Association ball should have an average circumference of not less than 27 inches and not more than 28 inches and that the ball to be used in all matches for the Association Challenge Cup should be of this regulation size.

2.1.4 OTHER FORMS OF FOOTBALL

The Rugby Football Union (RFU) was formed in 1871, eight years after the FA was established. The first rugby balls were spherical and very similar in appearance to soccer balls. However, the introduction of rubber inflatable bladders to replace animal bladders enabled ball shape and size to be determined and regulated. In 1892 the RFU stipulated that a rugby ball should be ovoid with a circumference around the centre of 25.5 - 26 inches, although there was no specification of length (in 1931 the circumference would be reduced to between 24 - 25.5 inches) (Mann, 1998). The fledgling Rugby Union experienced dramatic changes in 1895 when a breakaway group of northern clubs formed the Rugby League. This new code featured slightly different rules to Rugby Union and permitted the payment of professional players.

After the formation of the RFU in 1871 other variations on the game of football were developing throughout the world. In the United States after a meeting at Princeton in 1874 it was decided to adapt the English rugby code, but with teams of 11-a-side and American football was born. These rules were later refined and by 1880, US College football was launched (Kippen, 2002). Gaelic football was regulated in Ireland in 1884, and Australian Rules football; a variation on rugby football played on cricket pitches, was regulated in Australia in 1896. Although soccer and Gaelic football used spherical balls, Rugby Union, Rugby League, American football and Australian Rules football all used ovoid balls (Morris, 1981).

2.1.5 A PERIOD OF GROWTH

In the years following the formation of the FA the game grew steadily. According to Murray (1994), in 1867 the FA had only ten members yet by 1871 this number had risen to fifty. The FA Challenge Cup was first introduced in 1871, and the first international match between England and Scotland played in Glasgow in 1872. According to Viney and Grant (1978) large numbers of clubs were being formed throughout the British Isles, although rugby was the more popular game in Wales and the West Country. National football associations were formed in Scotland (1873), Wales (1876) and Ireland (1880). One year later in 1886 the International Board was formally established featuring representatives from
England, Scotland, Wales and Ireland. The board became responsible for all law making decisions, and in 1889, updated the ball specification to include a weight requirement, stating: 'The circumference if the Association ball shall be not less than 27 inches and not more than 28 inches; and in international matches, at the commencement if the game, the weight of the ball shall be from 12 to 15 ounces.'

In 1905 an addition to the law was made stating that the outer casing of the ball must be made from leather, and that no material must be used in the construction of the ball which would constitute a danger to the players (Green, 1953).

The introduction of stipulated ball regulations helped to improve the ball manufacturing process significantly. Shillcock (1997) described the soccer ball manufacturing process for the late 19th century. Cowhide leather sections were wetted in warm water before being stretched and put through rollers under pressure. The sections were then hung up to dry before the individual panels were cut out using a knife. Finally the ball sections could then be sewn together using waxed hemp thread. At the end of the 19th century the number of leather panels used to make up the outer casing of balls was beginning to be reduced to eight segments, secured together by small leather discs at the poles, rather than the buttons previously used. This sparked a minor revolution in tactics, as heading was made significantly easier with the exclusion of buttons at the ball poles, although it should be remembered that heading could still be very painful especially in wet conditions. Nevertheless on the 2nd February 1878 Scotland beat England 7-2 in Glasgow with headed goals making up the majority of the Scottish goals scored.

The English Football League was founded in 1888 and the overall standard of play improved significantly. More regular competition increased demand for balls in matches; consequently balls began to be mass produced for the first time. The two biggest soccer ball manufacturers at the end of the 19th century were Mitre of Huddersfield, England and Tomlinson's of Glasgow, Scotland (FIFA Magazine, 1998). Mitre and Tomlinson's were instrumental in improving ball sphericity by changing ball outer casing from leather sections joined together at the poles, to a series of leather interlocking shaped panels. Rugby football had become a popular sport in its own right, and the biggest manufacture of rugby balls was James Gilbert of Rugby, England. The similarities between soccer ball and rugby ball manufacture are evident in an article by Gilbert (1931), in which he describes the manufacturing process for rugby balls. The respective ball manufacturers had identified that the key to a good ball was the rigidity of the shape, the strength of the leather and the skill of
the stitchers. At the turn of the century ball manufacturers began to change ball panel configurations from the typical eight panels to 10, 12 or 18 panel designs. According to Thornber (1952) this was done to reduce the risk of ball shape distortion through the stretching of the large leather panels used to make up the 8 panel balls. Increasing the number of panels encasing the ball reduced the risk of ball distortion. According to Hornby (2000) ball manufacturers first began to stencil their names on to the ball panels around 1900.

2.1.6 INTERNATIONAL SOCCER

By the end of the 19th century there was sufficient interest in the game to encourage a number of countries to set up an international soccer federation. The Fédération Internationale de Football Association (FIFA) was formed in 1904 and the first FIFA World Championship took place in Uruguay in 1930, although many European teams did not attend. In the early days of international competition there were frequent arguments and disputes surrounding the choice of ball to be used. British teams used a size five ball from 1872, whereas European teams used a size four ball up to the 1940's. The finalists of the first World Cup final, Uruguay and Argentina could not agree on the size of the ball to be used so a compromise was reached. An Argentine ball was used for the first half (Argentina led 2-1 at the break), before switching to a Uruguayan ball for the second. This switch appeared to benefit the Uruguayan players as they scored three times to win the inaugural World Cup 4-2. The tournament is played every four years and has become the world's most popular sporting event after the Olympics.

2.1.7 TWENTIETH CENTURY BALL DEVELOPMENT

The premier soccer ball in the UK in the early 20th century was Shillcock's McGregor ball, named after William McGregor, the founder of the football League in 1888 (Russell, 1997). The ball consisted of 10 panels that fitted together at different angles, giving a more stable ball than the other balls available at the time. Between 1898 and 1932 the McGregor ball was used in fourteen FA Cup Finals, ten Scottish Cup Finals and sixteen internationals between England and Scotland. The most popular soccer ball during the 1930's and 40's was Tomlinson's Greban ball, more commonly known as the T-ball. The ball was first introduced in 1925 and consisted of eighteen panels with each panel effectively at right angles to each adjacent panel. In the season 1937/38 Stanley Rous, Secretary of the Football Association, redrafted the rules of soccer into their modern form. Rous amended the ball weight specification for international matches to '14 to 16 ounces' instead of the '12 to 15 ounces' previously specified.
Ball manufacture changed very little over the first part of the 20th century until the late 1940's when a strong cloth carcass was introduced between the bladder and the leather panels giving improved ball shape retention and durability. The water resistance qualities of balls were also improved with the addition of new synthetic coatings that helped to repel the ingress of water. According to Thompson (1986), white synthetic ball coverings were developed in Europe that eventually led to the first white soccer balls. Developments such as these were partially due to manufacturing advances made during World War II. Although the Second World War had improved ball manufacturing processes, the lack of good quality leather in the post war years initially had a detrimental effect on soccer balls. According to Radnedge (1994) the ball used in the 1946 FA Cup Final between Derby County and Charlton Athletic actually burst whilst being shot on goal. Amazingly, the following year history repeated itself when the ball burst again during the 1947 Charlton Athletic versus Burnley final.

White soccer balls were permitted for the first time in 1951 (Morris 1981), primarily to help spectators view the ball, particularly when games were played under floodlights, a new development in the 1950's. Although there are claims that white balls were first used as long ago as 1892, by dipping the balls into whitewash (FIFA Magazine, 1998). Orange soccer balls were also permitted for the first time in the 1950's for use on snow covered pitches. Thomber (1952) describes the soccer ball manufacturing process in the early 1950's. Firstly cowhides would be tanned for a period of around 3 - 4 months in order to ensure that the resultant leather was strong yet pliable. The tanned leather would then be shaved to a uniform thickness in a process known as 'currying'. The leather would then be impregnated with fats and oils to lubricate the fibres and improve ball water resistance, before finally being processed through rolling machines to eliminate any potential stretching. After maturing for several weeks individual panels would be stamped out from the leather using a 'press knife', then hand sewn together to form a ball.

2.1.8 THE USE OF SYNTHETIC MATERIALS IN SOCCER BALLS

Until the 1960's laces had always been used to fasten the final seam after bladder insertion. However, the introduction of valves enabled direct access to the bladder for inflation, and a new technique was developed for stitching the last closing seam on a ball, making the need for laces redundant. By the 1960's ball manufacturers such as adidas, Minerva, Sondico and Slazenger had joined Mitre and Tomlinson's in an increasingly competitive soccer ball market (FIFA Magazine, 1998). The 1960's saw the first use of a completely synthetic soccer ball in top class competition, although leather balls were still the
preferred choice. Moulded soccer balls made entirely from synthetic materials were introduced as an alternative to hand sewn leather soccer balls during the 1970's. Moulded balls were produced by winding several layers of nylon around the bladder, then coating the bladder with a rubber material to form a carcass. Construction was complete when the carcass was covered by a moulded rubber or synthetic leather cover. Although moulded balls were durable and offered good water resistance properties, they did not have the same performance characteristics as stitched balls (Tucker, 1979).

The popularity of synthetic panel materials for stitched soccer balls increased throughout the 1970's. Rugby balls manufactured from synthetic materials were also being produced and according to Mann (1998) the first synthetic rugby balls were used in the 1975-76 season. Although soccer balls with asymmetrical panel configurations were still popular in the UK in the 1960's and 70's, European nations favoured 32-panel balls. The last 18-panel ball to be used in the World Cup was in 1966 when a Slazenger ball was chosen for the final. According to Kippen (2002) adidas began manufacturing soccer balls in 1963 and made the first official World Cup ball in 1970. Since the 1970 World Cup adidas have manufactured the official ball for every World Cup, and this has always been a 32-panel ball. During the 1970's the popularity of 32-panel balls on the continent caused UK ball manufacturers to develop these for the UK market. An example of a traditional British 18-panel design is shown in Figure 2.1, with an example of a 32-panel ball shown in Figure 2.2. Prior to 1983 the maximum permissible inflation pressure for soccer balls in top class matches was 69 kPa (10 psi). However, following a successful trial in the 1982 World Cup finals, FIFA stipulated a new inflation range from 69 kPa (10 psi) to 103 kPa (15 psi) (Holmes and Bell, 1985).

The 1986 Mexico World Cup saw the debut of a non-leather completely synthetic hand stitched ball in World Cup competition. The ball performed well in the tournament and
consequently the use of leather panels began to diminish, although for a period in the early eighties some people considered that leather balls offered superior dynamic performance. Previous advocates of leather balls were eventually persuaded by the superior performance characteristics of the synthetic balls. Since 1986, all top class soccer balls have been manufactured with synthetic materials replacing leather, usually polyurethane (PU) or polyvinyl chloride (PVC). The most popular soccer ball in the UK during the 1980's and 90's was the Mitre Ultimax. This ball originally featured an 18-panel design in a cubic arrangement although later versions were altered to similar 26-panel configurations. Mitre had been the official ball supplier of the FA Premiership since its conception in 1992, however in 1999 Mitre lost the contract to US sports firm Nike who introduced a 32-panel ball.

2.1.9 MODERN SOCCER BALL CONSTRUCTION

The latest synthetic soccer balls are essentially of four-piece construction - the bladder, the stitching, the lining and the outer casing. An exploded diagram of a typical modern soccer ball is shown in Figure 2.3.

![Figure 2.3 - Exploded view of soccer ball constituent parts (Soccer Ball World, 2003)](image)

2.1.9.1 The Bladder

Ball bladders are usually made from carbon latex, which due to its porous skin allows pressure to escape slowly over time. Allowing air to escape over a period of time gives prolonged life to the stitches by preventing possible deformation and breakage, allowing the ball to retain its shape for a longer period of time. High quality bladders feature internal ridges that help create a homogeneous distribution of air pressure inside the ball, therefore aiding overall ball sphericity. In addition supplementary weights are sometimes moulded into the bladder to help counter-balance the valve weight and minimise any ball unbalance. The bladder is extremely important to the ball performance as it governs the overall ball sphericity.
2.1.9.2 The Stitching

The ball panels are stitched together using a polyester or similar material thread. The thread is waxed prior to the commencement of stitching in order to make the thread waterproof. The stitching of top class balls is still currently carried out by hand, although some lower quality balls are now beginning to be machine stitched. According to Thompson (1986) each hand stitched ball will take a skilled stitcher around three and a half hours to complete. It is very important that a constant tension is kept on each stitch throughout the stitching process so that the ball remains stable and rigid when complete. The stitching tension is localised around each panel by knotting the thread once each panel is complete. More than 75% of the world’s soccer balls are manufactured in the Sialkot region of Pakistan (FIFA, 1998), although China is rapidly developing its soccer ball manufacturing capability.

2.1.9.3 The Lining

Fabric lining is glued to the back of the outer casing material in order to provide stiffness and reinforcement, preventing plastic deformation of the panels. The inner layer of fabric laminate is essential to the balls shape and size retention qualities as it creates a stable framework, giving the ball consistency. The lining is often a laminated material consisting of up to four layers and is adhered to the outer casing material in sheet form prior to the individual panels being stamped out. Typical materials used for lining include polyester, cotton and viscose.

2.1.9.4 The Outer Casing

The outer casing is usually made from polyurethane (PU). PU materials have good durability and water resistance properties as well as offering a feel similar to leather. The PU material is produced in sheet form via a foaming process enabling the production of consistent thickness materials, unlike the use of leather in the past, variance in material thickness is in the region of +/- 0.1mm. There are a number of panel configurations for soccer balls currently on the market, varying from as little 6 to as many as 62 panels. A range of ball panel designs currently available is given in Appendix 1. The vast majority of balls however are 32-panel balls based on the truncated icosahedron model. This design can be traced back to the carbon 60 molecule, the strongest molecule known to man. Traditionally this is the design that has been favoured by the European nations whereas the British have tended to favour more traditional designs based on the cubic model.
2.1.10 THE MODERN GAME

According to Gerhardt (2003), the number of countries affiliated to FIFA in 1950 was 73. Fifty years later in 2000 that number had risen to 204 members in every part of the world. Soccer is clearly the most popular sport in the world and is played by over 8 billion people. An estimated 28.8 billion people around the world watched the 2002 World Cup tournament, which took place in Korea and Japan. The final itself was watched by an estimated 1.1 billion individuals, making it the most viewed game in FIFA World Cup history (FIFA, 2002). This makes the FIFA World Cup final the most watched single sports event in the world's history, not surpassed even by the Olympics.

2.2 THE EARLY SPORTS SCIENTISTS

The study of projectile aerodynamics can be traced back over 300 years ago when Isaac Newton (1672) commented on how the flight of a tennis ball was affected by spin.

"I remembered that I had often seen a tennis ball describe such a curveline. For, a circular as well as a progressive motion being communicated to it by that stroke, its part on that side, where the motions conspire, must press and beat the contiguous air more violently than on the other, and there excite a reluctance and reaction of the air proportionally greater."

Sir Isaac Newton (1642 - 1727)

Seventy years after Newton, the English mathematician and engineer Benjamin Robins (1742) investigated the flight characteristics of spinning cannon balls. Robins speculated that the spinning motion of spherical shot could be the cause of lateral deflections observed from their expected straight-line course. Robins developed a technique for detecting lateral aerodynamic forces of spinning spheres by suspending the sphere from a pendulum.

More than a century after Robins, the German physicist Gustav Magnus (1852) carried out a study to determine why spinning shells deflected to one side whilst on trajectory to their target. Magnus found that a rotating cylinder moved sideways when mounted perpendicular to the airflow. Fifteen years later, Lord Rayleigh (1877) attributed the irregular flight of a tennis ball to the lift caused by circulation produced when the ball was 'cut' or 'sliced'. In his paper Rayleigh credited the first 'true explanation' of spinning projectiles to Magnus. From this point onwards the results of Magnus's study formed the basis for subsequent understanding of the phenomenon, and the lateral deflection of projectiles in flight was later renamed the Magnus effect. Based on the work by Robins and Magnus, Tait
(1896) carried out a study into the aerodynamic forces acting on golf balls in flight by observing the trajectory and time of flight. Tait determined initial ball velocity by means of a ballistic pendulum, and derived a set of differential equations for the flight of a golf ball. Since 1900 ball games have expanded and significant equipment businesses have developed, which has resulted in numerous studies by scientific sports enthusiasts and professionals.

2.3 AERODYNAMICS

The trajectory of a sports ball is obviously of considerable significance and the characteristics of a projectile in flight are determined by a number of factors. In the case of a soccer ball these factors include size, mass, surface roughness and internal pressure. However, a significant factor affecting the flight of a soccer ball is that of aerodynamic forces. The aerodynamic forces acting on a soccer ball in flight are drag and lift, together with gravity these forces determine the ball trajectory. Drag is the resistive force acting against the forward motion of the ball caused by air resistance, and lift is the resultant force caused by ball rotation, and acts perpendicular to the balls forward motion.

2.3.1 DRAG FORCE

The drag force acting on a soccer ball is the resistive force acting against the forward motion. The drag force \( F_D \) can be calculated as follows:

\[
F_D = \frac{1}{2} C_D \rho AV^2
\]  

Where:

- \( F_D \) Drag force (N)
- \( C_D \) Drag coefficient
- \( \rho \) Density of air \( (Kg m^{-3}) \)
- \( V \) Velocity \( (m/s) \)
- \( A \) Cross sectional area \( (m^2) \)

The drag force on a soccer ball will increase with the square of the ball velocity providing the air density and ball cross sectional area remain the same (Griffing, 1987). Unfortunately, the drag coefficient is not constant and varies, sometimes dramatically with the velocity of the ball. The drag force generated by a soccer ball is the summation of two processes: frictional drag, related to the roughness of the ball and pressure drag, related to the size of the ball (Chadwick and Haake, 2000; Cooke, 2000). Frictional drag is the result of the viscous
nature of the airflow and pressure drag is due to the formation of a low-pressure region behind the ball called a wake. The wake causes retardation and is the major component of drag. The size of the wake is highly dependent on the airflow conditions as this dictates the point at which the flow becomes separated from the ball. If the boundary layer around the ball consists of laminar airflow, the viscous forces dominate and the separation point will be around the ball centre line. However, if the boundary layer grows sufficiently or if the airflow turbulence intensity is increased then local instabilities develop and the laminar structure in the boundary layer becomes turbulent. A turbulent boundary layer will remain attached to the ball past the centre line, resulting in a smaller wake and subsequent reduction in drag force.

2.3.2 REYNOLDS NUMBER

The nature of the airflow around the ball is of considerable importance to the aerodynamic forces acting on the ball. Reynolds number is a dimensionless factor/parameter that defines the nature of the airflow for a given body irrespective of the body size and the flow viscosity. The Reynolds number for a soccer ball can be calculated as follows:

\[ R_e = \frac{V D}{\nu} \]  

(2.2)

Where: 

- \( R_e \) Reynolds number
- \( V \) Velocity \((m/s)\)
- \( D \) Ball diameter \((m)\)
- \( \nu \) Kinematic viscosity \((m^2/s)\)

Scientific studies have led to the definition of a critical Reynolds number for many objects, including spheres. When the critical Reynolds number is reached, the airflow around a soccer ball will change from being laminar to turbulent, resulting in a sudden dramatic reduction in \( C_D \) as the size of the wake is reduced significantly, as shown in Figure 2.4. This critical transition region is however, highly dependent on the surface roughness of the ball, with more rough spheres entering transition much earlier (Goldstein, 1965; Achenbach, 1974; Adair, 1994). This makes it difficult to define an exact critical Reynolds number for all soccer balls, due to differences in construction and materials between different ball types. Although a soccer ball is fundamentally a sphere with a largely smooth exterior, the presence of seams between stitched panels dictates a departure from a completely smooth surface. Therefore, the critical Reynolds number for a soccer ball would be expected to be less than that for a
smooth sphere, but higher than that for a golf ball (Metha and Pallis, 2001). Generally the critical Reynolds number for a soccer ball is assumed to be around 200,000 (Daish, 1972; Metha and Pallis, 2001).

![Critical Reynolds number region](image)

**Figure 2.4 - Transition from laminar to turbulent airflow (adapted from Metha and Pallis, 2001)**

Table 2.2 outlines the critical Reynolds number for a number of sports balls. It should be noted that the critical Reynolds number for balls with seams (such as cricket balls and baseballs) is highly dependant on ball orientation. The point at which transition between laminar and turbulent airflow occurs can vary significantly depending on which sector of the stitched seam is in contact with the airflow (Adair, 1995).
<table>
<thead>
<tr>
<th>Sport</th>
<th>Critical Reynolds Number</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf</td>
<td>40,000</td>
<td>Bearman and Harvey (1972)</td>
</tr>
<tr>
<td>Tennis</td>
<td>100,000</td>
<td>Metha and Pallis (2001)</td>
</tr>
<tr>
<td>Cricket</td>
<td>140,000</td>
<td>Sayers et al. (2002)</td>
</tr>
<tr>
<td>Baseball</td>
<td>155,000</td>
<td>Metha and Pallis (2001)</td>
</tr>
<tr>
<td>Soccer ball</td>
<td>200,000</td>
<td>Daish (1972)</td>
</tr>
</tbody>
</table>

Table 2.2 - Approximate critical Reynolds numbers for various sports balls

2.3.3 Lift force

The lift force acting on a soccer ball acts perpendicular to the ball's forward motion. The lift force ($F_L$) can be calculated as follows:

$$F_L = \frac{1}{2} C_L \rho A V^2$$

Where:
- $F_L$ - Lift force (N)
- $C_L$ - Lift coefficient
- $\rho$ - Density of air ($Kg m^{-3}$)
- $V$ - Velocity ($m/s$)
- $A$ - Cross sectional area ($m^2$)

The lift force occurs as a result of ball rotation. When spin is applied to a ball its flight characteristics can be changed significantly. The spinning motion changes the way in which air flows past the ball, and results in the ball experiencing an additional force (the Magnus effect), which acts perpendicular to the ball's direction of flight (Daish, 1972). The lateral deflection of sports balls in flight is often termed swing, swerve or curve, and is used deliberately in many ball sports. Examples include: free kick and corner situations in soccer, pitching the 'curve ball' in baseball, tennis serves and fast bowlers attempting to 'swing' the ball in cricket.

Until the start of the 20th century the Magnus effect was explained by the use of Bernoulli's principle. According to Bernoulli's principle air travels faster relative to the ball centre where the periphery of the ball is moving in the same direction as the airflow, which
causes a local pressure reduction. The opposite effect occurs on the other side of the ball, where the air travels slower relative to the ball centre. There is therefore an imbalance in the forces and the ball deflects in the same sense as the spin (Townend, 1984; Asai et al., 1998).

At the start of the 20th century Prandtl (1904) introduced the boundary layer concept, and showed that the Magnus effect was in fact due to asymmetric boundary layer separation. When a soccer ball is spinning in flight, a thin boundary layer is formed around the ball surface. The viscous drag on the air caused by the ball rotation will be limited to this narrow boundary layer, and because of the nature of the viscous forces, Bernoulli's principle is not valid (Wesson, 2002). The effect of the rotation is to delay separation on the side of the ball that is moving with the airflow, and to induce separation more rapidly on the side of the ball moving against the airflow, although this can only occur at post-critical Reynolds numbers when transition has occurred at both sides (De Mestre, 1990). The asymmetric separation generated by the rotation induces a deflection to the airflow behind the ball as shown in Figure 2.5, and by Newton's 3rd Law the Magnus force acts in the opposite direction to that of the deflection (Metha, 1985).

![Figure 2.5 - The Magnus effect caused by asymmetric boundary layer separation (adapted from Wesson, 2002)](image)

Clearly the faster the ball spins the greater the difference in separation and the more the ball will deflect. Furthermore, it is also clear that a slow moving ball with a large amount of spin will generate a larger Magnus force than a fast moving ball with an equal amount of spin, because the difference in the airflow velocity and periphery velocity is greater. This suggests
that one of the most important factors in the generation of Magnus force is not the spin rate alone but the ratio of air speed to periphery speed (Maccoll, 1928).

Sports balls are sometimes observed to swing one way then the other during flight. This phenomenon is usually termed 'reverse swing' and occurs frequently in cricket (Metha, 2000; Sayers, 2002). Considering a ball that is spinning at a relatively low spin rate during flight, the airspeed relative to the ball's surface is higher on the side of the ball moving against the airflow. Therefore, it is possible that as a spinning ball slows down towards the end of its trajectory, the side of the ball moving against the airflow may remain in the post-critical Reynolds number range, whilst the side of the ball moving with the airflow will change to the pre-critical Reynolds number range. This will result in the asymmetry of the flow pattern being the exact opposite of the asymmetry that occurs during the conventional Magnus effect, therefore initiating a negative Magnus force (Wesson, 2002). Reverse swing is more likely to take place if the surface finish of the ball is rough and the initial velocity is high (Sayers, 2002).

Occasionally soccer balls are seen to exhibit lateral movement during flight in the absence of spin. This is caused by the development of an asymmetric flow pattern around the ball, largely dependent on the orientation of the seams on the ball surface (Metha and Pallis, 2001). In the same way as the seams on a cricket ball can have a significant effect on the ball flight characteristics, the presence of the seams on soccer balls can have a significant effect on boundary layer transition, causing unpredictable performance in certain conditions. Another example occurs in baseball, where a type of pitch called the 'knuckleball' can result in the ball exhibiting lateral movement with very little or no spin (Adair, 1995). Watts and Sawyer (1975) attributed the 'erratic' behaviour of a baseball trajectory to the generation of asymmetrical lift forces caused by the location of the seams. Wind tunnel experiments showed that a small ball rotation during flight could change the location of the seams and cause an asymmetrical velocity distribution across the ball. A study carried out by Willmarth and Enlow (1969) concerned with assessing the lift force on spheres helped explain the 'knuckleball' effect. The study observed small lift force fluctuations for a fixed sphere when held stationary without spin.

2.3.4 EXPERIMENTAL AERODYNAMICS STUDIES ON SPHERES

Published data on the aerodynamic forces of soccer balls is negligible, however there have been some aerodynamic studies carried out on smooth spheres and other spherical balls (mainly golf, cricket and baseball). A number of investigators have performed wind tunnel
tests on smooth spheres. Wilmarth and Enlow, (1969) and Achenbach (1972 & 1974) conducted wind tunnel tests on stationary hollow smooth spheres constructed from aluminium and Styrofoam respectively. Achenbach (1972 & 1974) estimated the critical Reynolds number for a smooth sphere as 370,000. Chadwick and Haake (2000) used a wind tunnel to investigate the $C_D$ of stationary tennis balls with no spin at flow speeds of up to 61 m/s. It was found that the $C_D$ remained relatively constant at the different flow speeds tested, although changing the size of the nap around the ball could alter the $C_D$ by as much as 6% in comparison with a standard diameter ball.

2.3.4.1 Spinning Spheres

Generally there are two main methods used to calculate the aerodynamic forces acting on spinning spheres, and both methods require the use of a wind tunnel. The first method involves dropping a ball through the airflow of a wind tunnel and observing the drift (Davies, 1949; Briggs, 1959). The second method involves using a wind tunnel balance to directly measure the three aerodynamic forces lift, pitch and drag (Bearman and Harvey, 1976; Watts and Ferrer, 1975). When using a wind tunnel balance it is important that any ball holding or spinning mechanisms employed in the test do not adversely affect the flow stream.

Maccoll (1928) carried out a study into the aerodynamic forces acting on a spinning smooth sphere. The sphere was 0.15m in diameter and was mounted in a wind tunnel on a spindle. The results showed that it was possible to obtain a negative $C_L$ at an equatorial to flow speed ratio of less than 0.5, helping to explain the phenomenon of reverse swing. Davies (1949) conducted wind tunnel tests on golf balls using a device that spun a ball between two rotating cups at spin rates between 16.7 and 133 revs/s, before releasing the ball into the air stream and observing the drift. It was shown that golf balls with a dimpled surface could be driven longer distances due to the benefits of reduced drag caused by an earlier transition point. Briggs (1959) repeated the golf ball study by Davies (1949), substituting baseballs for golf balls. The results suggested that the lift force was proportional to the square of the flow speed, and the ball rotation. Barkla and Auchterlonie (1971) used a spinning sphere pendulum technique similar to that used by Benjamin Robins, to assess the aerodynamic forces acting on a small sphere rotating at spin rates between 6.7 and 23.3 revs/s. Unlike the studies by Maccoll (1928) and Briggs (1959) that observed a relationship between lift force and rotation, the results found that $C_L$ was only loosely proportional to spin rate. An overview of spin rates obtained in soccer and other ball sports is given in Table 2.3.
<table>
<thead>
<tr>
<th>Spin Rate (revs/s)</th>
<th>Sport</th>
<th>Type of Spin</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - 10</td>
<td>Soccer</td>
<td>Swerve around wall</td>
<td>Asai and Akatsuka (1998)</td>
</tr>
<tr>
<td>10</td>
<td>American football</td>
<td>Forward ‘spiral’ pass</td>
<td>Brancazio (1985)</td>
</tr>
<tr>
<td>14</td>
<td>Cricket</td>
<td>Spin delivery</td>
<td>Metha (1985)</td>
</tr>
<tr>
<td>25</td>
<td>Tennis</td>
<td>Medium topspin</td>
<td>Cottey (2002)</td>
</tr>
<tr>
<td>30</td>
<td>Baseball</td>
<td>Curveball</td>
<td>Adair (1995)</td>
</tr>
<tr>
<td>50</td>
<td>Tennis</td>
<td>Heavy Topspin</td>
<td>Cottey (2002)</td>
</tr>
<tr>
<td>58</td>
<td>Golf</td>
<td>Backspin (Driver)</td>
<td>Metha (1985)</td>
</tr>
<tr>
<td>130</td>
<td>Golf</td>
<td>Backspin (Iron)</td>
<td>Cochran and Stobbs (1968)</td>
</tr>
<tr>
<td>110 - 140</td>
<td>Table tennis</td>
<td>Topspin</td>
<td>Seydal (1992)</td>
</tr>
</tbody>
</table>

Table 2.3 - Spin rates found in various ball sports

Bearman and Harvey (1976) investigated the aerodynamic forces acting on golf balls using a wind tunnel balance to measure lift, pitch and drag forces. A hollow golf ball model, 2.5 times full scale was constructed and a small motor and bearing assembly inserted into the ball to provide rotation. The results showed that increasing the spin on a ball produced a higher \( C_l \), and therefore a bigger Magnus force. However, increasing the velocity at a given spin reduced the \( C_l \) suggesting that the Magnus force can be more pronounced as a ball slows down. Furthermore, it was found that balls with hexagonal dimples had a higher \( C_l \) and slightly lower \( C_D \) than balls with round dimples. Watts and Ferrer (1987) assessed the aerodynamic forces acting on baseballs in a wind tunnel. The balls were mounted on spindles in the wind tunnel test section and rotated to the required spin rates. The results of the study were not consistent with the data obtained by Davies (1949) or Briggs (1959), however they were in agreement with Bearman and Harvey (1976). The results suggested that the \( C_l \) for baseballs is principally a function of the ratio of ball equatorial speed to the tunnel flow speed, and the ball surface roughness. In contrast to the work carried out by Briggs (1959), Watts and Ferrer (1987) concluded that the \( C_l \) is only very weakly dependant on Reynolds number.

2.3.5 Trajectory Analysis

The characteristics of sports balls in flight have inspired many scientists to perform investigations in order to attempt to predict trajectories. Traditionally, sports such as golf have been at the forefront of aerodynamic ball trajectory analysis (Erlichson, 1983; Smits and Smith, 1994; Tavares et al., 1999), with relatively few studies carried out into soccer balls.
However, there have been a number of recent studies concerned with soccer ball trajectory analysis (Luhtanen et al., 1993; Asai et al., 1998; Ireson, 2001; Carré et al., 2002; Bray and Kerwin, 2003), although the lack of published quantitative aerodynamic data for spinning soccer balls makes the validation of trajectory models difficult. The construction of ball trajectory models typically requires the derivation of equations of motion along with the collection of experimental data. A series of differential equations for modelling the flight of a rotating ball in the atmosphere are given by Fuchs (1991). Solving algorithms are typically used on the equations of motion to calculate values for $C_D$ and $C_L$.

### 2.3.5.1 Soccer Ball Trajectory Analysis

Predictions for the flight of a soccer ball can be obtained mathematically (Luhtanen, 1993; Asai et al., 1998; Ireson, 2001), however without the use of experimental data the accuracy of such studies is questionable and the results approximate. The flight of a soccer ball through the air was analysed by Carré et al. (2002) from experimental data. A ball launching machine was used to project test balls over a given trajectory and high-speed video used to obtain data on the velocity and spin rate of the balls in flight. Equations of motion for the ball trajectories were derived in order to calculate $C_D$'s and $C_L$'s for two different trajectories: a straight kick with zero spin, and a spin kick with the spin axis horizontal. The data was then used to simulate typical free kicks in a game situation. Bray and Kerwin (2003) performed a similar study concerned with modelling the trajectory of a swerve kick. A theoretical model for ball trajectory was derived and experimental data obtained from player tests. Two synchronised digital cameras were used to obtain data on ball velocities produced by the kicker, but ball spin rates were not measured. The models produced by Carré et al. (2002) and Bray and Kerwin (2003) both assumed that $C_D$ and $C_L$ remained constant throughout the trajectory. However, this assumption can only be valid if post critical Reynolds numbers prevail throughout the entire ball flight, and this cannot be guaranteed if ball velocity reduces significantly towards the end of a trajectory. The results for $C_D$ and $C_L$ obtained by both studies are shown in Table 2.3.

<table>
<thead>
<tr>
<th>Study</th>
<th>$C_D$ Estimation</th>
<th>$C_L$ Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carré et al. (2002)</td>
<td>0.20 - 0.30</td>
<td>0.20 - 0.26</td>
</tr>
<tr>
<td>Bray and Kerwin (2003)</td>
<td>0.25 - 0.30</td>
<td>0.23 - 0.29</td>
</tr>
</tbody>
</table>

Table 2.4 - Soccer ball $C_D$ and $C_L$ estimation from trajectory models
2.3.5.2 Trajectory Analysis of Other Sports Balls

The trajectories of ellipsoidal balls such as rugby and American footballs are considerably more difficult to predict than spherical soccer balls. However, there have been a number of studies that attempt to model ellipsoidal ball trajectories (Aldis et al., 1992; Brancazio, 1985; Hartschuh, 2002). Unlike soccer balls, the cross sectional area of ellipsoidal balls is not always constant throughout a trajectory, and this can lead to changes in ball orientation during flight. Aldis et al. (1992) investigated the flight characteristics of Australian rules footballs and gathered experimental data for a range of kicks. The data was used in conjunction with a trajectory model to predict values for $C_D$ with reasonable accuracy. Brancazio (1985) studied the relationship between kicking length and flight time with initial ball velocity and elevation in American football games. The data was used to construct a trajectory model giving the optimum launch angle for successful kicks. In a similar study to that of Brancazio (1985), Hartschuh (2002) used a standard digital camera set at a shutter speed of 1/8000 to obtain impact velocity and launch elevation data for punt kicks in American football. The experimental data was used to develop simple models for ball flight time and distance travelled, although the models neglected the effects of drag.

Golf ball aerodynamic performance has been the subject of numerous studies over many years. Erlichson (1983) attempted to calculate the optimum ball launch angle in order to achieve maximum distance in the golf shot. A trajectory model was derived and the theoretical optimum launch angle calculated through numerical integration techniques. Other studies have centred upon the construction of spin rate decay models for a golf ball in flight (Smits and Smith, 1994; Tavares et al., 1999), however methods have differed. Smits and Smith (1994) conducted wind tunnel tests in order to establish a model whereas Tavares et al. (1999) gathered experimental data on a driving range using a radar spin measurement system. Notable trajectory models carried out for other ball sports include a theoretical study of the kinematics of the basketball shot suggesting an optimum angle of release (Brancazio, 1981), and the determination of the important aerodynamic parameters affecting the flight of table tennis balls (Seydel, 1992). Alaways and Hubbard (2001) investigated the aerodynamic forces on baseballs using high-speed video to measure ball trajectories. A series of differential equations were developed, and iterative solving techniques used to estimate $C_D$ and $C_L$. The study showed that the lift force on four-seam baseballs can be significantly higher than the lift force on two-seam baseballs.
2.4 BALL IMPACTS

Ball impacts are a fundamental part of all ball sports and can occur due to impact with an implement (such as in golf and tennis), a body part (such as the foot in soccer), or due to impact with posts or the playing surface. There are a number of texts that have presented the mechanics of ball impacts in sport (Daish, 1972; Townend, 1984; De Mestre, 1990), providing analysis of impact scenarios and including simple mathematical impact models. Ball impacts are usually termed either elastic or inelastic. If the impact is elastic, each colliding body preserves some kinetic energy, and the sum of the kinetic energy of the colliding objects will be the same both before and after the collision. The collisions between a soccer ball and a foot, head or goalpost are examples of inelastic collisions. In inelastic collisions the ball loses energy during impact as the ball deforms, dissipating energy in the form of sound and heat.

2.4.1 COEFFICIENT OF RESTITUTION

The coefficient of restitution (COR) of an impact is a measure of the elasticity of the collision. A perfectly elastic collision will have a COR equal to 1, whereas a completely inelastic collision will have a COR equal to 0. In sports ball testing the COR is typically measured by dropping balls onto a flat surface from a set height and measuring the rebound height. The coefficient of restitution can be determined from the formula:

\[
e = \frac{\text{rebound height}}{\sqrt{\text{initial drop height}}} \quad (2.4)
\]

Alternately, the COR can be determined by dividing the ball velocity after impact by the ball velocity before impact:

\[
e = \frac{\text{velocity after impact}}{\text{velocity before impact}} \quad (2.5)
\]

There have been numerous studies carried out concerned with the development of impact models for colliding spheres. However, in most cases the moving bodies have been classed as solid non-deforming objects (Maw, 1976; Sondergaard et al., 1990), and the impacts assumed to be elastic. The Hertz law of contact allows the prediction of ball impact characteristics for balls that exhibit small amounts of deformation at impact (Goldsmith, 1960). Although the Hertz theory has been shown to be suitable for golf ball impacts (Jones,
2003), it is not suitable for soft spheres that exhibit significant deformation at impact (Tatara, 1983). Consequently, the Hertz law of contact is unsuitable for soccer ball impacts and alternative models have to be used to simulate the impact of hollow spheres.

2.4.2 SOCCER BALL IMPACTS

In a typical game of soccer the ball can feature in collisions with many different objects. As well as impacts with the playing surface and goal posts, the ball is likely to be involved in numerous collisions with various parts of a player's anatomy. The dynamic response of a soccer ball at impact will largely depend on its internal pressure, ball construction, impact surface characteristics, and the impact surface-ball friction properties. If the internal pressure of the ball is increased, the rebound height increases (Holmes and Bell, 1985), although this effect will not be as noticeable if the impacted surface is soft, as the surface may dominate the behaviour of the ball.

Under normal playing conditions when a soccer ball impacts with the ground, the ball will tend to skid and/or roll, reducing its forward velocity and imparting spin. Skidding or sliding often occurs in the early stages of the ball motion before pure rolling is established. For pure rolling to occur there must be a match between the forward velocity of the ball and the rate of rotation. Surface friction will reduce the forward velocity of the ball, whilst at the same time increasing the amount of spin. The amount of forward velocity that is lost will depend on the frictional interaction between the ball and the surface. If the reduced forward velocity of the ball and the increased spin rate match, skidding will cease and the ball will begin to roll (Daish, 1972). If the playing surface is damp or wet, the ball will skid more easily as friction is reduced, consequently losing less forward velocity and rebound height. In wet conditions the friction between the ball and the boot is also reduced, therefore the ability to impart spin becomes more difficult and the ball will generally swerve less. If a ball is allowed to bounce along the ground a gradual reduction in vertical bounce will occur, before the ball eventually comes to rest with all the energy within the ball expended (Wesson, 2002). It should be noted that ball performance can vary considerably in different playing conditions and different parts of the pitch can exhibit different surface friction properties. If an area of the pitch contains lush grass, the surface friction will be relatively higher than an area of the pitch that is worn (Lees, 1996b).

2.4.2.1 Kicking Soccer Balls

The collision of a ball with the foot can be split up into three phases related to the ball deformation. Firstly after initial contact with the ball the foot velocity decreases up to the
point of peak deformation and subsequently stabilises. After impact ball velocity steadily increases until loss of contact with the foot. At the instant of maximum deformation the ball velocity is more than 50% of the release velocity (Tsousidis and Zatsiorsky, 1996). Classical impact theory has traditionally been used to assess the ball-foot interaction during the soccer kick (Huang et al., 1982). This theory assumes the duration of the collision to be negligible, however for a soccer kick the duration of the collision is not negligibly small. Unlike other ball sports such as golf and baseball, which have relatively small contact times, impact durations in soccer are significantly longer. A comparison of impact durations between soccer and other ball sports is given in Table 2.5. Estimations for soccer ball contact times range from 12 ms (Asami and Nolte, 1983) to 16 ms (Tsousidis and Zatsiorsky 1994).

<table>
<thead>
<tr>
<th>Sport</th>
<th>Impact Contact Duration (ms)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golf</td>
<td>0.5</td>
<td>Roberts et al. (2001b)</td>
</tr>
<tr>
<td>Baseball</td>
<td>1</td>
<td>Adair (1995)</td>
</tr>
<tr>
<td>Tennis</td>
<td>4</td>
<td>Dignall et al. (2000)</td>
</tr>
<tr>
<td>Soccer</td>
<td>12 - 16</td>
<td>Asami and Nolte (1983), Tsousidis and Zatsiorsky (1994)</td>
</tr>
</tbody>
</table>

Table 2.5 - Impact contact duration for various ball sports

The soccer ball-foot impact was investigated by Asai et al. (2002) as part of an analysis into swerve kicks. University standard soccer players were captured kicking using a high-speed camera, and the data used to develop a finite element model (FEA) of a soccer swerve kick. FEA simulations showed that spin could still be imparted to a ball even if the coefficient of friction was reduced to equal or nearly equal to 0, and in this case the deformation caused by the off centre impact appeared to cause the ball rotation. Therefore, the FEA model predicted that the offset from the ball centre at impact has a greater effect on the generation of spin than variations in the coefficient of friction. However, the agreement between the FEA model and the experimental data deteriorated during the latter half of the impact, and the inherent error within FEA approximations should be considered in light of the results.

2.4.2.2 Heading Soccer Balls

The potential dangers of heading soccer balls have received widespread media attention over recent years, and a number of investigations to establish the potential for injury are currently ongoing. Further work to establish the extent of any potential danger to players is
particularly important taking into account the prevalence of litigation in modern society. There have been a number of examples of high profile former soccer players who have suffered brain and memory problems in later life. A notable example in the UK is that of former West Bromich Albion and England forward Jeff Astle who died in January 2002. At an inquest into his death the coroner ruled that Astle had suffered from a degenerative brain disease, and suggested that the likely cause had been through ‘repeated small traumas to the brain’ related to heading the old leather soccer balls. Although synthetic balls with excellent water resistance properties have superseded the leather soccer balls used in Astle’s playing days, the possible link between heading soccer balls and brain injuries should not be ignored and is currently a topic of investigation.

2.4.2.3 Impact Force Measurements

As a result of media interest into the effects of heading soccer balls, soccer ball impact forces have been investigated in a number of studies. Typically, impact forces have been measured by dropping test balls vertically downwards onto a force measuring platform (Dowell et al., 1991; Levendusky et al., 1988; Armstrong et al., 1988). Dowell et al. (1991) compared the impact characteristics of a number of sports balls in a simple drop test. Compressible hollow sports balls such as soccer balls and basketballs were shown to exhibit significantly smaller impact forces per unit area than smaller rigid balls such as golf balls and baseballs. Although the study showed that baseball and golf ball impacts can result in larger impact forces per unit area, the effects of repeated impacts were not considered.

Soccer ball design and construction can have a significant effect on ball impact characteristics (Holmes and Bell, 1985). Levendusky et al. (1988) investigated the impact characteristics of a range of stitched and moulded soccer balls. The balls were dropped from a height of 18m onto a force platform, resulting in an impact velocity of 18 m/s. The impact force measured for the stitched ball was found to be around 6% higher than that of the moulded ball. The study concluded that ball construction could affect ball impact force, although further work would be needed to fully investigate the dangers of heading. Armstrong et al. (1988) continued the investigation by assessing the effect of inflation pressure and water absorption on ball impact force. The balls were dropped onto a force platform from 6m, resulting in an impact velocity of 9.8 m/s. It was found that a wet ball could increase the impact force by about 5% due to the extra weight as a result of water retention. Additionally, it was found that an increase in ball pressure from 41 to 83 kPa (6 to 12 psi) could increase ball impact force by around 8%. These results clearly show that a high-
pressure ball used in wet conditions could have a serious effect on the impact force sustained by the head during the heading activity.

Other investigations have included the development of a mathematical model of a heading collision (Townend, 1988), and the use of accelerometers to measure head acceleration during impact (Burslem and Lees, 1988). The mathematical model developed by Townend (1988) was based on an oblique impact between two rigid moving spheres. The study estimated the average acceleration at impact for a ball travelling at 10 m/s, to be around 20 - 25 g. According to the model, head acceleration increases with a reduction in player body mass, and with an increase in ball mass. Consequently, it was recommended that lighter and smaller balls should be used for juniors, although no values were suggested. Burslem and Lees (1988) attached a pair of accelerometers to a subject in order to measure the head acceleration from a headed impact with a ball travelling at around 7 m/s. The linear and rotational head accelerations calculated were not deemed to be of sufficient magnitude to cause head injury or concussion for a single impact. However, the ball velocity used in the study was low and higher velocities are common during actual playing conditions.

The impact studies were generally in agreement that heading a soccer ball should not by itself be considered a dangerous activity. However, generally the studies did not take into account the long-term effect of sustained repeated impacts throughout the course of a professional playing career. Heading is an important skill in soccer, and heading technique needs to be practiced from an early age. The results have shown the importance of ensuring that junior players use smaller, lighter balls in order to minimise ball impact forces during the heading activity. With litigation becoming more prevalent in modern sports, consideration of the effects of equipment/ball characteristics on injury will provide a considerable area for further work.

2.4.2.4 COR Testing

The COR for soccer balls was standardised as part of the FIFA Denominations program in 1996. The FIFA standardisation of ball COR has proved popular with players, as the dynamic performance of top class balls has been made more predictable and consistent. The ability to stop a long pass with a chest, thigh or foot is an essential skill that top players must possess. Players have to know exactly how much rebound to expect from the ball so that they can position their body accordingly to control the ball. In the existing FIFA test, balls are dropped vertically onto the exposed end of a steel cylinder in a guided free-fall from a height of 2m. Movement of the test balls after release is constrained by a steel ring attached
to a vertically sliding arm, which prevents any rotation and ensures a consistent collision. To qualify for the 'FIFA Inspected' hallmark balls must have a COR of 0.76 - 0.91. To qualify for the more prestigious 'FIFA Approved' hallmark balls must have a COR of 0.77 - 0.91. There is little difference in the COR range for 'FIFA Inspected' and 'FIFA Approved' designation balls and the COR range for soccer balls is quite high compared with specified COR ranges for other ball sports. The International Tennis Federation (ITF) specify a COR range of 0.73 - 0.76 for approved tennis balls, considerably lower than the existing FIFA specification (ITF, 2003). In order to differentiate the higher quality 'FIFA Approved' balls from the 'FIFA Inspected' the COR tolerance for 'FIFA Approved' standard balls may require revision.

The simplicity of the drop test ensures that it is often employed to calculate COR (Plagenhoef, 1972; Johnson et al., 1972; Townend, 1984), although unlike the guided FIFA method, balls are often dropped in free fall and are subject to additional aerodynamic forces that can result in inaccurate results. The COR drop test is also often employed as an assessment of playing surface quality (Bell et al., 1985). Plagenhoef (1972) and Townend (1984) both specified the COR for a soccer ball as 0.75 using simple drop test techniques. Johnson et al. (1972) developed a series of equations of motion for the impact and rebound of a pressurised, but inextensible and completely flexible, shell against a flat surface. A soccer ball was used in order to gather experimental data on impact velocity, rebound velocity, contact area and contact time. A later study carried out by Percival (1976) corrected the impact equation of motion originally derived by Johnson et al. (1972). Bull Anderson et al. (1999) used 7 amateur soccer player as subjects and measured the COR direct from a soccer kick. The mean COR was found to be 0.575 with a range of 0.463 - 0.681. From the kicking tests it was concluded that ball velocity is dependant on both the velocity of the foot before impact and the impact COR.

2.4.3 OTHER SPORTS BALL IMPACTS

There have been many studies into ball impacts in sports and a summary of more recent relevant work is given below. Generally golf science is in advance of study into other ball sports and is worth studying, although the significant difference is the solid construction of golf balls compared with hollow soccer balls. The impact characteristics of golf balls have been assessed in many studies from Tait (1896), to many current scientists (Cochran and Stobbs, 1968; Gobush, 1990; Scheie, 1990; Chou et al., 1994; Ujihashi, 1994). A popular method of assessing the dynamic characteristics of golf balls involves firing balls onto a steel target with an air cannon. The impact force is typically measured using a force transducer.
mounted on the steel target (Gobush, 1990; Chou et al., 1994; Ujihashi, 1994). High-speed video or stroboscopic photography are typically used to capture the ball impacts and calculate COR. Chou et al. (1994) developed an FEA model of the ball impacts from experimental data obtained using stroboscopic photography. The golf equipment business has also developed a number of stroke simulators or robots, which enable examination of ball and club impacts under closely controlled conditions. Information on contact time (Roberts et al., 2001b) and impact forces (Hocknell, 1998) has been determined which has only recently become a feature of research in other ball sports.

Stroboscopic photography was also used by Carré et al. (1998) in an analysis of cricket ball impacts. Ball velocities, spin rates and impact angles were calculated from the images obtained in order to compare the properties of two different types of pitches. The experimental data was later used to create mathematical models for sports surface impacts (Carré and Haake, 2001). In tennis, there have been a number of studies concerned with the analysis of tennis ball impacts (Brody, 1984; Cross, 1999; Dignall et al., 2000). Tennis ball COR tests were used in a number of studies to assess tennis ball characteristics (Dunlop et al., 1987; Knowles and Cooke, 2000; Cross, 1999). The study by Dunlop (1987) dropped balls onto the surface of a spinning wheel, with the rotational speed adjusted so that the test balls rebounded vertically. This system allowed the analysis of ball spin as well as the COR after impact. The potential implications of reducing tennis ball COR in order to reduce serving speeds was investigated by Cross (2000). It was theoretically shown that the extreme measure of reducing ball COR to zero, would only actually reduce service speeds by 20% on impact with the racket.

Recently the dynamic characteristics of sports balls has become an area of study. Work by Shannon and Axe (2002) and Axe et al. (2002) has studied the effect of golf ball impacts on vibration and sound. This is an interesting area of study from player comfort, injury and perception viewpoints, however no work in this field has yet been reported in soccer.

2.5 BIOMECHANICS

Kicking is fundamental to the game of soccer and therefore a study of the science involved can provide significant information on ball performance. In the early days of soccer the toe kick was widely used, however today this method is seldom used, perhaps due to changes in boot design and technology. There are a number of kick variations used in soccer, largely dependant on the particular situations that arise during a game. For low velocity passes, the ball is often struck with the side of the foot. For high velocity long distance passes
or shots on goal the ball is often struck with the upper part of the foot (Nunome et al., 2002). In order to impart spin to a ball, it is necessary to strike the ball off centre; backspin can be achieved by striking the ball at the bottom, and sidespin can be achieved by moving the foot across the ball during impact (Wesson, 2002).

2.5.1 Soccer Ball Kicking

Numerous studies have been undertaken into soccer ball kicking which can be split into five main phases: the approach run, the placement of the non-kicking foot on the ground, the swinging of the leg to accelerate the foot, the impact of the foot on the ball, and finally the follow through of the leg (Wang and Griffin, 1997). The leg movement in a typical soccer kick is shown in Figure 2.6. To achieve a high velocity kick it is necessary to bend the knee as the foot is taken back during the approach, this enables the foot to be accelerated through a longer distance. The leg muscles accelerate the thigh, which pivots around the hip, and accelerate the calf and foot to an even greater extent. Finally the leg straightens until the foot is locked firmly with the leg as the foot makes contact with the ball (Wesson, 2002).

![Figure 2.6 - Leg movement in a typical soccer kick (adapted from Wesson, 2002)](image)

The biomechanics of the soccer kick have been investigated in a number of different studies. In many studies correlations between ball velocity and foot velocity before impact are high (Lees and Nolan, 1998), therefore ball velocity appears to be dependent on foot velocity. Plagenhoef (1971) investigated the mechanics involved in the collision between the foot and the ball and suggested that the velocity of the ball is dependent on the mass of the player's leg and foot, the mass of the ball and the coefficient of restitution. Using this model the ball velocity ($V_{ball}$) can be calculated as follows:
\[ V_{\text{ball}} = V_{\text{foot}} \frac{M(1+e)}{M+m_b} \]  

(2.6)

Where: 

- \( V_{\text{ball}} \) Ball velocity (m/s) 
- \( V_{\text{foot}} \) Foot velocity (m/s) 
- \( M \) Mass of leg and foot (kg) 
- \( m_b \) Mass of ball (kg) 
- \( e \) Coefficient of restitution

Lees (1996a) estimated that \( \frac{M}{M+m_b} = 0.8 \) and \( e = 0.5 \), this allows the equation to be approximated to:

\[ V_{\text{ball}} = 1.2 \ V_{\text{foot}} \]  

(2.7)

Muscle strength has been identified as having a significant effect on kicking performance, largely because the muscles are directly responsible for increasing the velocity of the foot (Lees and Nolan, 1998). Studies by Narici et al. (1988) and Poulmedis et al. (1988) both measured ball velocity as an indication of kicking performance, and found a high correlation between maximum ball velocity and isokinetic muscle torque. However although muscle strength undoubtedly has a significant effect on ball velocity, it is not the sole determinate of a good kick. Good kicking technique and timing are other significant contributing factors in order to achieve high ball velocities.

Soccer players of all levels usually have a preferred foot with which to perform the kicking action. Although there are some examples of top class ambidextrous players equally skilful with either foot, generally players will be more skilled with a particular foot (Carey et al., 2001). Generally soccer players have a preferred foot from an early age; therefore as the player develops the preferred side becomes stronger and more skilled from increased usage. The biomechanical differences between the preferred and non-preferred foot have been analysed in soccer by Dörge et al. (2002), and in rugby by Bauer (1982). Dörge et al. (2002) compared maximal velocity instep kicks using both the preferred and non-preferred foot and found that the preferred foot achieved higher ball velocities. The study conducted by Bauer (1982) assessed kicking performance of the rugby punt kick using the preferred and non-preferred foot. The study was in agreement with that of Dörge et al. (2002), confirming that
kicking with the non-preferred foot was generally inferior. It was speculated that the inferior performance might be due to a lack of coordinated muscle contraction.

2.5.2 **The Instep Swerve Kick**

The ability to swerve the ball is an important soccer skill that can be used by attacking players to deceive goalkeepers. In order to achieve 'swerve' the ball must be struck off centre in order to induce a rotation, and for lateral 'swerve' this can be achieved using either the instep or the outstep of the foot. Alternatively, in order to create trajectory dip or lift the top of the foot can be used to impart topspin or backspin to a ball. For a successful swerve kick, the approach angle should be no greater than $45^\circ$ (Wang and Griffin, 1997). The instep kick is used frequently in soccer for high velocity shots and passes, and a number of biomechanics investigators have measured ball velocities during a kinematic analysis of the instep kick (Roberts and Metcalfe, 1968; Plagenhoef, 1971; Togari *et al*., 1972; Asami and Nolte, 1983; Isokawa and Lees, 1988; Nunome *et al*., 2002). The results from these previous studies have shown that ball velocities produced from instep kicks are typically in the range 18 - 34 m/s. A detailed analysis of the results and procedures used in each study are given in Section 4.1.

2.6 **Computational Modelling**

The application of engineering research in order to develop innovative sports products has gained importance amongst equipment manufacturers striving to develop a competitive edge. Consequently, computer aided engineering (CAE) systems are frequently employed to model sports equipment and perform design analysis. Although computer aided design (CAD) is the standard method for generating equipment models, other computational systems including finite element analysis (FEA) and computational fluid dynamics (CFD) are used to perform mechanical analysis and simulations.

**FEA** is a numerical analysis procedure used in engineering to obtain approximate solutions to particular product design problems. FEA is an analytical tool in which a continuous elastic structure is considered as a number of smaller elements joined together at nodes. The properties of the structure are determined by the number of elements, nodes per element and the number of degrees of freedom per node. A field quantity in polynomial form (e.g. displacement) is interpolated for each element from the field quantity at the nodes. The field quantity can then be interpolated throughout the structure by joining all the elements using an array of polynomial expressions (Champion, 1992). FEA is an approximate technique that can be subject to errors, however when used correctly it can provide a powerful analytical tool, particularly when complex form products are considered.
One of the few applications of FEA in soccer was a study undertaken by Asai and Akatsuka (1998) who developed an FEA model of the ball-foot interaction in a 'curve ball' kick. Experimental data was obtained using university standard subjects filmed using a high-speed camera running at 4,500 frames per second. An FEA model of the foot was coupled with a very basic model of the ball, to simulate the ball-foot interaction during impact. The model was in good agreement with the experimental data and was used to show the effect of striking the ball at different points offset from the ball centre line. As the offset distance was increased, ball spin increased and ball velocity decreased. In a later study Asai et al. (2000a) adapted the existing FEA model to compare the impact characteristics of the curve ball kick with a straight instep kick. University standard subjects were employed as kickers and a 3D motion capture system used to track the positions of the lower leg, foot and ball during impact. FEA simulations of each kick type were produced and found to be in good agreement with the experimental data during the first half of the impact, but deteriorated somewhat during the second half. The FEA simulation examined the pressure distribution in the foot during impact, but neglected to assess the pressure distribution within the ball. Although a geometrical representation of the foot has been developed, the foot's functional properties have not been described. Clearly the foot is a complex structure and this area of activity will present a considerable challenge. Furthermore, no data regarding the ball construction or materials was discussed.

CFD is a method of modelling a virtual fluid flow around an object, eliminating the need for extensive experimental wind tunnel testing. CFD allows the user to computationally model any flow field around an object, provided that the geometry of the object is known (Hanna, 2002). Applications of CFD in sport include modelling the flow around Formula 1 racing cars, yachts, racing bikes and sports balls. Asai et al. (2000b) generated a CAD model of a 32-panel soccer ball with seams, and performed a CFD analysis on the model. The results from the study showed that the $C_L$ for a soccer ball increased as the spin rate increased at a given flow speed, but that the $C_L$ decreased as the flow speed was increased at a given spin. These results agree with the golf ball results obtained experimentally by Bearman and Harvey (1976) in conventional wind tunnel tests, and suggest that $C_L$ can increase as a ball slows down towards the end of its trajectory providing ball spin does not decay significantly. The study was slightly limited in that the simulation assumed a constant lift force throughout the entire trajectory. Hanna (2002) also conducted a CFD analysis on the flight of a soccer ball, not suprisingly commenting that the laminar to turbulent transition during the flight of a ball will have the single biggest effect on the balls flight trajectory.
2.7 BALL LAUNCH SYSTEMS

The ability to provide a consistent and repeatable launch platform is essential for the evaluation of dynamic sports ball performance and for the potential determination of standards. Furthermore, launching devices must be capable of achieving ball launch velocities comparable to those that occur in a game situation. In golf, the small size of the ball facilitates that a compressed air canon can often be used as a launching device in dynamic impact studies (Chou et al., 1994; Ujihashi, 1994). However, in order to consider the effects of spin, robots capable of swinging clubs at high velocities can be used to assess initial flight characteristics. In baseball, cricket and tennis a bowling machine is often used as a launch platform (Alaways and Hubbard, 2001). Bowling machines consist of a pair of rotating wheels, one rotating clockwise and the other anti-clockwise. The test ball is positioned between the two wheels, and pushed forward allowing the motion of the rotating wheels to propel the ball forward. The rotational speeds of the launching wheels can be independently controlled so that spin can be imparted, and the launcher can be set at a range of different launch angles.

Bowling machines although originally designed for baseball, cricket and tennis, have been adapted for soccer balls by two companies: Bola and Jugs. However, the interaction between the rotating wheels and the ball causes significant damage to the ball surface after a small number of launches. This shortcoming limits the potential for extensive testing, although bowling machines can be used effectively for a small number of launches (Carte et al., 2002). FIFA have adapted a wheel launch system for their durability test, they use smooth steel wheels rotating at a constant and equal velocity. A more complex launch system for soccer balls is that of a robotic kicking leg. Schempf et al. (1995) designed and manufactured a robotic kicking leg for adidas consisting of torso, hip, thigh, shank and foot components. The robot was designed with a combination of active and spring-assisted actuator modules to facilitate the transfer of momentum from the leg to the ball. The robot had a reasonable accuracy on target of +/- 1 ball diameter (0.22m) from a distance of 20m, however reliability of the machine was very poor and the leg malfunctioned frequently. The robot was eventually replaced by adidas with the more simple and reliable pneumatic kicking leg discussed in detail in Chapter 6.

2.8 BALL FLIGHT MEASUREMENT AND TRACKING SYSTEMS

Systems capable of measuring ball launch characteristics and/or trajectories are extremely useful for the assessment of dynamic ball performance. Contemporary ball tracking systems are now used frequently for virtual television replays in sports such as tennis.
Many of the companies responsible for the development of projectile tracking systems are involved with military applications, however for security reasons, details on these systems are not in the public domain. Many of the sports ball tracking systems currently in use have evolved from golf ball trajectory monitoring systems which were developed confidentially for golf equipment manufacturers, therefore with some exceptions information is generally not in the public domain.

Simple ball trajectory monitoring systems typically measure the initial, post impact, ball flight characteristics. The Flightpath measurement system was developed in conjunction with the Sports Technology Research Group at Loughborough University in 1993, and can be used to measure initial ball launch parameters. A detailed description of the Flightpath measurement system is given in Section 4.5. Gobush *et al.* (1994) developed an automated system for the assessment of golf ball launch characteristics (ball velocity, spin rate and elevation) using a standard video camera and stroboscopic photography to obtain two ball images within 1ms of each other. Test balls had a specific arrangement of reflective markers applied to the ball surfaces in order to determine the rotation between images. The image capture was triggered at impact by an acoustic sensor, and grey scale thresholding techniques employed to identify the position of the markers on each ball. A series of algorithms were then used to calculate the launch characteristics based on the spatial difference between the markers on each image. These systems are limited to static ball impacts because of ball marking positioning.

The Accusport golf ball Vector Launch System (Accusport, 2003) uses infrared light to measure initial launch characteristics (velocity, elevation and back spin), using balls with added black markings around the equator. Similarly, coverage of ice hockey on Fox television use an infrared system developed by Vista Development to enhance the puck visibility on television (Vista Development, 2003). The puck is modified to accommodate an infrared emitter which gives off pulses to infrared sensors located around the edges of the playing surface. The infrared sensors at surface level synchronise the pulses and another infrared camera located in the arena roof detects these synchronised pulses and computes the puck position. The puck location can then be graphically enhanced for superior visibility on television. A more simplified system has been used for tennis line calls, where an infrared camera located above the court identifies ball impact position from the heat emitted.
Modern television coverage of tennis matches now includes virtual replay animations in order to determine if a controversial line call was correct. Pingali et al. (2000) developed an automated system for tracking tennis balls in order to produce virtual simulations of ball trajectories. The system utilises six monochrome progressive scan cameras operating at 60 frames per second positioned around a court. The cameras are all connected to a central workstation PC and linked in pairs to form a set of four stereo pairs. The system uses a multi-threaded approach to tracking whereby each thread tracks the ball using a pair of cameras based on ball motion, intensity and shape. Each thread consists of a number of processing steps and is associated with each pair of cameras. This approach performs stereo matching to obtain the 3D ball trajectory, is able to detect when a ball goes outside the camera field of view, and initialises and triggers a subsequent thread. Problems can arise within the system if a player obscures the ball, as the accuracy of the system depends on good quality ball images. The system is capable of operating in variable lighting conditions through the use of auto-iris lenses on the cameras.

The Hawk-Eye ball tracking system was introduced during televised cricket coverage in 2001, and laterally during tennis coverage at the 2003 Wimbledon Championships. Hawk-Eye is a video processing system that utilises 3 calibrated high-speed cameras to track ball movement. Algorithms are then used to determine the 3D ball location in a number of consecutive frames, before using the ball positional data to predict the future ball trajectory (Sherry and Hawkins, 2001). The primary use of the system is for lbw decisions in cricket, and for ball-line violation decisions and shot data analysis in tennis.

In soccer, there are very few examples of ball tracking systems. During post match analysis of games on television, the trajectory of a shot on goal is sometimes highlighted, and the velocity estimated during a replay. However, the accuracy of estimating velocity from standard video footage can be questioned, and there is currently no instantaneous feedback on ball performance during a game. However, there are currently a number of companies striving to develop systems capable of tracking player and ball movement during a game. The most publicised system is being developed by Cairo Technologies AG, and is concerned with the tracking of players and the ball. The system utilises small sensors (carried in the shin guards of the players) that transmit signals to receivers positioned around a ground. A central processing unit collaborates the signal data and computes the position of each sensor (Braun et al., 2001). In order to track the ball it will be necessary to position a sensor on or within the ball itself. However, the introduction of a sensor to the ball may present problems due to the potential for damage caused by the large deformation and contact forces the ball experiences.
during kicking. Furthermore, the addition of a sensor to the ball must not significantly alter the ball mass distribution as this could lead to an unbalanced ball and have a detrimental effect on dynamic performance. A significant factor with all of the tracking systems in use to date is their cost. The cost of installing a Hawkeye system around a cricket ground is £300,000 and the Cairo system £400,000.

There are a number of patents filed related to the analysis of ball flight performance. Marinelli (2000) describes a system for measuring the flight characteristics of various sports balls. The system requires a radio transmitter to be embedded within a ball, which will send signals to a central processor. It is claimed that the processor unit could then display the flight characteristics of the ball including spin rate. However, the system would likely be costly, and the addition of the radio transmitter whilst not adversely affecting ball performance could prove difficult. Onuki et al. (1998) describes a system for measuring the spin rate of spherical sports balls that have been marked with a reflective material. The system projects light onto a ball in flight and calculates spin rate by the frequency of the fluctuations of the reflected light. However, the system requires an extended period of measurement in order to determine the fluctuation frequency, and gives no indication of the axis of spin.

2.9 CONCLUSIONS

This chapter reviewed published literature related to the potential development of new dynamic testing criteria for soccer balls. The FIFA Denominations program provides the basis for the regulation of ball manufacturing consistency, however with the notable exception of a low velocity COR rest, the Denominations program currently does not provide an assessment of dynamic ball performance. Furthermore, manufacturing defects that often occur during the manufacturing process, such as ball out-of-balance, can affect the ball flight characteristics, and are not assessed by the existing FIFA Denominations program.

There is relatively little published literature on the aerodynamics of soccer balls, although Carré et al. (2002) and Bray and Kerwin (2003) have experimentally derived estimations for $C_D$ and $C_L$ through trajectory analysis. The analysis of soccer ball aerodynamics in a wind tunnel would be an extremely worthwhile project, however this activity would be an extensive undertaking, which due to time constraints, is beyond the scope of this research project. Sports ball impact theory is covered in a number of texts (Daish, 1972; Townend, 1984), and soccer ball impacts have been examined by a number of investigators (Johnson et al., 1972; Levendusky et al., 1988; Armstrong et al., 1988). However,
the sound and vibration characteristics of soccer balls have still to be investigated, and whilst not given consideration within this research project, this is an area of significant potential.

A number of biomechanics investigations into kicking have measured ball velocities (Roberts and Metcalfe, 1968; Asami and Nolte, 1983), however few studies have used the optimum combination of elite players and high-speed video in order to obtain measurements. As far as the author is aware, only one of these studies (Asai and Akatsuka, 1998) has measured ball spin rate using high-speed video. The lack of a comprehensive study into elite player kicking capability suggests that an evaluation of a significant number of professional players is required and will be included in this work.

Ball tracking systems are frequently used during television coverage of ball sports in order to predict trajectories (Pingali et al., 2000; Sherry and Hawkins, 2001). However, although there are soccer ball tracking systems currently in development (Braun et al., 2001), they are likely to be expensive, and their potential accuracy remains unclear. There are currently no existing systems capable of obtaining automated measurements of soccer ball flight characteristics. In order for a governing body to assess the performance characteristics of a range of soccer balls, a system capable of obtaining automated measurements of velocity and spin rate would be extremely beneficial. Used in conjunction with a suitable ball launching device, it would be possible to determine if balls conformed to standards for parameters such as velocity, spin rate and COR.
CHAPTER 3

AN EXACT METHOD FOR THE SPHERICITY MEASUREMENT OF SOCCER BALLS

The popularity of ball sports has led to the creation of ball testing procedures to determine their suitability for use in competition. These testing procedures ensure consistency of top competition balls and assure the players of ball quality. The majority of ball sports use spherical balls, therefore sphericity assessment is often used as a test procedure. However, no sports games actually specify a true sphericity assessment method and generally use a diameter, circumference or ring test. Generally these methods give a reasonable reflection of sphericity although this is not always the case. The existing sphericity test employed by FIFA uses diameter measurements to indicate ball sphericity, but this method can be subject to human error. Consideration of a sphericity specification in isolation is not a dynamic factor, however poor sphericity can effect ball flight and roll and is therefore of considerable interest. The most important ball performance consideration to professional players is ball consistency, and poor sphericity can be the cause of unpredictable behaviour both at impact and in flight. This chapter outlines a new automated method for accurately measuring the sphericity of a soccer ball. This method could also be employed for providing accurate sphericity assessments for other spherical balls used in sport.

3.1 THE NEED FOR SPHERICITY

The FIFA Denominations program outlined in Section 1.2 was introduced to ensure the global consistency of the world's top soccer balls. To qualify for the basic 'FIFA Inspected' ball standard FIFA specify that balls have to satisfy 6 criteria: weight, rebound, durability, pressure retention, circumference and sphericity (FIFA, 2003a). Sphericity is an important property for soccer balls to exhibit, in order for them to perform in a consistent manner. If a ball is 'out of round' this error may have a serious effect on aerodynamic flight, dynamic behaviour at impact and roll performance.
The FIFA test criteria outlined in Section 1.2 states that ball circumference should be between 68 - 70cm for the ‘FIFA Inspected’ designation; and 68.5 - 69.5cm for the ‘FIFA Approved’ designation. Since accurate circumference measurement is difficult, this is further redefined in terms of a diameter measurement. The FIFA sphericity test involves taking 16 measurements of the ball's diameter, before calculating the difference between the highest and lowest values, and using this variation as an indication of sphericity. Unfortunately consistency of diameter or circumference does not guarantee sphericity and lobed constant diameter objects can exist.

A review of current standards has revealed that there are no specific British Standards for soccer balls. BS 5993:1994 specifies a method of circumference measurement for cricket balls but does not specify any measurement of sphericity. BS 7172:1989 specifies procedures for measuring the position, size and departure from nominal form for a series of geometric features. It states that the distribution of measured data points around an object such as a sphere should generally be set up for uniform coverage of the shape. However, the distribution should not be so regular that it is possible for it to follow systematic or periodic deformations and a certain amount of randomness and lack of regularity in the distribution of points is generally desirable.

BS 6740:1987 and BS 3730:1987 detail methods for determining departures from roundness for 2D circles by measuring variations in radius. The measurement methods require the calculation of a least squares circle in order to assess roundness. BS 3290:2001 specifies a method for the measurement of sphericity for rolling bearings and balls, where sphericity (or deviation from spherical form) is specified as the greatest radial distance, in any equatorial plane, between the smallest circumscribed sphere and the greatest inscribed sphere, with their centres common to a least square sphere centre.

3.1.1 SOCCER BALL PLAY CHARACTERISTICS

Play characteristics for different balls will vary depending on the particular sport. Some games involve the balls being kicked by the feet (as is the case in soccer); other games involve the ball being carried in the hands (for example rugby), whilst other games involve the ball being struck by an additional piece of equipment (for example golf and tennis). Soccer can be a thrilling and spectacular game played with one very simple piece of equipment - the ball. However, players can only use their skills to the best effect when they know that the ball is going to be consistent in its performance. Although there are differences between sports, ball
consistency is a key factor in all ball sports and deviations in sphericity can have a major effect on both the dynamic and aerodynamic performance of balls.

The design and manufacture of a ball will generally determine its quality and the factors affecting the roundness of a soccer ball are:

- Panel construction
- Ball materials
- Number of panels
- Pressure
- Bladder construction
- Stitching quality

3.2 EXISTING METHODS OF MEASUREMENT

The FIFA Denominations program currently specifies a sphericity test that although giving some indication of whether or not a ball is out of shape, does not provide an accurate measure of sphericity. To test sphericity, the ball is inflated to 80 kPa, then measured at 16 defined points to calculate the highest and lowest diameters. The sphericity of the ball in millimetres is indicated by the difference between the highest and lowest diameters. The percentage sphericity variation is then determined by comparing the ratio of the difference between the highest and lowest diameters with the average ball diameter. To qualify for the ‘FIFA Inspected’ designation only 2% variation in sphericity is allowed, and to qualify for the more prestigious ‘FIFA Approved’ designation only 1.5% variation is allowed.

Constant diameter lobed shapes, such as tubes and bearings, frequently occur in engineered products or as a result of the manufacturing process. It is worthwhile examining a simple 2D shape to appreciate the phenomena. Figure 3.1 shows a 3-lobed configuration developed from an equilateral triangle. The lobed shape is generated by striking arcs of radius R1 from each vertex and a second arc R2 from the opposite vertex to be tangential to R1. The apparent diameter will always be R1+R2, yet the diameter of a true circle to envelope the shape would clearly be bigger in fact: \( D = 2(R1 + s) \) (Hume, 1968).
This simple 2D explanation can be transformed into the spherical case by considering the generating prism as a tetrahedron. There are many instances of this type of effect in manufactured products where the lobed arrangements are generally generated as odd number lobed shapes. Clearly both the diameter and circumference methods would not detect the lobe errors described above and a new approach is worth consideration.

Poor sphericity is often described as 'ball out-of-roundness'. A simple test to establish if a ball is 'out-of-round' is a roll test, in which a ball is simply rolled along a flat surface in a controlled movement. If a ball travels in a straight line then the ball can be considered round, however, if a ball rolls to the side then the ball is considered out-of-round, i.e. not spherical. This method, however, does not determine the extent of sphericity error and the path deviation can also be a result of uneven mass distribution within the ball. It is interesting to note that this test is specified by FIFA for indoor soccer balls, but not outdoor balls.

3.3 LEAST MEAN SQUARES METHOD

An improved sphericity test has been devised utilising a Ferranti Metrology Systems Merlin coordinate measuring machine (CMM) fitted with a Renishaw probe system (Neilson and Jones, 2003a). CMM machines are multi-axis devices with 2 to 6 axes of movement, each of which provides an out of position or displacement. Typically, CMM machines are used for the measurement and inspection of complex 3D components for both prismatic and sculptured surfaces. They are designed to record the position of a probe as it moves along its coordinate axis, and also to probe points in 3D space, giving the position of the probed point to a high accuracy.
CMM machines consist of a platform on which the ball being measured can be secured. A touch trigger probe (TTP) attached to a moveable head capable of lateral and vertical movements is then used to record all measurements. The TTP utilises touch forces of less than 1 g so that ball deflection is negligible. The TTP can also be rotated enabling it to probe complex surfaces with the probe orientation to the surface remaining constant. The measurements obtained using the TTP are fed into a computer, which uses software to calculate sphericity values based on a least squares sphere approximation. A common method for determining best fit of data to lines, planes etc. is the use of a least mean squares (LMS) calculation. In this approach it is desired to fit a figure which can be described by an equation. When the sum of the squares of the errors of the data is a minimum then the fitting figure is unique and described as a best fit. This least squares approach will be used to determine sphericity errors in soccer balls (Dagnell, 1976). Figure 3.2 shows the experimental set up for ball sphericity measurement.

![Figure 3.2 - Ball sphericity measurement on CMM](image)

The proposed method needs to take a representative sample of the sphere surface data to enable assessment and because of the panel configuration of soccer balls measuring points should be on a mid panel surface to overcome seam effects. Although a certain amount of randomisation is preferable in the selection of data points, as outlined in BS 7172:1989, in this case the TTP is set to measure the approximate centre position of each panel. The
presence of the seams on the ball surface makes it impractical to probe the surface randomly as this would lead to an inaccurate representation of sphericity. Therefore, for a 32-panel icosadodecahedron ball 32 readings are used to fit a I.MS approximation to a sphere to the ball data. The computer software then calculates the ball diameter and ball sphericity. The software that is utilised in the system is the International Metrology Systems (IMS) Accudat system.

3.3.1 PARAMETERISATION OF LEAST MEAN SQUARES METHOD

A detailed description of the method used for the calculation of sphericity using a least mean squares approximation to a sphere (Bui and Kamaraj, 2001) is given in Appendix 3. A brief description of the method is given here:

A sphere is specified by its centre \((x_o, y_o, z_o)\) and radius \(r_o\). Any point on the sphere surface satisfies the equation \((x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2 = r^2\). (3.1)

A minimizing function has to be identified to obtain an initial estimate for the centre and radius. Consider the function \(f_1 = r_i - r\)

Where \(r_i = \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2}\). (3.2)

Differentiating this function with respect to \(x_o, y_o, z_o\) and \(r_o\) will result in equations which are difficult to solve. Therefore, consider the function \(f_2 = r_i^2 - r^2\). Differentiating this function with respect to \(x_o, y_o, z_o\) and \(r_o\) will obtain initial estimates of centre and radius.

Thus the minimizing function to obtain initial estimates for a sphere is:

\[ f = r_i^2 - r^2. \] (3.3)

After obtaining the initial estimates for the centre and radius \(r\), the Gauss Newton method is used to arrive at the final values for centre and radius.

The minimizing function is given by \(d_i = r_i - r\) (3.4)

Other ball panel arrangements can be evaluated, although each different ball panel arrangement requires a separate program to be written for the TITP movements around the ball surface. For a cubic 26-panel ball the TITP was set to take readings for 38 points, with 12
of the longer panels being touched by the probe in 2 different positions. Ball diameter and ball sphericity were then calculated using the Accudat software based on a LMS approximation to a sphere. A significant advantage of this system is that the CMM can be programmed to operate automatically and a set of ball data can be captured in 30 minutes, including 3 repeat readings.

3.4 AUTOMATED BALL SPHERICITY MEASUREMENT PROCEDURE

In order to evaluate the proposed methods of sphericity measurement with the existing FIFA method a series of tests were undertaken. The testing stage involved taking readings for 6 leading ball types used in major competitions. The 6 leading ball types tested were the adidas Terrestra Silverstream, Mitre Ultimax, Nike Geo Merlin, Puma Cellerator, Puma Shudoh and Puma King SL. More information on the 6 test balls can be found in Appendix 4. A sample of four balls of each type were tested giving a total of 24 balls.

Five of the test balls were 32-panel construction and a probe movement program was written within the Accudat software in order to automatically ‘touch’ the approximate centre of each panel with the TTP. The movement program required the TTP angles to be constantly changed during the first manual operation, however once the program had been successfully implemented it could be quickly recalled and run automatically for each subsequent ball. The Mitre Ultimax ball was of 26-panel construction and required a separate probe movement program to measure 38 points on the ball. The measuring procedure, once initiated, was totally automatic. Three sets of results were taken for each ball giving a measurement time of 30 minutes. The test balls were placed on a machined plastic ‘ball-holder’ on the CMM platform which featured a cut-away section in order for the TTP to access the bottom panel of the ball. The balls were all positioned with the valve at the top of the ball. The measurement data was in Cartesian form with reference to the machine global datum.

The repeatability of the sphericity measurements obtained using the CMM method was +/- 0.1mm; therefore the results can be treated as consistent. Three sets of readings were taken for each individual ball, with the ball ‘re-spotted’ on the ball holder after each reading had been taken. This was done to ensure that the probe was touching the ball panels in a different position each time a set of readings were taken. The CMM was linked to a PC that processed the data obtained from the TTP. The software calculated an x,y,z coordinate relative to the ball centre for each point measured as well as calculating the ball diameter. Furthermore, the software was capable of fitting a LMS approximation to a sphere to the ball
data, giving a value for sphericity in mm. The sphericity value calculated is the sum of the maximum inner and outer values from the least mean squares sphere. The sphericity % was calculated from the maximum variation in measured values as a percentage of the LMS diameter. A 2D representation of the LMS approximation to a sphere is given in Figure 3.3.

![Least squares spherical diameter](image)

**Figure 3.3 - 2D representation of a LMS approximation to a sphere (adapted from Dagnall, 1976)**

### 3.5 RESULTS

Three sets of readings were taken on the CMM for each individual ball tested and the full set of results can be found in Appendix 5. Table 3.1 shows a summary of the results obtained. All balls were inflated to a constant pressure of 86 kPa (12.5 psi), the exact midpoint of the FIFA pressure stipulation.
<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Av. Diameter (mm)</th>
<th>Sphericity Range (mm)</th>
<th>Sphericity Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Terrestra</td>
<td>220.29</td>
<td>1.47 - 2.11</td>
<td>0.67 - 0.96</td>
</tr>
<tr>
<td>Mitre Ultimax</td>
<td>217.29</td>
<td>2.12 - 2.75</td>
<td>0.97 - 1.26</td>
</tr>
<tr>
<td>Nike Geo Merlin</td>
<td>218.83</td>
<td>1.52 - 2.35</td>
<td>0.69 - 1.08</td>
</tr>
<tr>
<td>Puma Cellerator</td>
<td>220.41</td>
<td>1.29 - 1.71</td>
<td>0.59 - 0.78</td>
</tr>
<tr>
<td>Puma Shudoh</td>
<td>218.29</td>
<td>1.44 - 2.12</td>
<td>0.65 - 0.97</td>
</tr>
<tr>
<td>Puma King SL</td>
<td>219.61</td>
<td>1.19 - 1.58</td>
<td>0.54 - 0.72</td>
</tr>
</tbody>
</table>

Table 3.1 - CMM sphericity results

In order to compare the CMM and FIFA methods, each individual ball was also measured using a vernier height gauge in accordance with the FIFA method which requires 16 measurements per ball. Ball diameter was measured using a vernier height gauge at 16 defined points and the smallest and largest diameters determined. The sphericity of the ball in millimetres was estimated by calculating the difference between the smallest and largest diameters. The percentage sphericity variation was determined by comparing the percentage difference of the sphericity estimate against the average ball diameter. Three sets of readings were taken for each individual ball tested and the full set of results can be found in Appendix 6. Table 3.2 shows a summary of the results obtained. All balls were inflated to a constant pressure of 86 kPa (12.5 psig).

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Av. Diameter (mm)</th>
<th>Sphericity Range (mm)</th>
<th>Sphericity Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Terrestra</td>
<td>220.31</td>
<td>1.02 - 3.02</td>
<td>0.46 - 1.38</td>
</tr>
<tr>
<td>Mitre Ultimax</td>
<td>217.47</td>
<td>2.98 - 4.58</td>
<td>1.36 - 2.12</td>
</tr>
<tr>
<td>Nike Geo Merlin</td>
<td>218.70</td>
<td>1.5 - 2.26</td>
<td>0.68 - 1.03</td>
</tr>
<tr>
<td>Puma Cellerator</td>
<td>220.36</td>
<td>1.06 - 2.46</td>
<td>0.48 - 1.12</td>
</tr>
<tr>
<td>Puma Shudoh</td>
<td>218.60</td>
<td>1.72 - 2.74</td>
<td>0.79 - 1.25</td>
</tr>
<tr>
<td>Puma King SL</td>
<td>219.55</td>
<td>1.46 - 2.06</td>
<td>0.67 - 0.94</td>
</tr>
</tbody>
</table>

Table 3.2 - FIFA test sphericity results

Measurement repeatability using the CMM was calculated from repeated tests as +/- 0.1mm, giving a sphericity % error of +/- 0.05%. The repeatability of measurement using the
vernier height gauge over the same number of tests was +/- 0.8mm, giving a sphericity % error of +/- 0.36%.

To qualify for the ‘FIFA Inspected’ designation test balls must have a percentage sphericity variation of not greater than 2%. Furthermore, to qualify for the more prestigious ‘FIFA Approved’ designation the balls must have a percentage sphericity variation of not greater than 1.5%. As is evident from the results, the CMM method of sphericity calculation resulted in all 24 test balls fulfilling the requirements of both the ‘FIFA Inspected’ and ‘FIFA Approved’ designations. Conversely, however, the results obtained for the existing FIFA method showed that one of the test balls (Mitre Ultimax #2) had not fulfilled the sphericity requirements for the ‘FIFA Inspected’ designation, and two of the test balls (Mitre Ultimax #2 and Mitre Ultimax #4) had not fulfilled the requirements for the more stringent ‘FIFA Approved’ designation.

Figure 3.4 shows sphericity measurements obtained by the CMM and FIFA methods. Figure 3.5 shows the average diameter measurements obtained by the CMM and FIFA methods.

![Boxplot of Sphericity by Ball Type](image)

Figure 3.4 - Box plot of sphericity by ball type
A t-test analysis was carried out in order to compare the sphericity error of the CMM sphericity measurement procedure with that of the FIFA procedure. A comparison of the data from all 24 test balls produced a result of $p=0.034$ indicating a significant difference in the results at the 5% confidence level. Table 3.3 shows the results of t-test comparisons on the two methods for each individual ball type. The Mitre Ultimax and Puma King SL ball types produced t-test results of $p=0.025$, indicating significant differences between the CMM and FIFA methods in each of these cases at the 5% confidence level. However, the four other ball types produced t-test results greater than 0.05, suggesting that the difference between methods was not significant.
<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Av. Sphericity % (CMM Method)</th>
<th>Av. Sphericity % (FIFA Method)</th>
<th>T-Test Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Terrestra</td>
<td>0.82</td>
<td>0.94</td>
<td>0.623</td>
</tr>
<tr>
<td>Mitre Ultimax</td>
<td>1.15</td>
<td>1.76</td>
<td>0.025</td>
</tr>
<tr>
<td>Nike Geo Merlin</td>
<td>0.86</td>
<td>0.79</td>
<td>0.633</td>
</tr>
<tr>
<td>Puma Cellerator</td>
<td>0.67</td>
<td>0.84</td>
<td>0.331</td>
</tr>
<tr>
<td>Puma Shudoh</td>
<td>0.79</td>
<td>0.99</td>
<td>0.137</td>
</tr>
<tr>
<td>Puma King SL</td>
<td>0.61</td>
<td>0.85</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Table 3.3 - T-test analysis of sphericity results by ball type

From the CMM test data it appears that as well as being the most spherical, the Puma Cellerator and Puma King SL sample balls are also the most consistent. The sphericity % values obtained for the Puma Cellerator and Puma King SL balls samples had ranges of 0.19 and 0.18 respectively. Conversely the sphericity % ranges obtained for the other ball types were not as consistent, varying from 0.29 for the adidas Terrestra and Mitre Ultimax balls, 0.32 for the Puma Shudoh ball and 0.39 for the Nike Geo Merlin ball.

3.6 DISCUSSION

The premise for the sphericity study described in Chapter 3 was that poor sphericity could effect ball flight and roll, and that the FIFA specified method using diameter assessment is a debatable representation of sphericity. The CMM method using a formalised approach, automated measuring method and least squares assessment provides a more rigorous and accurate method. It has been shown that the differences in the results obtained from the two methods of measurement are significant, and that the sphericity results for the FIFA diameter assessment method show larger error than the least squares method. The reasons for this discrepancy could be due to the differences in measurement repeatability, +/- 0.1mm for the CMM method compared to +/- 0.8mm for the vernier height gauge FIFA method, and the automated and unambiguous method due to least squares assessment.

Evaluation of the CMM sphericity test results shown in Figure 3.4 show that the sphericity percentage values are not consistent with those obtained by the current FIFA measuring method. It has been argued that the FIFA ball diameter measurement approach is a debatable representation of sphericity, and there is considerable potential for human error during the measurement of the ball diameters using a vernier height gage. The results indicate that the FIFA method would fail the Mitre Ultimax ball, whilst it would be passed by the
proposed method. This would have serious cost implications for manufacturers. Figure 3.5 shows the diameter measurements from both the FIFA and CMM methods in box plot form. It is evident from the box plot that the average diameter measurements from each ball type are approximately the same. Unlike the FIFA method that calculates sphericity based on variation in ball diameter, the CMM method calculates sphericity based on a LMS approximation to a sphere. Furthermore, the CMM method is automated, not subject to any human interpretation and provides a more consistent measurement of sphericity.

3.7 CONCLUSION

The sphericity measurement of soccer balls has been investigated in order to develop a more consistent and representative method than that currently employed by FIFA. The LMS method suggested here gives a unique assessment of sphericity, and the errors obtained from the LMS approximation to a sphere are such that the FIFA error specification may need reconsideration. The CMM provides a quick and automated method of sphericity measurement for manufacturers to high orders of repeatability. From the LMS approximation to a sphere results it is evident that balls which have been rejected using FIFA methods may in fact be satisfactory which may have implications for ball manufacturers.
CHAPTER 4

DETERMINATION OF SOCCER BALL PERFORMANCE PARAMETERS

The launch velocity and spin rate imparted to a soccer ball at impact have a significant effect on the ball flight characteristics. In order for players to impart lateral 'swerve' or 'swing' to a ball through the influence of the Magnus Effect, it is essential to obtain a large amount of spin at impact. Of the 171 goals scored during the 1998 World Cup tournament, 42 goals came from set pieces, with 50% coming from free kicks, and 47.6% from corner kicks (Grant et al., 1999). In order to develop dynamic ball performance test criteria and ensure that ball velocities and spin rates are controlled, it is essential to have an appreciation of ball launch values obtainable from elite players. Data gathered from elite players could be used as a benchmark to suggest appropriate limiting standards for ball velocity and spin rate. Furthermore, an evaluation of ball performance parameters is essential in order to perform dynamic tests at velocities and spin rates that are likely to occur in a game situation. This chapter presents a comprehensive study of ball launch velocities and spin rates obtained from professional soccer players.

4.1 MEASUREMENT OF BALL VELOCITY AND SPIN RATE

A number of investigators have reported initial ball velocity after kicking to be in the range of 18 - 34 m/s, typically as part of a biomechanics investigation into the kicking action. However, many of the investigations calculated ball velocity from low speed video captures of amateur or ex-professional subjects, therefore the relevance and accuracy of the results obtained can be questioned. Roberts and Metcalfe (1968) used a combination of professional and amateur subjects and recorded ball velocity values in the range of 23 - 31 m/s. The test subjects were filmed using a camera set at 64 frames per second with a shutter speed of 1/400s. Plagenhoef (1971) filmed one ex-professional test subject with an unspecified camera and measured ball velocities in the range 24 - 28 m/s. The results showed that the greatest foot velocity before impact did not always result in the greatest ball velocity, however other
studies do not confirm this. It was speculated that the rigidity of the foot during impact was equally as important as foot velocity when producing a 'power-kick'.

Togari et al. (1972) examined the relationship between foot velocity and ball velocity and found a high correlation between the two. Asami and Nolte (1983) conducted an analysis of a maximum velocity instep kick using six subjects including four professional players and two amateurs. The maximum ball velocity measured was 34.0 m/s and the average velocity 29.9 m/s. The study reported a significant correlation (0.74) between ball and foot velocities. Two high-speed cameras operating at 500 and 100 frames per second were used to film the kicks, one from the side and one from behind the kicker, respectively. The use of high-speed cameras to determine ball velocity should ensure a relatively high degree of results accuracy. Isokawa and Lees (1988) investigated the effect of approach angle for an instep kick on foot and ball velocities and measured ball velocities in the range 18 - 22 m/s. Six amateur subjects were instructed to strike a stationary ball with a one step kick at different approach angles of 0, 15, 30, 45, 60 and 90°, with 0° representing the direction of ball travel. A camera set at 150 frames per second was used to measure ball velocity. The results showed that leg shank maximum velocity was obtained at 30°, and maximum ball velocity was obtained at 45°. A significant correlation (0.52) was observed between ball and foot velocities for approach angles in the range 0 - 30°. Although ball spin was not taken into account, the results suggested an optimum approach angle of 30 - 45° for maximum ball velocities.

Nunome et al. (2002) performed a kinetic analysis of the side foot and instep soccer kick; identifying significant ball velocity differences between the two kick types. The average ball velocity for a range of side foot kicks was 23.4 m/s, significantly lower than the instep kick average (28.0 m/s). Tsaousidis and Zatsiorsky (1996) used two amateur test subjects to perform a toe kick, reporting ball velocities in the range 24 - 26 m/s. A high-speed camera operating at 4000 frames per second was used in the testing. Asai and Akatsuka (1998) used three amateur players as subjects, and measured average ball velocities in the range 22-27 m/s with an average of 23.38 m/s for an instep swerve kick. A high-speed camera running at 4,500 frames per second was used to measure ball spin rates in the range of 7 - 10 revs/s. A summary of the work carried out by previous investigators is summarised in Table 4.1.
Table 4.1 - Initial ball velocity reported by previous investigators

<table>
<thead>
<tr>
<th>Previous Investigators</th>
<th>Kick Type</th>
<th>Ball Velocity (m/s)</th>
<th>Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roberts and Metcalfe (1968)</td>
<td>Instep</td>
<td>23 - 31</td>
<td>Professionals/Amateurs</td>
</tr>
<tr>
<td>Plagenhoef (1972)</td>
<td>Instep</td>
<td>24 - 28</td>
<td>1 Ex-Professional</td>
</tr>
<tr>
<td>Asami and Nolte (1983)</td>
<td>Power Kick</td>
<td>22 - 34</td>
<td>4 Professionals/2 Amateurs</td>
</tr>
<tr>
<td>Isokawa and Lees (1988)</td>
<td>Instep</td>
<td>18 - 22</td>
<td>Amateurs</td>
</tr>
<tr>
<td>Tsaousidis and Zatsiorsky (1996)</td>
<td>Toe Kick</td>
<td>24 - 26</td>
<td>2 Amateurs</td>
</tr>
</tbody>
</table>

There is relatively little published data on soccer ball performance parameters and all relevant studies have used a small number of players as test subjects. The studies have utilised either a small number of amateur or professional players or a combination of both. Only one of the previous studies measured spin rate as well as velocity and this was obtained using three amateur players. For kicking data to have credibility a more comprehensive study was required using elite players. Because of commercial and playing commitments it was not possible to test the leading players in the sport. However, the players tested are considered to represent state of the art performance.

4.2 PARTICIPANTS

Twenty-five young professional soccer players were used for the study. The subjects were drawn from five different senior English football clubs: Aston Villa FC, Everton FC, Hull City FC, Leicester City FC and Norwich City FC. The subjects consisted of 14 right-footed and 11 left-footed players and included 2 full internationals and five U-21 internationals. The subjects all wore their own boots, consisting of designs from five different major boot manufacturers. An overview of subject age, weight, height and shoe size details are outlined in Table 4.2. Full details on individual subject characteristics can be found in Appendix 8.
<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.68</td>
<td>2.17</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>76.04</td>
<td>7.78</td>
</tr>
<tr>
<td>Body Height (m)</td>
<td>1.81</td>
<td>0.06</td>
</tr>
<tr>
<td>Foot Size (UK size)</td>
<td>8.02</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 4.2 - Subject data (n=25)

4.3 TESTING PROCEDURE
The subjects were instructed to perform three different types of free kick on a stationary ball from a position approximately 20m from goal. Firstly the subjects were requested to perform a full power kick in order to transmit maximum velocity to the ball. Secondly the subjects were requested to perform an instep swerve kick and impart maximum spin to the ball. Thirdly the subjects were requested to perform an outstep swerve kick and impart maximum spin to the ball. The subjects were each required to take five good kicks of each type, giving a total of 15 kicks per subject (Neilson and Jones, 2003b).

Testing was conducted at the training grounds of each of the respective five clubs. All the tests were carried out on artificial surfaces, three of which were indoors and two outdoors. A range of seven white unbranded 'FIFA Approved' standard soccer balls were utilised during the testing. The balls were inflated to a pressure of 86 kPa (12.5 psi), the exact mid-point of the FIFA stipulated pressure range. The use of unmarked balls negated any player brand bias and also enabled the addition of circumferential markings to the balls. Two black circumferential lines were added to each of the balls at 90 degrees to each other. These markings enabled the accurate determination of ball spin during the digitising process. The unbranded test balls are illustrated in Figure 4.1.
4.4 EQUIPMENT

A NAC 500 colour high-speed camera operating at 500 frames per second (2 ms/frame) was used to capture the initial ball trajectory after impact. The shutter speed was set to 1/1000s in order to improve image clarity and the resolution was set at 640 x 480 pixels. The camera was positioned ‘side-on’ perpendicular to the initial ball trajectory, approximately 2m from the impact point. The indoor testing carried out at two clubs required additional floodlighting to be used in order to attain good quality images. Two high intensity floodlights were positioned either side of the camera, as illustrated in Figure 4.2.
During testing the high-speed video captures were recorded directly onto standard video home format (VHS) videocassettes using a video recorder linked up to the NAC system. This video footage was later converted into digital format using MGI VideoWave 4 video capturing software. In order to compute ball velocities, elevation and spin rates for each capture, two ball images were required for comparison. Corel Photopaint software was used to identify and extract two suitable frames from within each video capture and the time interval between each pair of images was noted. The position of the camera was fixed throughout each capture; therefore it was possible to combine two frames to form one composite image containing two ball images. Typically the time interval between frames was around 30 ms. The process is illustrated in Figure 4.3.
Figure 4.3 - Creation of composite image for digitising

4.5 FLIGHTPATH TRAJECTORY ANALYSIS SOFTWARE

The composite ball images were digitised and analysed for position using Flightpath software which had originally been developed for the measurement of golf ball launch conditions. In order to use the software to obtain measurements for ball velocity, and elevation the system must first be calibrated. The first ball image was used as a reference environment, with the top, bottom, left and right boundaries of the ball manually identified by the user. This process effectively used the known ball diameter to calibrate the image pixel environment. The time interval between each image was also set during the calibration procedure.
Once calibrated, the positions of the two balls within the image were digitised by marking an enclosing square around each ball. The software then fitted a circle to the inside of each square, allowing the ball centre positions to be calculated. Once the position of each ball had been identified, a trajectory line passing through the centre of each ball was produced. Ball velocity and elevation were then calculated based on the time interval and distance between ball positions.

As the ball trajectory captures were obtained from a camera positioned ‘side on’ to the impact, Flightpath was used to measure ball backspin. In order to achieve this the spin plane of each ball was identified. This was achieved by manually digitising the centre of each ball and creating a floating projected line that was then aligned with the ball circumferential markings. Ball rotation was then calculated based on the difference in angular orientation between each floating projected line. A typical Flightpath analysis of an initial ball trajectory is illustrated in Figure 4.4.

![Figure 4.4 - Flightpath analysis software](image)

Although the Flightpath system was capable of measuring topspin or backspin, the software was not capable of measuring 3D spin. Traditionally ball spin has been specified in 3 components; backspin, sidespin and rifle spin (Gobush et al., 1994). In some ball sports such as golf the spin component is primarily backspin, but in dynamic games an oblique spin axis is generally created. The instep and outstep swerve kicks were found to produce an
oblique spin axis when viewed from the side. In this instance the spin measurement has been estimated by evaluating the number of frames for a quarter ball rotation. The values reported are spin around the oblique axis, but the axis orientation is not defined.

The accuracy of the Flightpath software was calculated using a calibration standard containing an image of three balls with known velocity, elevation and spin rate (Cottee, 2002). The calibration standard gave accuracy values of +/- 0.02 m/s, +/- 0.05° and +/- 0.07 revs/s with repeated digitising. For a typical captured image of a soccer ball in flight the repeatability was found to be +/- 0.1 m/s, +/- 0.3° and +/- 0.4 revs/s with repeated digitising.

4.6 RESULTS

The mean, standard deviation and range of the ball velocity results obtained from the high-speed video footage are summarised in Table 4.3.

<table>
<thead>
<tr>
<th>Kick Type</th>
<th>Mean</th>
<th>SD</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Power</td>
<td>27.05</td>
<td>2.23</td>
<td>33.10</td>
<td>20.72</td>
</tr>
<tr>
<td>Instep Swerve</td>
<td>23.52</td>
<td>2.31</td>
<td>28.91</td>
<td>18.06</td>
</tr>
<tr>
<td>Outstep Swerve</td>
<td>20.85</td>
<td>3.08</td>
<td>27.70</td>
<td>13.50</td>
</tr>
</tbody>
</table>

Table 4.3 - Ball launch velocity data

The results show significant differences in launch velocity between kick types. The full power kick produced the highest velocities of the three kick types, with a mean velocity of 27.05 m/s and a range of 20.72 to 33.10 m/s. The full power kick produced a maximum-recorded velocity of 33.10 m/s and this was slightly less than the maximum value of 34.0 m/s recorded by Asami and Nolte (1983). The range of values recorded for the full power kick is supported by the data taken by Roberts and Metcalfe (1968), who recorded ball velocity values in the range 23 - 30 m/s. However, the maximum recorded velocity of 33.10 m/s observed in this study is significantly higher than that of Roberts and Metcalfe (30 m/s). This could be due to the use of professional players however, the significant developments in camera technology and ball and boot manufacture since 1968 should also be taken into account. Furthermore, as with all sports, player development has been significant, particularly with the advent of television exposure and the associated rewards for success.
The instep swerve kick velocities recorded were generally higher than those for the outstep swerve kick. The mean velocity for the instep swerve kick was 23.52 m/s, compared to a mean velocity of 20.85 m/s recorded for the outstep swerve kick. The mean value of 23.52 m/s recorded for the instep swerve kick compares favourably with Asai and Akatsuka (1998) who measured an average ball velocity for an instep kick of 23.28 m/s. The range of velocity values observed were higher than those of 18 to 20 m/s recorded by Isokawa and Lees (1988), which may have been due to the use of professional players rather than amateurs.

The mean, standard deviation and range of the ball spin rate results obtained from the high-speed video footage are summarised in Table 4.4. The mean spin rate values calculated for the instep and outstep swerve kicks were similar, 7.91 revs/s for the instep swerve kick and 7.87 revs/s for the outstep swerve kick. However, it is evident that there is considerable variation in spin rate values which indicates the difficulty of performing spin kicks. There was a slightly larger range of spin values recorded for the outstep kick; from 13.89 revs/s down to 2.60 revs/s, indicating that consistency of performance for the outstep serve kick is difficult to achieve.

<table>
<thead>
<tr>
<th>Kick Type</th>
<th>Mean</th>
<th>SD</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instep Swerve</td>
<td>7.91</td>
<td>2.27</td>
<td>13.89</td>
<td>2.92</td>
</tr>
<tr>
<td>Outstep Swerve</td>
<td>7.87</td>
<td>2.46</td>
<td>13.89</td>
<td>2.60</td>
</tr>
</tbody>
</table>

Table 4.4 - Ball spin rate data

Figure 4.5 shows the ball launch velocity for the three different kick types. Figure 4.6 shows the variation in ball spin rate for instep and outstep swerve kicks.
Boxplots of Ball Velocity by Kick Type

(means are indicated by solid circles)

Figure 4.5 - Box plot of ball velocity data

Boxplots of Ball Sidespin by Kick Type

(means are indicated by solid circles)

Figure 4.6 - Box plot of ball spin rate data
4.7 STATISTICAL ANALYSIS OF TEST SUBJECT DATA

Prior to the commencement of testing the subjects were asked to fill out a short questionnaire designed to outline their individual characteristics. Subjects were required to state their name, age, height, weight, playing position, shoe size and preferred foot. A copy of the questionnaire is contained in Appendix 7 and a table detailing the subject characteristics is contained in Appendix 8. The subject data was analysed to determine if correlations existed with ball velocity and spin rate data for the three kick types.

The correlation between player characteristics and ball velocity and spin rates were investigated using multiple regression analysis. The player characteristic data was set as the independent variables and the ball performance parameters (velocity and spin rate) set as dependent variables. The independent variables were removed from the model one at a time, if they did not contribute significantly to the regression.

4.7.1 BALL VELOCITY ANALYSIS

The factors identified from the multiple regression analysis as significantly affecting velocity data are shown in Table 4.5.

<table>
<thead>
<tr>
<th>Kick Type</th>
<th>Characteristic</th>
<th>R²%</th>
<th>S.E.E.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Power</td>
<td>Age</td>
<td>21.6332</td>
<td>1.70891</td>
<td>0.0191</td>
</tr>
<tr>
<td>Instep Swerve</td>
<td>Height</td>
<td>20.1582</td>
<td>1.72253</td>
<td>0.0244</td>
</tr>
<tr>
<td>Outstep Swerve</td>
<td>Age</td>
<td>12.037</td>
<td>2.65698</td>
<td>0.0893</td>
</tr>
</tbody>
</table>

Table 4.5 - Average ball velocity multiple regression analysis

For the full power kick only one of the subject characteristics (age) can be classed as a significant predictor of average ball velocity at the 95% confidence level. The multiple regression formula, at the 95% confidence level is:

\[
\text{Ball Velocity (m/s)} = 18.9851 + 0.404291 \times \text{Age}
\]

Age accounts for 21.63% of the variability in the multiple regression analysis. A positive correlation coefficient of 0.465116 shows that the variables vary in the same direction. The model suggests that average ball velocity for the full power kick increases with subject age. However, the oldest subject tested was 25 years old, and clearly, if older players had been used this may have changed matters.
For the instep swerve kick only one of the subject characteristics (height) can be classed as a significant predictor of average ball velocity at the 95% confidence level. The multiple regression formula, at the 95% confidence level is:

\[
\text{Ball Velocity (m/s) } = -2.80606 + 14.4899 \times \text{Height}
\]

Height accounts for 20.16% of the variability in the multiple regression analysis. A positive correlation coefficient of 0.448979 shows that the variables vary in the same direction. The model suggests that average ball velocity for the instep swerve kick increases with subject height. Within reason this might be expected since limb levers are longer in taller players.

For the outstep swerve kick, none of the subject characteristics can be classed as a significant predictor of average ball velocity at the 95% confidence level. However, Table 4.5 shows that one of the subject characteristics (age) is significant at the 90% confidence level. The multiple regression formula, at the 90% confidence level is:

\[
\text{Ball Velocity (m/s) } = 11.8459 + 0.442567 \times \text{Age}
\]

Age accounts for 12.03% of the variability in the multiple regression analysis. A positive correlation coefficient of 0.346944 shows that the variables vary in the same direction. The model suggests that average ball velocity for the outstep swerve kick increases with subject age.

4.7.2 BALL SPIN RATE ANALYSIS

The analysis of the average ball spin rate data using multiple regressions is shown in Table 4.6.

<table>
<thead>
<tr>
<th>Kick Type</th>
<th>Characteristic</th>
<th>R²%</th>
<th>S.E.E.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instep Swerve</td>
<td>No correlation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outstep Swerve</td>
<td>Age and Height</td>
<td>22.7368</td>
<td>1.93781</td>
<td>0.0586</td>
</tr>
</tbody>
</table>

Table 4.6 - Average ball spin rate multiple regression analysis

For the instep swerve kick, none of the subject characteristics can be classed as a significant predictor of average ball spin rate at the 95% or 90% confidence level.
For the outstep swerve kick, two of the subject characteristics considered together (age and height) can be used as a significant predictor of average ball spin rate at the 90% confidence level. The multiple regression formula, at the 90% confidence level is:

\[
\text{Ball Spin Rate (revs/s)} = (-17.0203) - (0.354104 \times \text{Age}) + (17.6014 \times \text{Height})
\]

Age and height account for 22.74% of the variability in the multiple regression analysis. A positive correlation coefficient of 0.340543 suggests that average ball spin rate increases with subject height. A negative coefficient of -0.168094 suggests that average ball spin rate decreases with subject age.

The multiple regression analysis showed that player age and height were the most significant characteristics affecting ball dynamic performance. The R² values calculated for full power and instep swerve kick ball velocities were around 20%, indicating relatively good correlation for a single characteristic. Older, more experienced players appear to be able to achieve higher ball velocities for a full power kick, possibly as a result of a more developed technique. Taller players appear to be able to impart more velocity to the ball for an instep swerve kick, possibly due to the presence of longer limbs in the leg.

The R² value calculated for the outstep swerve kick ball velocities (12.04%) suggests a weaker correlation with age, although more data could possibly provide significance at the 95% confidence level. The ball spin model developed from the outstep swerve kick data suggests that age and height are related to ball spin, with a positive correlation coefficient for height and a negative correlation coefficient for age. The R² value is relatively weak (22.74) taking into account the presence of 2 characteristics within the model. Further testing would need to be undertaken across a wider age range to establish if there were any significant differences.

The formulae obtained through the multiple regression analysis could be used to predict ball launch velocity, however it is important to be aware of the limitations. The age range of the 25 subjects was relatively small (17 - 25), and no results were obtained from older more experienced professional players. For a more comprehensive evaluation a significantly larger group of test subjects ranging in age from 17 - 33 should be considered.

4.8 DISCUSSION

The full power kick produced the highest velocities of the three kick types, with a mean velocity of 27.05 m/s and a range of 20.72 to 33.10 m/s. The maximum velocities obtained for both instep and outstep swerve kicks were similar (28.91 and 27.70 m/s for the instep
and outstep kick respectively), however the lowest ball velocity values recorded for each kick type were significantly different. The lowest ball velocity recorded for the instep kick was 18.06 m/s, whereas the lowest velocity recorded for the outstep kick was 13.50 m/s, a difference of 4.56 m/s. This data suggests that players are capable of obtaining higher ball velocities using the instep of the foot. It can also be seen that the variation in results for the outstep kick is considerably larger. It is generally accepted that the outstep kick is a more difficult technique to perform and an analysis of the goals scored in the 1998 World Cup shows that the most frequent kicking techniques used to score goals were kicks performed using the inside and instep of the foot. The instep kick was used for almost half of the 108 goals scored from open play during the tournament (Grant et al., 1999).

The spin rate data obtained from both the instep and outstep kicks show that the mean, range and standard deviation for each set of results are similar. Considering the ball velocity and spin rate data together, the data suggests that players are equally adapt at producing high spin rates with either the instep or outstep of the foot. However, the outstep swerve kicks show more variability indicating a lack of control. This perhaps supports the reason why this kick is not so popular for free kick situations.

The maximum spin rate values recorded for both the instep and outstep swerve kicks was the same, 13.89 revs/s. It is of interest that the players who achieved the two highest spin rates were both goalkeepers. Goalkeepers were also responsible for some of the top velocities measured for the power kick, which is not as surprising taking into account the importance and regularity of goal kicking for goalkeepers. When comparing the measured ball velocity and spin rate data with those of earlier studies carried out using amateur players it is evident that professional players achieve higher ball velocities and maximum spin rates are significantly higher.

4.9 CONCLUSION

The data presented here provides a thorough study into soccer ball launch velocities and spin rates that could be used to set appropriate dynamic standards for soccer balls to ensure ball performance consistency and limiting conditions. The data presented generally concurs with the work from previous investigators, suggesting that initial ball velocity for a range of typical kicks is in the range 14 - 33 m/s, dependent on kick type. Spin rates obtained by professional players using the instep and outstep are more inconsistent with maximum values of 13.89 revs/s, although typically in the range 6 - 10 revs/s. The study has produced accurate data showing that professional players are capable of imparting initial velocities of

73
up to 33 m/s and spin rates of up to 14 revs/s to a soccer ball. It has been shown that professional players are capable of obtaining similar spin rates using both the instep and outstep of the foot. However, ball velocity for the outstep swerve kick is generally lower. Comparing the data with previous studies, it is evident that the use of professional players is a necessity for an accurate representation of ball performance at the highest level.

Ball velocity and spin rate tests would be essential elements of a dynamic ball testing program as these factors are a key determinant of ball performance. Ball velocity and spin rate limits could be specified based on the results from further controlled tests encompassing player perception, anticipation, control and safety factors. However, based on the ball performance results obtained in this study, it is suggested that initial ball velocity and spin rate for highest quality balls in a controlled test should not exceed 31.5 m/s (70 mph), and 12.5 revs/s (750 rpm).
CHAPTER 5

MEASUREMENT OF OUT OF BALANCE FORCES IN SOCCER BALLS

Although sports balls are designed and expected to behave consistently, variations in mass distribution can occur because of material and manufacturing variability. Mass distribution is an important property for any projectile, as uneven mass distribution will result in out of balance forces acting on the ball and subsequent inconsistent performance. However, mass distribution within sports balls is generally not specified as part of the test criteria. This chapter reports a method of accurately assessing the position and magnitude of unbalance forces present within soccer balls.

5.1 THE PRESENCE OF UNBALANCE IN SOCCER BALLS

The existing FIFA outdoor soccer ball test criteria outlined in Section 1.2 does not provide an assessment of ball unbalance. Unbalance forces within soccer balls are caused by an unequal distribution of mass within the ball and the rate at which the ball spins. The variation in mass distribution is usually a by-product of inconsistencies emanating from the ball manufacturing process. Variations in panel thickness, uneven seam tension and the position and weight of the valve can all contribute to uneven mass distribution. On January 1st 2000 FIFA introduced a series of tests for indoor soccer balls, including a ball unbalance test. To test for the presence of unbalance a ball is rolled down an inclined slope onto a table with a predetermined rolling direction. Any significant unbalance within the ball will result in an irregular roll path. However, this technique is an extremely crude method of measurement, it does not provide an accurate estimate of the unbalance force magnitude and the irregular roll path may be a result of poor sphericity rather than ball unbalance.

5.2 UNBALANCE THEORY

There are numerous industrial applications of balancing machines used to dynamically balance shafts, wheels and other rotationally symmetrical components. Unbalance is assessed by measuring the vibration generated by rotating components and converting this signal into a measurable figure. Schneider (1991) states that the balancing of rotating parts can lead to
increased life, improved performance, and provide additional sales advantage through vibration free operation. There are two types of balancing operations, static balancing and dynamic balancing.

5.2.1 Static Unbalance

Static unbalance occurs when the unbalanced masses all lie in a single plane, the resultant unbalance is then a single radial force. Static unbalance in a circular disc-axle assembly can be detected in a simple test as illustrated in Figure 5.1. The assembly is placed on a pair of horizontal rails and allowed to freely roll, until it comes to rest with the unbalance point located directly below the axle (Wilcox, 1967).

![Figure 5.1 - System with static unbalance](image)

5.2.2 Dynamic Unbalance

Dynamic unbalance results from the centrifugal forces created when an object is rotated, this is further complicated when the unbalanced masses appear in more than one plane, producing a resultant unbalance force and a rocking moment. A simple static test as shown in Figure 5.1 could detect the resultant force, however the rocking moment cannot be detected without rotating the assembly. Figure 5.2 shows an axle and two circular disks with equal unbalanced masses 180° apart. Although the assembly is statically balanced about the axle, rotation of the axle will result in the discs generating a rotating centrifugal force, subsequently rocking the axle on its bearings.
Balancing machines are used to rotate components and measure unbalance forces. Essentially balancing machines consist of a series of spring mounted support bearings with sensors that detect the presence of unbalance forces by their motion. By measuring the amplitude of each bearing and their relative phase, it is possible to determine the unbalance of the component and if necessary apply corrections (Thompson, 1993). In industry there are typically two types of machines that carry out the measurement of unbalance. Horizontal balancing machines are used for long components such as rotors and spindles and vertical balancing machines are used for squat rotationally symmetric components. Vertical balancing machines generally utilise a standard spindle interface that interconnects with the component to be balanced. BS 2953:1999 outlines the relevant standards for balancing machines and associated instrumentation.

5.2.3 UNBALANCE MODEL

The presence of out of balance forces in soccer balls can be due to a number of contributing factors, usually inconsistencies from the manufacturing process as discussed in Section 5.1, however the valve unit can also be a significant factor. Assuming that each of these factors can produce a separate unbalanced mass, the overall ball unbalance will be an effective summation of the individual unbalanced masses. The overall ball unbalance can therefore be considered as a single unbalanced mass, \( u_w \), acting at a point on the ball periphery a radial distance \( r \) from the ball center, in a soccer ball of total mass \( m_b \) (Price et al., 2003). This model is shown in Figure 5.3.
A single unbalanced mass, $u_m$, acting at the peripheral radial distance $r$ within a soccer ball of total mass $m_b$.

Figure 5.3 - Representation of unbalance in soccer balls

5.3 SOCCER BALL UNBALANCE MEASUREMENT

The spherical nature of a soccer ball dictates that a vertical balancing machine is more suitable than a horizontal balancing machine for dynamic unbalance measurement. BTD, a Birmingham based balance machine company, granted access to a vertical balancing machine suitable for experimental work. A schematic diagram of the machine is shown in Figure 5.4. The machine utilises a digital rotary optical encoder mounted onto a spindle working in conjunction with a light source and photocell arrangement. This allows both rotational velocity control and the determination of the angular orientation of the unbalance. Furthermore an accelerometer connected to the spindle is used to convert mechanical vibrations caused by the presence of unbalance into electrical signals, which allows the magnitude of the unbalance force to be estimated. The machine operates under computer control and the orientation and magnitude of the unbalanced mass is given.
5.3.1 VERTICAL BALANCING MACHINE

In order to measure unbalance the component to be measured is loaded onto the spindle interface and appropriately restrained to prevent lateral movement. The machine drive unit (MDU) brings the component up to the required rotational speed, and maintains this speed. The accelerometer vibration pick-up arrangement produces a voltage signal relating to mechanical vibration amplitude. This vibration response takes the form of a sinusoidal wave with the peak amplitude proportional to the acceleration of vibration. The vibrational signal then undergoes two stages of conditioning. In the first stage, the signal voltage is converted from an acceleration proportional voltage to an amplitude proportional voltage using an integrated circuit. In the second stage, demodulation is carried out using a band pass filter in order to improve the signal clarity. Finally, the signal is amplified to allow for analysis and results generation.

Simultaneously, the photosensitive probe generates a square wave for each full revolution of the component. This is the most effective wave form to allow analytical comparison with the vibration sine wave. The interfacing computer analyses the peak amplitude of the vibration response and subsequently generates a magnitude of unbalance based on a non-dimensional equation relating to the amplitude of vibration. The interfacing computer then compares the trailing edge of the square wave pulse signal with the peak of
the sinusoidal vibration response wave in order to calculate the angular orientation of the unbalanced force. This process is shown in Figure 5.5.

![Vibration signal after demodulation and amplification. (Generated from accelerometer)](image1)

![Square wave pulse signal. (Generated from photosensitive probe)](image2)

Figure 5.5 - Comparison of square wave pulse and vibration response peaks in order to generate unbalance angular orientation

5.3.2 BALL FIXTURE

In order to assess unbalance within soccer balls it was necessary to prevent the test balls from moving whilst they were rotated. A special fixture was manufactured to fit onto the standard spindle interface on the vertical balancing machine and secure the test balls in position. It was essential that the fixture was rigid as any vibration within the fixture could seriously distort the unbalance results. The fixture was manufactured from 10mm aluminium plate material. The premise for the design was that balls would be loaded into the fixture in a slightly deflated state, and then inflated whilst within the constraints of the fixture. A four pronged frame secured to a retaining ring held the ball securely once inflated and the base of the fixture was designed to mate with the spindle interface via two 35mm screws. Although an adjustable fixture capable of accommodating balls of different diameters would have been preferable, the need for rigidity deemed that a size appropriate for most balls was the most suitable design in the first instance. The fixture had to be suitable for soccer balls ranging from 680 - 700mm in circumference (diameter range 218 - 221.2mm). Therefore, the inner surface of the restraining ring was tapered to prevent the balls from slipping out whilst the fixture was being rotated. The inner diameter of the top of the retaining ring was set at 214mm and the inner diameter of the bottom 217mm. A diagram of the fixture design is shown in Figure 5.6.
The selection of the inner diameter of the retaining ring and the presence of the four-pronged frame resulted in the balls experiencing a certain amount of deformation whilst held in the fixture. Once in position inside the fixture the balls were inflated until any movement was sufficiently constrained by the fixture. Although ideally the balls would not be subject to any deformation, it was deemed more essential that the balls were held securely whilst the fixture was rotated.

5.3.3 Fixture Calibration

Prior to the start of testing it was necessary to calibrate the fixture, as shown in Figure 5.7. The fixture was secured to the spindle interface and a slightly deflated soccer ball was positioned within the fixture in an arbitrary orientation. The ball was then inflated within the constraints of the fixture and the machine drive unit switched on bringing the spindle to a rotational velocity of 6.67 revs/s (400 rpm). A rotational velocity of 6.67 revs/s was selected to simulate a common spin rate likely to occur during a game, based on the data gathered from elite soccer players in Chapter 4. After a few seconds the machine registered a value for unbalance as a summation of the fixture and the ball, which was then logged within the computer interface system. The ball was then taken out of the fixture, rotated through 180°, then reinserted into the fixture and another measurement of unbalance recorded. Although the ball orientation within the fixture changed by 180°, the orientation of the fixture remained constant in both cases. The system recognised the change in orientation of the ball, enabling the calculation of the unbalance force present within the fixture. This value could then be used to correct subsequent ball unbalance measurements. A diagram of the calibration process is shown in Figure 5.8.
Figure 5.7 - Fixture calibration on BTD vertical balancing machine

$u_m$ is the unbalance within the ball, $u_f$ is the unbalance within the fixture. $R_1$ is the resultant unbalance.

When the ball is rotated 180°, the unbalance within the ball ($u_m$) is also rotated 180°. The unbalance within the fixture ($u_f$) remains the same. $R_2$ is the resultant unbalance.

Unbalance within the fixture ($u_f$) equals the resultant of $R_1$ and $R_2$. This correction value can then be applied to subsequent results to provide an accurate measurement of ball unbalance.

Figure 5.8 - Diagram of calibration process
5.4 TESTING METHODOLOGY

Once the machine had been calibrated the magnitude and angular position of out of balance masses within soccer balls could be calculated. Test balls were positioned in the fixture in an arbitrary orientation and the magnitude and angular position of unbalance calculated. The interfacing computer displayed the angular orientation of the unbalance on a screen, therefore by ‘shuffling’ the ball within the fixture and employing ‘trial and error reduction’ techniques it was possible to reposition the ball step by step until the unbalance mass acted at the top. When the unbalance mass was positioned at the top of the ball the unbalance magnitude was zero and the point of unbalance on the ball surface was marked using a permanent marker. With the position of unbalance identified, the ball was rotated 90 degrees so that the unbalance mass acted at a point on the ball equator; the unbalance magnitude is always a maximum when positioned on the ball equator. The machine was activated and the unbalance magnitude and angular orientation measured. If necessary this approach can be simplified by using a simple ball flotation method, where by the unbalanced mass will move to the bottom dead centre and can be easily identified, however this method is not as accurate as using the vertical balancing machine.

5.5 SYSTEM EVALUATION

In order to evaluate the accuracy and consistency of the measurement system, a number of tests were carried out. In total four different tests were performed, and each test is described in turn in the following sections (5.5.1, 5.5.2, 5.5.3 and 5.5.4).

5.5.1 THE EFFECT OF BALL ORIENTATION ON UNBALANCE MEASUREMENT

The effect of ball orientation within the fixture on unbalance measurement was assessed. A single adidas Fevernova test ball was used for the study and the point of unbalance determined using the ‘trial and error’ technique described in Section 5.4. The retaining ring of the fixture was marked at 90° intervals, giving 4 ball location settings of 0, 90, 180 and 270°. The ball was orientated within the fixture with the point of unbalance located on the ball equator so that the angle with the vertical z-axis was 90°. The point of unbalance was then lined up with the 0° position on the retaining ring. The ball was inflated to a pressure of 55 kPa (8.0 psi) and the unbalanced mass determined. Measurements were taken 4 times, with the ball completely removed from the fixture and replaced in the same position between each measurement. After 4 measurements had been obtained the ball was moved 90° and the measurement process repeated. Further measurements were then obtained at 180° and 270°.
Upon completion of these sets of measurements around the equator, further measurements were then obtained with the point of unbalance positioned below the equator at an angle of 45° with the z-axis. The point of unbalance was set to line up with the 0, 90, 180 and 270° markings on the retaining ring used previously. This procedure was then repeated with the point of unbalance positioned above the equator at an angle of 135° with the z-axis. Figure 5.9 shows the angular measurement positions for the unbalanced mass. Taking into account that the unbalance magnitude will be zero when the point of unbalance is at the top and bottom, these measurements provided a comprehensive, 360° representation of unbalance around a soccer ball.

5.5.1.1 Results

The unbalance measurements obtained from moving the unbalanced mass around the fixture are summarised in Table 5.1. The values reported are the average readings taken from 4 measurements.
Table 5.1 - Effect of unbalanced mass location on unbalance measurement

Table 5.1 shows the unbalance results for the range of different unbalanced mass positions within the fixture.

Ball Orientation vs Unbalance

(means are indicated by solid circles)

Figure 5.10 - Boxplot of ball unbalance by ball orientation

Although the data is limited the unbalance measurements shown in Figure 5.10 show a close relationship between the results and the Sine function. The results confirm that unbalance measurement is a maximum when the point of unbalance is positioned on the equator, at 90° to the z-axis. Similarly Sine 0 is a maximum when θ=90°, reducing to zero at
0=0 and 0=180. The magnitude of the unbalanced mass is directly proportional to the amplitude of the sine wave vibration signal generated by the accelerometer as detailed in Section 5.3.1. Therefore, the effect of the position of unbalance on the measured unbalance magnitude could be predicted by a simple model containing the sine function.

If the unbalance measurement at the equator is calculated, the following model could be used to predict unbalance measurement when the point of unbalance is positioned at different angles to the z-axis.

Unbalance @ 0 to the z-axis = Sin 0 x Unbalance @ 90° to the z-axis

Figure 5.11 illustrates the relationship between the model given in Equation 5.2, and the experimental data gathered using the vertical balancing machine.

Figure 5.11 - Prediction of unbalance magnitude for a range of ball orientations

As might be expected, the results show that the measuring method is most sensitive when the point of unbalance is positioned at 90° to the axis of rotation. Thereafter all tests on ball unbalance assessment were undertaken with the point of unbalance in this position.

5.5.2 THE EFFECT OF BALL PRESSURE ON UNBALANCE MEASUREMENT

The effect of ball pressure on unbalance measurement was also assessed, since ball size variations and fixture limitations necessitated that test balls are inflated to different pressures. Two test balls were used and the respective points of unbalance determined as described in Section 5.4. The two test balls were an adidas Finale ball and a Puma Shudoh ball. Each ball was inserted into the fixture and inflated to a pressure of 38 kPa (5.5 psi). The point of
unbalance was positioned on the equator and 4 measurements taken at the 0, 90, 180 and 270° points on the retaining ring. After each measurement the balls were taken out of the fixture and repositioned. Each ball was then inflated to subsequent pressures of 59 kPa (8.5 psi) and 79 kPa (11.5 psi) and the measurement process repeated. Although, ideally measurements would have been taken across the FIFA stipulated pressure range of 69 - 103 kPa (10 - 15 psi), the limitations with fixture size discussed in Section 5.3.2, prevented the balls from being fully inflated.

5.5.2.1 Results

The unbalance results for a range of inflation pressures are summarised in Table 5.2. The values reported are average values taken from 4 measurements.

<table>
<thead>
<tr>
<th>Ball Pressure (kPa)</th>
<th>38</th>
<th>59</th>
<th>79</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Finale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. Mass (g)</td>
<td>9.50</td>
<td>9.46</td>
<td>9.34</td>
</tr>
<tr>
<td>SD</td>
<td>0.38</td>
<td>0.23</td>
<td>0.47</td>
</tr>
<tr>
<td>Puma Shudoh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. Mass (g)</td>
<td>9.56</td>
<td>9.57</td>
<td>9.46</td>
</tr>
<tr>
<td>SD</td>
<td>0.26</td>
<td>0.34</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 5.2 - Effect of ball inflation pressure on unbalance measurement

The results show that ball pressure has little effect on unbalance measurement, although the results suggest that unbalance is reduced slightly at higher ball pressures. Unbalance measurements for both test balls were similar at ball pressures of 38 and 59 kPa, yet dropped slightly by 0.1 g at the higher pressure of 79 kPa. Figure 5.12 and Figure 5.13 show the unbalance results for the two balls in box plot form. The average unbalance values calculated for the adidas Finale had a range of 0.16 over the three ball pressures. The average unbalance values calculated for the Puma Shudoh had a smaller range of 0.11.
Figure 5.12 - Box plot of ball unbalance for the adidas Finale at a range of inflation pressures

Figure 5.13 - Box plot of ball unbalance for the Puma Shudoh at a range of inflation pressures
From these results it can be concluded that ball pressure does not affect ball unbalance measurements significantly. Although, ideally all balls should be measured at the same inflation pressure, the limitations with the current fixture design prevent this. The results show that the fixture limitations do not have an adverse effect on measurement accuracy.

5.5.3 THE EFFECT OF SPINDLE SPEED ON UNBALANCE MEASUREMENT

The rotational speed of the spindle had been set at a constant speed of 6.67 revs/s (400 rpm) throughout all previous testing. In order to establish if ball unbalance measurement was affected by the rotational speed of the spindle, a set of unbalance measurements were taken at a range of different spindle speeds. Four Puma Shudoh soccer balls were tested and inflated to a pressure of 55 kPa (8.0 psi), unbalance measurements were then obtained for spindle speeds ranging from 5 - 13.33 revs/s (300 - 800 rpm). The maximum rotational velocity was set at 13.33 revs/s, in order to allow comparison with the maximum spin rate of 13.89 revs/s recorded during player testing and discussed in Chapter 4.

5.5.3.1 Results

The unbalance results for a range of spindle speeds are shown in Table 5.3.

<table>
<thead>
<tr>
<th>Spindle Speed (rpm)</th>
<th>Av. Mass (g)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Puma Shudoh 1</td>
<td>6.28</td>
<td>5.88</td>
</tr>
<tr>
<td>Puma Shudoh 2</td>
<td>8.91</td>
<td>9.66</td>
</tr>
<tr>
<td>Puma Shudoh 3</td>
<td>5.79</td>
<td>5.16</td>
</tr>
<tr>
<td>Puma Shudoh 4</td>
<td>9.05</td>
<td>10.56</td>
</tr>
</tbody>
</table>

Table 5.3 - Effect of spindle speed on unbalance measurement

Figure 5.14 shows the unbalance measurements for each ball in graphical form.
Unbalance measurements recorded for balls 1 and 3 reduced almost linearly as spindle speed increased. However, unbalance measurements recorded for balls 2 and 4 over the same speed range were considerably more erratic. The unbalanced masses present within balls 1 and 3 were relatively small, 5.88 and 5.16 g respectively, when measured at 6.67 revs/s. However, the unbalanced mass present within balls 2 and 4 was considerably higher, 9.66 and 10.56 g respectively, when measured at the same speed of 6.67 revs/s. This suggests that unbalance measurement across a rotational velocity range is more inconsistent for balls exhibiting larger unbalance magnitudes.

5.5.4 THE EFFECT OF ADDITIONAL MASSES ON UNBALANCE MEASUREMENT

In order to assess the accuracy of the measurement system additional weights of known mass were added to the point of unbalance on a test ball. A single adidas Finale was employed as the test ball and the point of unbalance identified using the techniques described in Section 5.4. The ball was inserted into the fixture and inflated to a pressure of 55 kPa (8.0 psi), and the point of unbalance was positioned on the equator at 90° to the axis of rotation. 4 measurements were taken at the 0, 90, 180 and 270° points on the retaining ring, and after each measurement the ball was taken out of the fixture and repositioned.

An additional mass was added to the ball in the form of a small metal washer, attached to the surface of the ball at the point of unbalance using double-sided adhesive tape (total mass 5.5 g) and the above procedure repeated. The process was repeated a second time but with a second larger washer (total mass 10.8 g), replacing the smaller variant.
5.5.4.1 Results

The unbalance measurements obtained for the test ball with additional masses added are shown in Table 5.4.

<table>
<thead>
<tr>
<th>Angular Position (deg)</th>
<th>Av. Mass (g)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>270</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 - Effect of external additional masses on unbalance measurement

The unbalance measurement for the adidas Finale ball in its normal state was 7.77 g. With the addition of a 5.5 g washer, the unbalance measurement was 13.27 g, a difference of exactly 5.5 g. With the addition of a 10.8 g washer, the unbalance measurement was 18.40 g, a difference of 10.63 g. The results demonstrate the accuracy of the vertical balancing measuring system. Taking into account all the data, measurement accuracy for the vertical balancing machine method can be stated as +/- 0.17 g, based on 4 repeat readings and 3 experimental mass settings.

5.5.5 SUMMARY

In order to obtain an accurate measurement of ball unbalance, it is essential that the point of unbalance be positioned so that it resides on the ball equator, at 90° to the axis of rotation. If the point of unbalance is positioned at a point away from the equator, the unbalance magnitude is reduced directly proportional to the sine function. It has been shown that ball pressure does not have an adverse effect on unbalance measurement accuracy, and consequently the current fixture design, is suitable.

The rotational speed of the spindle can have an effect on unbalance measurement. However, contrasting results have been obtained on the effect of varying spindle speed for different test balls. Finally, the accuracy of the system has been validated using additional masses attached to existing balls, based on these results the system is capable of a measurement accuracy of +/- 0.17 g.

5.6 UNBALANCE COMPARISON OF MAJOR BALL TYPES

In order to obtain an appreciation of the magnitude of unbalance in leading soccer balls the vertical balancing machine method was used to assess 4 different leading ball types used
in major competitions. The 4 leading ball types tested were the adidas Fevernova, Mitre ISO, 
Nike Geo Merlin and Puma Shudoh, all 'FIFA Approved' standard balls. More information 
on the 4 test balls can be found in Appendix 9. A sample of four balls of each type were 
tested giving a total of 16 balls. The test balls were positioned in the fixture and inflated to an 
approximate pressure of 55 kPa (8.0 psi), dependant upon ball size. The spindle was set to a 
rotational speed of 6.67 revs/s (400 rpm) and the system calibrated as discussed in Section 
5.3.3. Measurements were then taken for each ball as outlined in Section 5.4. Each ball was 
measured 3 times, with the ball completely removed from the fixture and replaced in the 
same position between each measurement.

5.6.1 RESULTS

Three sets of readings were taken for each individual ball tested and the full results can 
be found in Appendix 10. A summary of the results is shown in Table 5.5.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Av. Unbalance (g)</th>
<th>Unbalance Range (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Fevernova</td>
<td>9.66</td>
<td>8.62 - 10.49</td>
</tr>
<tr>
<td>Mitre ISO</td>
<td>8.80</td>
<td>7.92 - 10.25</td>
</tr>
<tr>
<td>Nike Geo Merlin</td>
<td>8.19</td>
<td>6.11 - 10.53</td>
</tr>
<tr>
<td>Puma Shudoh</td>
<td>9.70</td>
<td>7.34 - 12.77</td>
</tr>
</tbody>
</table>

Table 5.5 - Ball unbalance results for 4 major ball types

Figure 5.15 shows the unbalance results for the 4 major ball types in box plot form.
Figure 5.15 - Boxplot of ball unbalance by major ball type

Figure 5.15 shows that average unbalance measurements for a sample of 4 top class ‘FIFA Approved’ soccer balls are in the range 8 - 10 g. However, when the balls were assessed individually the unbalance values recorded were in the range 6 - 13 g. The Nike Geo Merlin ball exhibited the smallest average unbalance (6.11 g), and the Puma Shudoh ball the largest (12.77 g). Unbalanced masses calculated for the sample of adidas Terrestra balls were the most consistent, with the Mitre Ultimax sample exhibiting similar consistency. However, measurements obtained for the Nike Geo Merlin and the Puma Shudoh balls showed considerably more variation across sample ranges, with measurement range values of 4.42 and 5.43 respectively. Generally the unbalance forces were located at the valve position.

5.7 CONCLUSION

The assessment of out of balance using a vertical balancing machine has proved an accurate method of assessing the position and magnitude of out of balance forces within soccer balls. Extensive testing has shown that the measurement procedure gave consistent results with good repeatability, and was not adversely affected by variations in ball pressure. The system accuracy was shown to be +/− 0.17 g, which was validated using additional masses attached to existing balls. For an accurate measurement of unbalance it was essential that the point of unbalance was positioned on the ball equator, at 90° to the axis of rotation. Ball unbalance measurements in the range 6 - 13 g were obtained for samples of 4 ‘FIFA
Approved soccer balls, corroborating the need for an unbalance testing standard for top class soccer balls. The position of unbalance in all of the sample balls was found to be in close proximity to the valve.
CHAPTER 6

THE EFFECT OF OUT OF BALANCE FORCES ON DYNAMIC BALL PERFORMANCE

The unbalance results obtained for the 4 leading ball types described in Section 5.6 show that out of balance forces are present within top quality ‘FIFA Approved’ soccer balls. The presence of unbalance has the potential to significantly affect dynamic ball performance and flight characteristics, however the extent of any adverse effect has yet to be determined. This chapter presents an evaluation of the effect of unbalance on dynamic ball performance and encompasses two separate studies. The first study investigates the effect of ball unbalance and orientation on ball flight characteristics using a robotic leg launch platform. The second study assesses the ability of elite players to determine the effect of unbalance on ball performance through player perception testing.

6.1 UNBALANCE EVALUATION OF TEST BALLS

To assess the effect of unbalance on dynamic ball performance a range of soccer balls featuring varying degrees of unbalance were required. The vertical balancing machine was used to determine the overall unbalance within each ball, enabling individual balls to be selected for comparison in the tests. In order to determine the magnitude of unbalance required to initiate inconsistent ball flight, varying amounts of lead tape were added to a standard ‘FIFA Approved’ ball around the valve. The ball was then thrown with spin until ‘wobble’ became obvious to the observer, and this value was used to determine a range of mass additions required. A total of 30 ‘FIFA Inspected’ test balls featuring additional masses ranging from 2.5 to 15.0 g were obtained. The additional masses were added to the test balls during the manufacturing stage in the form of a piece of high-density rubber, moulded around the valve inside the bladder as shown in Figure 6.1. Samples of 5 balls were produced across the range of 6 additional masses. Each ball was measured for unbalance on the vertical balancing machine, using the procedure outlined in Section 5.4. The test balls were a standard design and identical in appearance.
Table 6.1 summarises the unbalance measurements obtained from the vertical balancing machine using samples of 5 balls per mass value. The full results for all 30 balls can be found in Appendix 11.

<table>
<thead>
<tr>
<th>Additional Mass (g)</th>
<th>Av. Unbalance (g)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>16.83</td>
<td>2.12</td>
</tr>
<tr>
<td>5.0</td>
<td>17.80</td>
<td>2.88</td>
</tr>
<tr>
<td>7.5</td>
<td>17.72</td>
<td>2.33</td>
</tr>
<tr>
<td>10.0</td>
<td>18.88</td>
<td>2.68</td>
</tr>
<tr>
<td>12.5</td>
<td>20.88</td>
<td>2.18</td>
</tr>
<tr>
<td>15.0</td>
<td>21.31</td>
<td>2.28</td>
</tr>
</tbody>
</table>

Table 6.1 - Unbalance measurements for balls containing additional masses

The calculated standard deviations for unbalance across the 5 ball samples were high, between 2.12 and 2.88 for each additional mass as shown in Table 6.1. This shows that the measured unbalance values were inconsistent across the ball sample ranges. The average unbalance measurements for each ball were significantly larger than the single additional masses, although the difference decreased as the size of the additional mass increased. It should be noted that the overall unbalanced mass is effectively a summation of the additional
mass and the inherent unbalance present within the ball, which could explain why the unbalance measurements obtained using the vertical balancing machine are significantly different to the single additional masses. In addition the test balls used in this study were 'FIFA Inspected' standard balls and not the superior 'FIFA Approved' standard, and the use of this lower quality standard may have resulted in larger inherent unbalance. The use of a non-standard manufacturing procedure may have been an additional factor.

![Boxplots of Unbalance by Added Mass](image)

Figure 6.2 - Boxplot of unbalance by additional mass value

The results are shown in boxplot form in Figure 6.2. The relatively long lengths of the boxes and whiskers highlight the unbalance inconsistencies within the test balls. It should be noted that the mean unbalance values (denoted within the boxplot as red circles), generally increase as the additional mass increases, although not in direct proportion.

### 6.2 TRAJECTORY ANALYSIS USING ROBOT KICKING LEG

In order to assess dynamic ball performance it is necessary to assess the flight characteristics of a ball after it has been kicked, and elite players are generally the preferred choice to perform kicks. However lengthy test periods are required to obtain sufficient amounts of data and player kicking capability and consistency can vary considerably. The effects of player fatigue over a lengthy testing period may also have a detrimental effect on the results obtained. Therefore, in order to experimentally assess the impact and flight characteristics of a soccer ball it is essential to use a launch platform that is capable of
consistent and repeatable launch conditions. A pneumatically driven ‘pendulum’ type kicking leg was used as a launch platform to assess the effect of ball unbalance and orientation on ball flight characteristics.

6.2.1 EQUIPMENT

Testing was carried out using the ‘Robo-Leg’ kicking platform located at the adidas Global Testing Centre in Scheinfeld, Germany. The leg mechanism acts in a pendulum motion and was driven through a rack and pinion by a pneumatic cylinder which drove the leg to the point of impact with the ball. A second pneumatic cylinder acted as a braking mechanism to slow the leg down immediately after impact. The air pressure in the cylinders was set to 600 kPa throughout the duration of the testing. The kicking leg was fixed to the floor and surrounded by a framework of 50 x 50mm steel tubing. For safety reasons the leg mechanism was guarded by the addition of Perspex sheeting between the steel framework. A schematic diagram of the kicking leg and enclosing framework is shown in Figure 6.3.

![Schematic diagram of pneumatic kicking leg](image)

**Figure 6.3 - Schematic diagram of pneumatic kicking leg**

Test balls were positioned on a teeing mechanism, adjustable in three main axes. The tee position was adjustable in order to allow the kicking leg to strike different points on a ball. A spherical end effector was manufactured and attached to the end of the leg to act as a striking implement. The end effector was specially manufactured from Delrin, a lightweight, and
durable, plastic material. The end effector is shown attached to the kicking leg in Figure 6.4. The spherical shape of the end effector, (diameter 105mm), was selected because of its resemblance to the end of a soccer boot. The mass of the leg and end effector was 7.15 kg and the system was capable of achieving end effector velocities of 12 m/s.

![Figure 6.4 - Spherical end effector attached to kicking leg](image)

### 6.2.2 The Effect of Unbalance on Dynamic Ball Performance

The effect of unbalance on dynamic ball performance was evaluated by gathering ball launch data from two test balls exhibiting different magnitudes of unbalance. The effect of the valve position at impact was also assessed as part of the study. It is apparent that many professional soccer players believe that valve position at impact can affect the ball launch characteristics, yet no published data exists to support this theory. The out of balance results presented in Chapter 5 suggest that the valve is the most common cause of unbalance within soccer balls. The position of the valve at impact and the subsequent unbalance force it can create within the ball may have an effect on the initial flight characteristics. In order to quantitatively determine the effect of unbalance forces on dynamic ball performance, a series of tests were undertaken using the kicking leg.
6.2.3 EXPERIMENTAL SET UP

To determine the effect of unbalance on dynamic ball performance 2 test balls featuring different magnitudes of unbalance were assessed. The 2 ball types were the ‘FIFA Approved’ adidas Fevernova, the official ball of the 2002 World Cup tournament and a specially manufactured unbalanced ball with additional mass added during the manufacturing stage, as described in Section 6.1. The unbalanced ball featured an additional piece of high-density rubber weighing 15 grams moulded around the valve in order to create a grossly out of balance ball. The overall unbalance within both test balls was assessed using the vertical balancing machine method and the angular orientation of unbalance within both test balls was found to emanate from the valve. The overall magnitude of unbalance for the unbalanced ball (22.6 g) was approximately double the unbalance within the adidas Fevernova ball (10.5 g), as shown in Table 6.2. The test balls were inflated to a constant pressure of 86 kPa (12.5 psi), throughout the duration of the tests.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Unbalance Magnitude (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Fevernova</td>
<td>10.5</td>
</tr>
<tr>
<td>Unbalanced ball</td>
<td>22.6</td>
</tr>
</tbody>
</table>

Table 6.2 - Unbalance force magnitude of test balls determined using vertical balancing machine

A schematic diagram of the instrumentation used to measure leg and ball velocity is shown in Figure 6.5. The spherical end effector was secured to the leg and the test balls positioned on the teeing mechanism. Two horizontal beam laser light gates spaced 0.1m apart were set up directly behind the ball tee to measure the leg velocity before impact. A set of vertical beam light gates spaced 0.69m apart were positioned in front of the ball tee in order to measure the initial ball velocity after impact. The first light gate was fixed in position directly in front of the ball tee, whereas the second light gate could be adjusted laterally, depending on the ball trajectory and direction after impact. The pendulum nature of the kicking leg motion ensured that the spherical impacter moved in a circular arc, as shown in Figure 6.5. The length of the leg from the pivot point to the end effector was 0.9m and the angle of the leg to the vertical at the point of impact with the ball on the tee was 6 degrees. This leg reached vertical position before impact and was beginning to rise as it struck the ball in order to achieve a trajectory elevation in the range 10 - 15°. The impact point of the end effector on the ball was approximately 1.5cm below the equator.
A target was erected exactly 15m from the ball tee. A large mat measuring 2m by 3m was turned on its side, and secured to the inside of a hockey goal, as is shown in Figure 6.6. A digital video camera running at 30 frames per second was positioned on a tripod 1m to the right of the kicking leg in order to capture the ball impact positions on the target. A metre square grid was marked on the mat using white tape in order to allow the ball impact positions to be digitised. The video footage of the test balls impacting on the target was later transferred into digital format using MGI VideoWave 4 video capturing software. Corel Photopaint software was then used to identify and extract the relevant individual frames showing the ball impact positions on the target.
The initial trajectory of the test balls after leaving the tee was captured by a high-speed video camera positioned side on, perpendicular to the initial ball trajectories. The camera was running at a speed of 500 frames per second, with a shutter speed of 1/1000s. Images obtained from the camera system were downloaded to disk in TIFF image format. Flightpath software, described in detail in Section 4.5, was later used to digitise the ball positions and calculate ball elevation and velocity.

6.2.4 Testing Procedure

Prior to the start of testing the teeing mechanism was positioned so that the end effector struck the vertical centre line of the ball. This ensured that no sidespin was imparted to the ball at the first test setting. Each ball was placed on the teeing mechanism in four different orientations: i) valve positioned on top of ball, ii) valve positioned on right of ball, iii) valve positioned on left of ball, iv) valve positioned at the point of impact, as outlined in Table 6.3. The end effector impacted on a pentagon panel for 3 of the ball orientations, the exception being a hexagon panel impact with the valve positioned on the right of the ball. Five impacts were recorded at each of the four ball orientation settings, giving an initial total of 20 impacts for each test ball.
Table 6.3 - Valve position at impact and impact panel

<table>
<thead>
<tr>
<th>Ball Orientation</th>
<th>Valve Position at Impact</th>
<th>Impact Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top of ball</td>
<td>Pentagon</td>
</tr>
<tr>
<td>2</td>
<td>Right hand side of ball (on equator)</td>
<td>Hexagon</td>
</tr>
<tr>
<td>3</td>
<td>Left hand side of ball (on equator)</td>
<td>Pentagon</td>
</tr>
<tr>
<td>4</td>
<td>Strike point</td>
<td>Pentagon</td>
</tr>
</tbody>
</table>

Upon completion of 40 impacts for the 2 test balls with zero spin, the teeing mechanism was moved 2cm to the left. This ensured that the end effector was striking the test balls at 2cm to the right of centre, and a further set of 40 impacts were recorded at the four different impact orientations. Upon completion of the second set of 40 impacts, the teeing mechanism was moved a further 2cm to the left, ensuring that the end effector was now striking the ball 4cm to the right of centre. A further set of 40 impacts were carried out for the two test balls at the four different impact orientations.

6.2.4.1 Ball 2D Position Measurement Software

The images of the balls striking the target were analysed using 2D position measurement software. Before the positions of the balls hitting the target could be measured the system needed to be calibrated. The system required an origin, a known distance along the x-axis and a known distance along the y-axis to be manually identified by the user. The addition of the metre square grid to the target made this task relatively simple, as the origin and two axes were marked by the white tape grid. In order to calibrate the system, an image of the target was obtained and the centre of the grid digitised to set the origin. Calibration was complete once the user digitised two further points: a known distance along the x-axis and a known distance along the y-axis. Successful calibration of the system enabled the impact positions of the balls on the target to be calculated relative to the position of the origin. Once calibrated, the positions of the balls striking the target were digitised by marking an enclosing square around the ball at the point of impact. The software then calculated the positional coordinates of the ball impact centres relative to the target centre.

6.2.5 RESULTS

The impact and launch data obtained for the adidas Fevernova ball is summarised in Table 6.4. All values reported are average values based on 5 repeat impacts.
<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Offset (cm)</th>
<th>Valve Location</th>
<th>Leg Velocity (m/s)</th>
<th>Vector Ball Velocity (m/s)</th>
<th>Ball Launch Elevation (deg)</th>
<th>Impact Point (x) (m)</th>
<th>Impact Point (y) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas</td>
<td>0</td>
<td>Top</td>
<td>10.71</td>
<td>20.48</td>
<td>15.96</td>
<td>-0.43</td>
<td>0.71</td>
</tr>
<tr>
<td>Fevernova</td>
<td></td>
<td>Right</td>
<td>11.00</td>
<td>20.82</td>
<td>14.65</td>
<td>0.74</td>
<td>-0.02</td>
</tr>
<tr>
<td>(10.5g)</td>
<td></td>
<td>Left</td>
<td>10.68</td>
<td>20.73</td>
<td>14.04</td>
<td>-0.71</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.42</td>
<td>20.77</td>
<td>14.80</td>
<td>0.64</td>
<td>0.26</td>
</tr>
<tr>
<td>adidas</td>
<td>2</td>
<td>Top</td>
<td>10.35</td>
<td>20.37</td>
<td>16.35</td>
<td>-3.15</td>
<td>0.36</td>
</tr>
<tr>
<td>Fevernova</td>
<td></td>
<td>Right</td>
<td>10.44</td>
<td>19.68</td>
<td>14.28</td>
<td>-2.05</td>
<td>-0.09</td>
</tr>
<tr>
<td>(10.5g)</td>
<td></td>
<td>Left</td>
<td>10.70</td>
<td>19.87</td>
<td>12.92</td>
<td>-3.36</td>
<td>-0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.35</td>
<td>20.32</td>
<td>14.42</td>
<td>-2.69</td>
<td>0.05</td>
</tr>
<tr>
<td>adidas</td>
<td>4</td>
<td>Top</td>
<td>11.22</td>
<td>17.92</td>
<td>12.61</td>
<td>-6.01</td>
<td>-0.47</td>
</tr>
<tr>
<td>Fevernova</td>
<td></td>
<td>Right</td>
<td>10.33</td>
<td>18.66</td>
<td>12.33</td>
<td>-5.43</td>
<td>-0.66</td>
</tr>
<tr>
<td>(10.5g)</td>
<td></td>
<td>Left</td>
<td>10.37</td>
<td>18.90</td>
<td>10.49</td>
<td>-6.00</td>
<td>-0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.37</td>
<td>18.41</td>
<td>10.82</td>
<td>-5.56</td>
<td>-0.81</td>
</tr>
</tbody>
</table>

Table 6.4 - adidas Fevernova ball launch data

Figure 6.7 shows the average impact positions of the adidas Fevernova ball on the target. The blue data points correspond to the valve positioned at the top of the ball at impact, the pink data points correspond to the valve positioned on the right, the yellow data points correspond to the valve positioned on the left and the light blue data points correspond to the valve positioned at the strike point. The target impact positions for the adidas Fevernova ball show clear differences between ball orientations for the three impact settings.
Figure 6.7 - Average impact positions for the adidas Fevernova ball

The impact and launch data obtained for the unbalanced ball is summarised in Table 6.5. All values reported are average values based on 5 repeat impacts. Figure 6.8 shows the average impact positions of the unbalanced ball on the target.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Offset (cm)</th>
<th>Valve Location</th>
<th>Leg Velocity (m/s)</th>
<th>Vector Ball Velocity (m/s)</th>
<th>Ball Launch Elevation (deg)</th>
<th>Impact Point (x) (m)</th>
<th>Impact Point (y) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbalanced ball (22.6g)</td>
<td>0</td>
<td>Top</td>
<td>11.95</td>
<td>20.67</td>
<td>19.89</td>
<td>0.24</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right</td>
<td>10.35</td>
<td>20.64</td>
<td>14.60</td>
<td>0.66</td>
<td>-0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>10.31</td>
<td>20.52</td>
<td>16.26</td>
<td>-0.91</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.29</td>
<td>20.52</td>
<td>16.68</td>
<td>0.34</td>
<td>0.06</td>
</tr>
<tr>
<td>Unbalanced ball (22.6g)</td>
<td>2</td>
<td>Top</td>
<td>11.64</td>
<td>19.76</td>
<td>17.09</td>
<td>-2.99</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right</td>
<td>10.58</td>
<td>20.08</td>
<td>11.53</td>
<td>-2.29</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>11.17</td>
<td>19.73</td>
<td>11.15</td>
<td>-3.95</td>
<td>-0.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.73</td>
<td>19.91</td>
<td>11.45</td>
<td>-2.92</td>
<td>-0.20</td>
</tr>
<tr>
<td>Unbalanced ball (22.6g)</td>
<td>4</td>
<td>Top</td>
<td>11.65</td>
<td>17.99</td>
<td>13.39</td>
<td>-5.96</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right</td>
<td>10.35</td>
<td>18.70</td>
<td>12.03</td>
<td>-5.15</td>
<td>-0.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>10.40</td>
<td>17.33</td>
<td>11.54</td>
<td>-6.46</td>
<td>-1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Strike</td>
<td>10.37</td>
<td>20.56</td>
<td>12.21</td>
<td>-5.86</td>
<td>-0.86</td>
</tr>
</tbody>
</table>

Table 6.5 - Unbalanced ball launch data
Clearly the target impact positions for the unbalanced ball show differences between ball orientations for the three impact settings.

6.2.6 DISCUSSION

The data presented in Table 6.4 and Table 6.5 shows that ball launch velocity remains relatively constant regardless of valve location. However, valve location at impact does appear to have an effect on ball launch elevation for the adidas Fevernova and unbalanced test balls. Table 6.4 and Table 6.5 show that ball launch elevation is considerably higher when the valve is positioned at the top of the ball. Furthermore, the launch elevations recorded for the unbalanced ball were considerably higher than those for the adidas Fevernova ball. The results suggest that the magnitude of the unbalance force emanating from the valve, may affect the extent of the increase observed in ball elevation.

Comparing the ball impact data for the two test balls it is clear that the position of the valve at impact and the resultant unbalance force acting at that point can have an effect on ball trajectory. However, the extent to which the ball trajectory is affected appears to depend on the magnitude of the unbalance force present within the ball. Ball impact dispersion on target for the adidas Fevernova ball exhibited noticeable variation in impact dispersion for the four valve positions. The dispersion results shown in Figure 6.7 show that generally ball elevation was larger when the valve was set at the top during impact with the kicking leg. Furthermore, the results suggest that moving the valve to the side of the ball causes the ball launch trajectory to experience an angular displacement towards the same side as the valve. For the centre position impact with zero spin, on average, the adidas Fevernova ball was
displaced approximately 0.7m from the straight-line position over the 15m trajectory. This equates to a sideways angular displacement of 2.7°.

The unbalanced ball was more inconsistent, and exhibited significant variation in impact dispersion for the four valve positions at impact. With the valve positioned at the top, the unbalanced ball experienced an upward vertical angular displacement. Similarly, with the valve positioned at the side, the ball appeared to experience an angular displacement towards the side at which the unbalance force acted. The angular displacement experienced by the unbalanced ball was more pronounced than that experienced by the adidas Fevrotova ball. For the centre position impact with zero spin, on average, the unbalanced ball was displaced approximately 0.8m from the datum position over the 15m trajectory. This equates to a sideways angular displacement of 3.1°.

The impact dispersion data for each of the two test balls was statistically analysed for consistency. The average ball impact position in cartesian coordinate form was calculated at each setting, and using simple trigonometry the displacement from each individual impact point relative to the average impact position was calculated. The process is illustrated in Figure 6.9.

\[
\text{Origin} = \text{Av. impact position of cluster data} \ (x, y).
\]

\[
\text{Variance} = \frac{\sum L_i^2}{n - 1}
\]

Figure 6.9 - Calculation of variance for ball impact positions

The variance of each set of impact data was then calculated using equation 6.1.

\[
\text{Variance} = \frac{\sum L_i^2}{n - 1} \quad (6.1)
\]
Table 6.6 shows the variance for each of the two balls. The adidas Fevernova ball produced variance values ranging from 0.12 - 0.55, indicating some variation in ball trajectories. The unbalanced ball produced variance values ranging from 0.38 - 1.08, indicating considerable variation in ball trajectories. These variations were a result of the four different ball orientations at impact.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Unbalance (g)</th>
<th>Offset (cm)</th>
<th>Variance of Impact Positions on Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>adidas Fevernova</td>
<td>10.5</td>
<td>0</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.12</td>
</tr>
<tr>
<td>Unbalanced ball</td>
<td>22.6</td>
<td>0</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 6.6 - Variance of impact positions on target

A t-test analysis was carried out in order to compare the variance of the adidas Fevernova data with the unbalanced ball data. A comparison of the test ball data for the centre impact produced a result of $p=0.004$ indicating a significant difference in the results at the 5% confidence level. A comparison of the data for 2cm and 4cm offset impacts produced results of $p=0.034$ and $p=0.00006$ respectively, both indicating significant differences in the results at the 5% confidence level.

Further evaluation of the results summarised in Table 6.6 shows that ball impact consistency for the two test balls improves as the impact point with the end effector is moved off centre. The most inconsistent set of ball impacts for each of the test balls were obtained with the end effector striking the ball in the centre. Figure 6.10 shows how the ball impact dispersion range reduces as the striking point was moved firstly to an offset of 2cm, then to an offset of 4cm. A t-test analysis showed that the reduction in dispersion range observed at 2 and 4cm offset impacts compared with the centre impact data was significant for both ball types. The Fevernova ball data produced results of $p=0.02$ and $p=1.6\times10^{-7}$ for 2 and 4cm offsets respectively, and the unbalanced ball data produced results of $p=0.02$ and $p=0.03$ for 2 and 4cm offsets respectively. All four results indicated a significant difference at the 5% confidence level.
Figure 6.10 - Effect of off-centre impacts on ball impact variance

Striking the test balls off centre imparted rotation to the balls, and the gradual improvement in trajectory consistency observed for the off centre impacts at 2 and 4cm could be due to the effect of spin. The spinning motion may reduce the effect of the out of balance mass on the trajectory, as its position will constantly change during flight. Conversely the centre impact produced nominal ball rotation therefore, the out of balance mass remained in a relatively constant position throughout the trajectory. Figure 6.11 shows the combined dispersion ranges for each of the two test balls on the target. The ellipses correspond to the range of impacts observed at each setting and clearly show that the adidas Fevernova ball is the most consistent ball in terms of trajectory and impact consistency. The graph also illustrates how trajectory consistency improves as the ball is struck away from centre.
Comparing the impact dispersion data for each of the 2 test balls at each of the 4 different valve positions, it appears that the most consistent results were obtained with the valve located at the striking point. With the valve positioned at a radial distance from the impact point, the initial ball trajectory experiences an angular displacement towards the location of the unbalanced mass during the impact process. Upon evaluation of the ball impact dispersion data, it appears that striking the ball on the valve itself can reduce the initial angular displacement, and provide a more consistent trajectory. The out of balance creates an unequal distribution of mass within the ball, and striking the ball on the point of unbalance (the valve), appears to reduce inconsistencies in launch trajectory.

6.2.6.1 Summary

The data presented has shown that unbalance forces in soccer balls can have a significant effect on ball launch trajectories, although they do not affect initial launch velocity. The extent to which the ball flight trajectory is affected depends on the magnitude of the unbalance force and the position of the point at which the unbalance acts, (in most cases the valve). The results show that out of balance forces between 10 and 22 grams in magnitude will significantly affect the ball flight characteristics. If the point of unbalance is positioned at the top of the ball, the ball will experience an angular displacement directly upwards during impact, causing ball elevation to increase. If the point of unbalance is positioned at the side of the ball, the ball will experience an angular displacement towards the side, causing lateral translation to the launch trajectory.

The results show that the effect of the out of balance force can be reduced by striking the ball on the point of unbalance itself, which in most cases is the valve. However, if there are significant out of balance forces present in a ball, differences in trajectory will still occur.
The effect of unbalance on ball trajectory appears to be greatest when the ball is struck in the centre. The results show a reduction in ball dispersion and subsequent improvement in trajectory consistency for off centre ball impacts.

6.3 THE ABILITY OF ELITE PLAYERS TO PERCEIVE BALL UNBALANCE

The detrimental effect of out of balance forces on ball trajectory consistency has been highlighted in Section 6.2. However, it is not clear if elite players are capable of perceiving the effect of unbalance on dynamic ball performance. Therefore, a study was designed to assess the ability of elite players to perceive differences between a selection of balls exhibiting varying degrees of unbalance. In order to assess the ability of players to perceive unbalance in soccer balls, it was essential that the difference in unbalance magnitude between the balls selected was distinct. To fulfil this requirement, three balls containing overall unbalanced masses of 14.80, 18.06 and 24.25 g were selected. Ideally, the intermediate ball would have contained an overall unbalanced mass of around 19.5, so that there were equal differences in unbalance magnitude between each ball, however there were no balls suitable amongst the 30 test balls. It would also have been preferable to include a fourth ball with an unbalanced mass of around 10.0 g to simulate a common ‘FIFA Approved’ ball, however this would have resulted in the test balls not appearing (outwardly) identical. It was essential that all test balls featured an identical design and colour scheme, so that player perceptions could not be biased by ball type. In order to distinguish one ball from another the balls were labelled A, B and C using permanent markers on the ball surface.

6.3.1 SELECTION OF APPROPRIATE TESTS

The assessment of sports ball performance is typically derived from technical parameters such as ball velocity, spin rate, distance covered, trajectory and impact dispersion on a target. However, in order to validate the effect of ball unbalance in game conditions, subjective player perception needs to be given consideration. Player testing was carried out in order to determine the amount of ball unbalance that elite players are capable of perceiving. There are a number of examples of common soccer skills tests designed to assess player capabilities. Hargreaves (1990), Reeves and Simon (1991) and Hughes (1994) specify a range of soccer skills tests and these were considered for the ball unbalance player perception testing. However, the majority of these skills tests are designed to improve the ability of the player, rather than for equipment assessment.

Previous studies have been carried out into the effect of physiological demands on the ability of soccer players to perform skills. Ali et al. (2002) designed a shooting test to assess
the skill of university standard soccer players. Subjects were assessed based on test completion time, shot velocity and the impact position of the ball in relation to the goal. McGregor et al. (2002) designed a similar skills test concerned with the assessment of dribbling and passing. Although these tests provide a reasonable assessment of player capability, the players are subject to fatigue whilst performing the tests, which could potentially have a damaging effect on their ability to perceive performance differences between balls. Furthermore, the ball trajectories involved in the two studies are relatively short, therefore limiting the time duration available to the players to assess ball performance.

After an evaluation of existing soccer skills tests, it was decided that more specific tests were required to assess player perception of soccer ball performance. It was essential that these tests did not result in the subjects becoming fatigued, as this could have a detrimental effect on player perception. A pilot study was carried out using university standard soccer players to determine suitable test procedures for ball performance assessment. Five tests were developed and trailed on a ‘rubber crumb’ artificial pitch as part of the pilot study. The five tests carried out were:

i) a dribble test over 10m

ii) a short passing test over 10m

iii) a long passing test over 30m

iv) a straight shot on goal from 20m

v) a swerve shot on goal from 20m

After evaluation of the results and consideration of participant feedback two specific test procedures were identified as being most suitable for the assessment of ball performance. The two tests selected were a short passing test along the ground and a long airborne passing test.

There are two main techniques that can be employed to assess sports equipment performance based on subjective player perception; qualitative assessment and quantitative assessment. Roberts et al. (2001a) used qualitative interview based techniques to elicit general player perception of golf equipment. However, the use of interview techniques requires considerable analysis in order to isolate key responses, and is perhaps not necessary for the specific assessment of ball unbalance. Consequently, it was decided that a quantitative means
of assessment would be most suitable, with the subjects being asked to assign rankings to balls based on their perception of ball performance after a kick.

6.3.2 PARTICIPANTS

Sixteen elite soccer players were used for the study. The subjects were a combination of trainee and professional players from 2 FA Premier clubs: Aston Villa FC and Leicester City FC. The subjects consisted of 11 right-footed and 5 left-footed players and included 3 U-20 internationals and 4 U-17 internationals. The subjects all wore their own boots, consisting of designs from four different major boot manufacturers. An overview of subject age, weight, height and shoe size details are outlined in Table 6.7. Full details on individual subject characteristics can be found in Appendix 13.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>18.06</td>
<td>1.39</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>73.50</td>
<td>9.51</td>
</tr>
<tr>
<td>Body Height (m)</td>
<td>1.79</td>
<td>0.07</td>
</tr>
<tr>
<td>Foot Size (UK size)</td>
<td>8.63</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Table 6.7 - Subject data (n=16)

6.3.3 TESTING PROCEDURE

Two different passing tests were employed in order to assess the ability of elite players to perceive unbalance in soccer balls, a short passing test along the floor and a higher velocity long distance airborne passing test. The objective of the study was communicated to the subjects prior to the commencement of testing. The subjects were then split into pairs and instructed to perform the two different passing activities with the 3 test balls featuring varying degrees of unbalance. In order to reduce any effects of fatigue the order in which the balls were given to the players was randomised for each pair as shown in Table 6.8.
In the first passing activity the subject pairs were requested to perform low velocity passes to each other along the playing surface over a distance of approximately 10m. Upon receipt of a pass the subjects were allowed to either pass the ball back with their first touch, or control the ball with one touch before passing depending on their personal preference. The subject pairs spent approximately 45 seconds with each test ball, striking approximately 10 - 15 passes each, before the next ball was introduced. During the test the subjects were instructed to evaluate the balls based on two criteria: i) the roll of the ball along the playing surface, and ii) the 'feel' of the ball whilst under close control. Upon completion of the short passing test for all three test balls the subjects were asked to rank the balls from 1 - 3 in order of which they preferred, 1 being the best rating and 3 being the worst.

In the second passing activity the subject pairs were requested to perform high velocity airborne long distance passes to each other over a distance of approximately 30m, as shown in Figure 6.12. Each subject struck each of the three balls to his partner in turn, before immediately ranking the balls from 1 - 3 in order of which they preferred. The balls were struck from a stationary position and the subjects instructed to strike the balls with a straight trajectory with minimal sidespin. The subjects were instructed to position the balls with the valve at the bottom of the ball. Positioning the unbalanced mass at the bottom of the ball at the point of impact prevents any of the subjects from witnessing stationary roll effects caused by the unbalanced mass. Upon receipt of all three test balls the partner then repeated this kicking procedure from the opposite end of the pitch. During the long passing test the subjects were instructed to evaluate the balls based on any noticeable unstable ball flight characteristics or 'wobble' effects caused by the unequal distribution of mass. Each subject was instructed to repeat the kicking procedure 5 times, and allowed to change their ranking order as often as they wished. After completion of 5 sets of kicks, the subjects were asked to give a final ranking order outlining which ball they preferred, 1 being the best rating and 3
being the worst. An answer sheet was used to document the subject rankings, a copy of which can be found in Appendix 12.

![Figure 6.12 - Long passing test at Aston Villa FC](image)

Testing was conducted at the training grounds of both clubs, with visibility in both cases being good. Testing carried out at Aston Villa FC was carried out on a ‘rubber-crumble’ artificial pitch made up of fibrous strands of artificial grass immersed with small rubber particles. Testing at Leicester City FC was carried out on a natural grass training pitch in slightly wet conditions. Ideally, both tests would have been carried out on the same type of surface, as the use of different surfaces will undoubtedly have an effect on the ball roll properties during the passing test. However, access to elite players and particular facilities is not always readily available, making it difficult to achieve an ideal test set up. The test balls were inflated to a pressure of 86 kPa (12.5 psi) during the tests, the exact mid-point of the FIFA stipulated pressure range.

6.3.4 RESULTS

The subject ranking orders for the short passing test are detailed in Table 6.9. The correct rankings are given in red.
In the short passing test 38% of the subjects ranked all three balls correctly. 50% of the subjects correctly identified the most unbalanced ball (24.25 g) with 44% of subjects correctly identifying the least unbalanced ball (14.80 g). The average ranking value for the ball with the largest unbalanced mass was 2.19, slightly higher than the average ranking values for the least unbalanced ball (1.94) and the intermediate ball (1.88). Perhaps surprisingly the ranking average was higher for the least unbalanced ball than for the intermediate ball. This suggests that although the subjects were generally able to identify the ball with the worst unbalance (24.25 g), they found it difficult to differentiate between the least unbalanced and intermediate balls.

The subject ranking orders for the long passing test are detailed in Table 6.10. The correct rankings are given in red.
In the long passing test 25% of the subjects ranked all three balls correctly. 56% of the subjects correctly identified the most unbalanced ball (24.25 g) with 31% of subjects correctly identifying the least unbalanced ball (14.80 g). The average ranking value for the ball with the largest unbalanced mass was 2.38, higher than the average ranking values for the least unbalanced ball (1.94) and the intermediate ball (1.69). Similar to the short passing test results, the ranking average was higher for the least unbalanced ball than for the intermediate ball. Therefore, it appears that the subjects were generally able to identify the ball with the worst unbalance (24.25 g), yet found it difficult to differentiate between the least unbalanced and intermediate balls.

### 6.3.5 Statistical Analysis of Ranking Data

The ranking responses of the test subjects were analysed in order to determine if correlations existed within the data. The Kendall’s coefficient of concordance (W) measures the agreement of raters, and was used to investigate the possibility of any correlation between

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ball Unbalance (g)</th>
<th>14.80</th>
<th>18.06</th>
<th>24.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>1</td>
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<td>3</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

| Av. Ranking | 1.94 | 1.69 | 2.38 |

**Table 6.10 - Ranking order for long passing test**
the ranking responses of the subjects on pairs of balls. An overview of the calculation of Kendall's coefficient of concordance (W) can be found in Appendix 14. The Wilcoxon Signed Ranks Test was used to determine pair wise differences in the data (i.e. which balls were rated significantly differently overall for each test). A detailed overview of the Wilcoxon Signed Ranks Test can be found in Appendix 15.

6.3.5.1 Kendall's Coefficient of Concordance

The results of the analysis are shown in Table 6.11.

<table>
<thead>
<tr>
<th>Test</th>
<th>Kendalls W</th>
<th>P (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Passing</td>
<td>0.121</td>
<td>0.144</td>
</tr>
<tr>
<td>Long Passing</td>
<td>0.051</td>
<td>0.444</td>
</tr>
</tbody>
</table>

Table 6.11 - Calculation of Kendall's coefficient of concordance

The Kendall's coefficient of concordance ranges from 0 (no agreement) to 1 (complete agreement). The results obtained (0.121 and 0.051) show that there is no overall significant agreement from the ball ranking responses in either test.

6.3.5.2 Wilcoxon Signed Ranks Tests

The results of the analysis are shown in Table 6.12.

<table>
<thead>
<tr>
<th>Test</th>
<th>Ball Comparison</th>
<th>Z</th>
<th>P (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Passing Test</td>
<td>Ball 1 vs. Ball 2</td>
<td>-0.449(a)</td>
<td>0.653</td>
</tr>
<tr>
<td></td>
<td>Ball 1 vs. Ball 3</td>
<td>-0.809(b)</td>
<td>0.419</td>
</tr>
<tr>
<td></td>
<td>Ball 2 vs. Ball 3</td>
<td>-1.380(b)</td>
<td>0.167</td>
</tr>
<tr>
<td>Long Passing Test</td>
<td>Ball 1 vs. Ball 2</td>
<td>-0.790(b)</td>
<td>0.430</td>
</tr>
<tr>
<td></td>
<td>Ball 1 vs. Ball 3</td>
<td>-1.294(a)</td>
<td>0.196</td>
</tr>
<tr>
<td></td>
<td>Ball 2 vs. Ball 3</td>
<td>-1.706(b)</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 6.12 - Wilcoxon Signed Ranks Test results

The results of the Wilcoxon Signed Ranks Test show that ball 2 was ranked differently to ball 3 for the long passing tests ($z = -1.706$, $p = 0.88$). However, this difference cannot be classed as significant as it was over the 0.05 confidence level that normally defines the presence of a significant relationship.
6.3.6 DISCUSSION

The inability of many subjects to differentiate between the least unbalanced (14.80 g) and intermediate (18.06 g) balls suggests that the flight and roll characteristics observed for the two balls were similar. However, it is unclear whether the subjects would have been able to differentiate between balls exhibiting unbalance in the range 14.80 - 18.06 g in comparison with a FIFA Approved standard soccer ball exhibiting unbalance in the range 6 - 10 g, as determined in Section 5.6.1. It should also be noted that the difference in unbalance magnitude between the worst and intermediate balls (6.19 g) was considerably larger than the difference between the intermediate ball and the least unbalanced ball (3.26 g). This difference could partially explain the failure of some subjects to differentiate between the intermediate and least unbalanced ball, whilst successfully identifying the worst ball.

The failure of the statistical analysis to identify significant correlation within the data is most likely a result of variability in the data. Because of the nature of the test, there exists a degree of inherent variability in the subjects ability to perceive unbalance. The use of two different playing surfaces during the course of the testing is likely to have had an effect on the accuracy of subject responses for the short passing test, but should not have influenced the long passing test.

6.3.6.1 Summary

Taking into account the variability caused by the use of two different playing surfaces, the short passing test results are in general agreement with the results from the long passing test. The subjects were generally able to identify the ball containing the largest unbalanced mass (24.25 g), yet were unable to distinguish between the other two balls containing smaller unbalanced masses. However, this could be due to the relatively small difference in unbalance magnitude (3.26 g) between the intermediate and lower unbalanced balls. Repeating the tests with 3 balls exhibiting unbalance magnitudes of around 24 g, 16 g and 8 g (a typical ‘FIFA Approved’ ball) may give more relevant results.

6.4 CONCLUSION

The trajectory analysis data obtained using the robot kicking leg testing has shown that unbalance forces in soccer balls can have a significant effect on ball launch trajectories. The extent to which the ball flight trajectory is affected depends on the magnitude of the unbalance force and the position of unbalance at impact. A statistical analysis of the target impacts showed that striking the ball off centre improved trajectory consistency significantly. The ability of elite players to perceive unbalance in soccer balls was also assessed, although
statistical analysis of the subject responses failed to establish any significant correlation. The majority of subjects were able to identify the ball containing the largest unbalance magnitude, but were generally not able to differentiate between the other test balls containing smaller unbalanced masses.
CHAPTER 7

AUTOMATED SOCCER BALL PERFORMANCE MEASUREMENT SYSTEM

The ability to measure soccer ball flight performance parameters is essential for the development of dynamic test criteria. Many of the shots on goal and long passes that take place in a game are struck at high velocities and with considerable spin, therefore a system capable of obtaining accurate measurements of ball velocity, spin rate and launch angle is essential for the assessment of different ball types and the potential development of standards. This chapter describes the development of an automated system to accurately measure soccer ball launch performance parameters.

7.1 INTRODUCTION

The major shortcoming with the existing FIFA soccer ball testing criteria is the absence of dynamic ball performance tests at velocities comparable to a game situation. A system capable of obtaining measurements of velocity, 3D spin and launch elevation would provide a valuable tool for the development of dynamic ball performance standards. Furthermore, if used with a consistent launch platform such as the pneumatic leg discussed in Section 6.1, the system could allow accurate dynamic comparison of different ball types and constructions.

There are a number of examples of launch analysis and tracking systems for golf balls (Gobush et al., 1994; Winfield et al., 2002), and contemporary television coverage of baseball, cricket and tennis now includes virtual ball trajectory simulations (Pingali et al., 2000). Gobush et al. (1994) developed a golf ball launch analysis system for Titleist capable of accurately evaluating 3D spin, however this system requires accurate location of the ball prior to impact and is not commercially available. None of the other systems currently available can accurately measure complex ball spin. In soccer there are currently no systems capable of accurately measuring ball performance. More recently television coverage of professional games has made measurements of ball velocity, however the measurements have not been obtained under controlled conditions and the accuracy can be questioned. Cairos
technologies AG are currently developing a player and ball tracking system using wireless technologies (Braun et al., 2001). It is claimed that the system will be capable of measuring ball velocity and ball spin through the use of a microchip contained within the ball. However, the method is still in development, the potential accuracy unclear and the system is likely to be expensive.

A key characteristic of dynamic sports ball behaviour is that of spin. The amount of spin imparted to a ball during impact with a foot or implement will determine the ball flight trajectory and the ball rebound characteristics after impact with the playing surface. The capability for measuring spin rate and the 3D axis of spin is not met by any of the existing ball launch and tracking systems. The techniques used within the Flightpath software program for the assessment of ball spin, discussed in Section 4.5, are subject to considerable measurement inaccuracies. The ‘enclosing square’ manual digitising technique necessary for the identification of ball location, and the alignment of the floating projected line with the circumferential ball markings necessary to determine spin rate, can both be subject to inherent human error. The limitations present within manual digitising systems such as Flightpath could potentially be eliminated through the development of an automated measurement system. An automated system would eliminate human digitising error and enable rapid computerised analysis in more dynamic sports scenarios.

7.2 BACKGROUND

The requirement for a new system capable of automated soccer ball performance measurement has evolved out of work carried out on two previous systems.

7.2.1 FLIGHTPATH SYSTEM

The Flightpath measurement system was developed in 1993 by a former researcher within the Wolfson School of Mechanical and Manufacturing Engineering, Mr Chris Sumpter. The system has since been used extensively by the Sports Technology Research Group and Dunlop Slazenger for the analysis of golf and tennis balls. The system has also been used for soccer ball performance measurement as discussed in detail in Section 4.5. The Flightpath system established the concept of capturing and digitising sequential images of a ball in flight in order to determine the ball flight parameters. However, the need to manually digitise the balls and spin axis limited its use to essentially 2D measurements that also require the static ‘pre-orientation’ of the ball prior to image capture.
7.2.2 SPINDOT SYSTEM

In an attempt to overcome the limitations within the Flightpath system, an improved system was developed by Chris Sumpter in collaboration with the Sports Technology Research Group. The system was named 'SpinDot' and used a 'total surface' marking scheme to measure both spin rate and 3D spin axis. The marking scheme required the addition of a number of simple single coloured dots over the surface of a ball, as shown in Figure 7.1. The size of the dots could vary, providing they were large enough to be identified on any required image. The marking scheme ensured that within any arbitrary view of the ball obtained through dynamic capture (i.e. a random 2D image), a unique pattern was observed from which the 3D ball orientation could be determined. To achieve this the dots were positioned on the ball surface in such an arrangement so that the spatial relationship between each dot and its near neighbours was unique.

![SpinDot ball spin measurement system](image)

A genetic algorithm determined that 50 dots placed around the ball was the minimum number of dots required in order for a unique pattern to be observed in any orientation. The SpinDot scheme could potentially be used on any ball surface and has been successfully implemented on golf and tennis balls. However, the tendency of tennis ball naps to 'fluff up' after repeated impacts, can potentially lead to inaccuracies with dot locations. Furthermore, the placement of the dots around a ball is a demanding and time consuming operation.

7.3 SOCCER BALL MEASUREMENT SYSTEM CONCEPT

The testing of elite soccer players to determine ball performance parameters, detailed in Chapter 4, emphasised the need for an automated system for measuring ball launch characteristics. A new system concept was originated by Chris Sumpter and Professor Roy
Jones, and with contribution from the author, a comprehensive ball performance measurement system has been developed. The author's major contribution to the development of the system is detailed in Section 7.37. The system has been patented (UK Patent Application PH/8562INT), with Chris Sumpter, Roy Jones and Paul Neilson named as inventors. The measurement system processes and analyses a sequence of images of a soccer ball in flight in order to determine the key flight parameters: ball velocity, spin rate, spin axis and launch elevation. Existing ball launch systems can typically only measure topspin and backspin whereas the new system measures ball spin about an arbitrary axis. The system could potentially allow governing bodies, equipment manufacturers, coaches and players alike to directly measure ball performance, giving instant feedback on dynamic ball flight characteristics.

The majority of soccer balls manufactured around the world are 32-panel balls based on the icosadodecahedron structure, consisting of 12 pentagons and 20 hexagons. The soccer ball performance measurement system utilises the 32-panel arrangement common to most soccer balls in order to create a 'total surface' marking scheme similar to that employed in the SpinDot system. However, the unique pattern requirement is achieved through assigning a series of colours to each of the 32 panels on the ball surface, in such a way so that the colour relationship between each panel and its neighbouring panels is unique. The marking scheme ensures that within any arbitrary view of the ball obtained through dynamic capture, a unique pattern is observed from which the ball orientation can be accurately determined.

7.3.1 PATTERN IDENTIFICATION CRITERIA

If a 'pattern' is considered to consist of a central panel surrounded by a number of adjoining neighbouring panels, then the geometry of an icosadodecahedron dictates that each 'pattern' will contain 6 or 7 panels (depending whether the central panel is a pentagon or hexagon respectively). In order to achieve pattern 'uniqueness' for any ball orientation, a number of rules must be adhered to:

i) Each 'pattern' must be unique compared to all other patterns.
ii) No adjoining panels must be of the same colour.
iii) The 'pattern' in view must be unique within itself, such that rotation of the pattern will not result in a duplicated arrangement of colours.
7.3.2 GENETIC ALGORITHM

If a soccer ball is thought to consist of N colours and p panels, there will be $N^p$ possible colour arrangements over the ball surface. If the panels on a 32-panel ball are assigned 5 different colours, there will be in excess of $2 \times 10^{22}$ possible arrangements. However, only a small number of these arrangements will satisfy the pattern identification criteria detailed in Section 7.3.1, therefore a genetic algorithm was devised to select a suitable arrangement of colours. A flow chart of the algorithm used is given in Appendix 16. The algorithm was adapted from the algorithm originally used for the SpinDot system by Chris Sumpter. The algorithm results decreed that 5 colours was the minimum number of colours required to fulfil the requirements of the pattern identification criteria. The panel colour arrangement required to produce ball ‘uniqueness’ in any orientation is given in Table 7.1. Each ball panel was assigned a reference number from 1-32, and each colour designated a number from 1-5.

<table>
<thead>
<tr>
<th>Panel No.</th>
<th>Panel Shape</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pentagon</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Pentagon</td>
<td>4</td>
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<tr>
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<td>16</td>
<td>Hexagon</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Panel No.</th>
<th>Panel Shape</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
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<td>Hexagon</td>
<td>2</td>
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</tr>
<tr>
<td>32</td>
<td>Hexagon</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.1 - Panel colour assignment determined from genetic algorithm
The presence of a unique pattern in a 2D ball image is detected by determining the colour and pixel centroid coordinates \((x, y)\) of each panel in the image frame. The distance of each panel centroid from the ball centre \((z\) coordinate) can be inferred from measurement of the ball radius within the image. The algorithm features a reference frame 'look-up' table that details the colour arrangement and chordal distances between each pair of panels around a virtual 32-panel soccer ball. Firstly, the algorithm attempts to match the details of a panel observed within the image frame with a panel contained in the reference frame. Subsequently, the algorithm attempts to find chordal distance and colour matches for the other observed panels in the image against the reference frame data. Digitising tolerances on chordal distances are allowed by the algorithm, however if these are exceeded failure will occur. The algorithm is of the tree-search variety that features a number of candidates at each level of the tree. If the tree is exhausted before a solution is found the pattern search fails, however if one or more solutions are found a final transformation test is carried out to determine the validity of the solution. The transformation test rejects any symmetrical patterns that the chordal search does not discriminate against. A single unique solution denotes a successful pattern match, if there are zero or more than one solutions, the algorithm has failed to find a match.

7.3.3 **SPIN MEASUREMENT**

Successful identification of a unique pattern within a 2D image is used to define the 3D ball orientation. Therefore, if unique patterns are obtained for two sequential images, the axis of spin and the spin rate about this axis can be determined. The 3D ball transformation is determined using the reference frame shown in Figure 7.2. The angles phi \((\phi)\) and psi \((\psi)\) indicate the spin axis with theta \((\theta)\) denoting the rotation. The X and Y-axis are in the observed plane, the Z-axis points towards the observer.
Figure 7.2 - Reference frame used to calculate 3D ball transformation for a unique pattern match

In an image capturing sequence comprising 2 images of a ball in flight, the 1st image becomes the reference frame for the second image. Therefore, by determining the 3D transformation that the reference frame has undergone in order to reach the position of the 2nd image, the angles phi ($\phi$), psi ($\psi$) and theta ($\theta$) can be calculated. If the time interval between frames is known, the angular rotation theta can be expressed as a rotational velocity.

7.3.4 IMAGE PRO PLUS OVERVIEW

An image analysis software package called Image Pro Plus (IPP) was used to develop an automated method of measuring panel centroid coordinates. The IPP software package offers the capability to acquire, process, measure and analyse images within a single application. Image analysis functions within the system include segmentation, filtering, arithmetic and measurement operations. Colour segmentation tools within IPP enable the interactive separation of specific features from the background based on colour characteristics, and these tools were utilised for the automated identification of ball locations and individual panel colours. A visual basic compatible macro language allows IPP to be customised for specific applications and a software development kit (SDK) enables the creation of tailored versions of IPP for specific analytical imaging.

7.3.5 IPP COLOUR MODELS

There are two common colour models used in imaging: the Hue, Saturation and Intensity (HSI) colour model, and the Red, Green and Blue (RGB) colour model. The HSI colour model describes a colour in terms of how it is perceived by the human eye and expresses colours in varying amounts of hue, saturation and intensity. The hue element
essentially governs the colour or pigment seen by the human eye and corresponds to the wavelength of the radiation. Saturation corresponds to the amount of white light mixed in with the hue, and allows pale ‘washed out’ colours to be portrayed. Intensity is the brightness of the colour and is a measure of the number of photons reaching the eye. The HSI colour model is typically represented by a three dimensional coordinate system called a Munsell colour cylinder, as shown in Figure 7.3. The hue is arranged around the periphery of the cylinder, the radius represents saturation, and the cylinder axis represents intensity (Tilley, 2000).

![Figure 7.3 - Munsell colour cylinder HSI colour model](image)

Prior to the start of testing it was envisaged that segmentation could be achieved by selecting the HSI colour model and thresholding hue values within IPP. Imposing thresholding limits for hue can isolate specific regions of the colour spectrum (shown in Figure 7.4), therefore enabling the automatic recognition of specific colours within an image.

![Figure 7.4 - The colour spectrum](image)

The RGB colour model expresses colours in varying amounts of red, green and blue and is used by most digital imaging devices. The numerical range of both the HSI and RGB colour models within IPP is 0 - 255. Therefore, thresholding limits for individual colours can be expressed numerically in terms of hue, saturation and intensity, or alternatively red, green and blue.
7.3.6 REGION OF CONFIDENCE

The analysis of surface features on two-dimensional images of spherical balls in flight is subject to inherent spatial positioning errors due to ball surface sphericity. If an image of a ball in flight is obtained from a camera perpendicular to the balls motion, equally spaced markings will appear closer together around the edge of the ball, than in the centre. Therefore, for images of spherical balls, a 'Region of Confidence' (ROC) may be defined (Zarifi, 1996). The ROC for a spherical object was shown by Zarifi (1996) to be approximately 80% of the surface area visible when examining dimples on golf balls. The successful identification of a colour pattern on a two-dimensional ball image is dependent on accurate panel centroid coordinate data. Therefore, if the ROC is specified as the central 80% of the ball, panel centroid coordinates obtained from panels located on the ball extremities can be discounted to avoid positional error.

7.3.7 PROJECT ACTIVITY

Whilst the system concept was still in the early stages of development, the commercial possibilities of a soccer ball flight performance system were identified. The award of a Gatsby Innovation award in 2002 aided the development of the system with a view to potential commercialisation. The additional resources supplied by the Gatsby award allowed Chris Sumpter to be employed as a consultant to support the development of the system. At this stage it was agreed that work on the system development would be split up between Chris and the author.

Chris would be responsible for:

i) Developing the algorithms required for pattern matching and the reverse kinematics.
ii) Writing appropriate software for the system user interface.
iii) Identifying and testing a suitable image capturing system.
iv) Developing and manufacturing a prototype system.

Whilst the author would be responsible for:

i) Manufacturing prototype balls.
ii) Determining the feasibility of the concept through testing.
iii) Developing a method of automatic ball detection and pattern analysis using IPP.
v) Conducting field-testing to determine system accuracy.
7.4 SYSTEM DEVELOPMENT

An extensive program of testing was undertaken in order to develop an automated method of ball performance analysis using IPP. Firstly, a feasibility study was carried out in order to determine if IPP software was capable of identifying different coloured panels through the use of image segmentation. Secondly, 5 panel colours were specified that would fulfil the segmentation requirements, and thirdly, a suitable camera system for capturing images of a ball in flight was identified. Finally, automated methods of identifying ball location, and coloured panel arrangement within an image were developed.

7.4.1 SYSTEM CONCEPT FEASIBILITY STUDY

The first stage of testing was essentially a feasibility study to determine if IPP was capable of automatic panel colour identification. The panels of a standard 32-panel plain white soccer ball were arbitrarily assigned 5 different colours using permanent markers. The five colours selected were red, green, blue, black and white, and the prototype ball is shown in Figure 7.5.

![Figure 7.5 - Prototype ball #1 featuring arbitrary arrangement of red, green, blue, black and white coloured panels](image)

A NAC 500 colour high-speed video camera operating at 500 frames per second (2 ms/frame) with a shutter speed set at 1/1000s, was used to capture images of prototype ball #1 in flight. The image resolution was set at 640 x 480 pixels and the camera positioned ‘side-on’ perpendicular to the initial ball trajectory. The images were obtained indoors, and two high intensity floodlights were positioned either side of the camera in order to provide sufficient lighting for image capture. The high-speed video footage obtained was recorded directly onto standard VHS videocassettes using a video recorder linked to the NAC system. This video footage was later converted into digital format using MGI VideoWave 4 video capturing software. Corel Photopaint software was used to identify and extract suitable
frames of the ball in flight from within each video capture. An image of prototype ball #1 in flight is shown in Figure 7.6.

![Figure 7.6 - Indoor image of prototype ball #1 obtained using NAC 500 high speed camera](image)

The use of floodlights in order to provide sufficient illumination of the ball is non-ideal in that the inherent directionality of the floodlights causes specular reflections at some critical angles of view. This effect is most noticeable on the green central panel where bright illuminant reflections have reduced the colour saturation markedly.

The successful identification of the coloured panels through segmentation is dependent on the establishment of threshold limits for each panel colour using the HSI colour model. In order to derive approximate threshold limits for each of the 5 colours, a specific area of interest (AOI) was created to fit inside each individual panel using the standard AOI function within IPP. The colour properties of the panel were then analysed using the HSI histogram function within IPP, and the HSI histogram obtained for the central green panel is shown in Figure 7.7. The histogram shows a localised peak for hue (red trace) around 100, with the limits at around 60 and 120. Using this data the green panels within the image could be identified by imposing threshold limits between 60 and 120. The same procedure was used to determine appropriate threshold limits for the other 4 panel colours.
The approximate threshold limits for each of the colours determined experimentally are shown in Table 7.2. The white panels could not be accurately segmented in terms of hue, therefore saturation and intensity threshold limits were used as an alternative.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Hue</th>
<th>Saturation</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>240 - 5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Green</td>
<td>60 - 120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue</td>
<td>145 - 170</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Black</td>
<td>80 - 150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>White</td>
<td>-</td>
<td>0 - 30</td>
<td>100 - 255</td>
</tr>
</tbody>
</table>

Table 7.2 - Threshold limits derived for coloured panels on prototype ball #1

The background of the image shown in Figure 7.6 contains considerable colour information that could potentially interfere with the identification of colours within the ball image; therefore it was essential to limit the colour segmentation exercise to a circular area of interest containing the ball. In the first instance the segmentation exercise was limited to the ball by manually creating a circular AOI around the ball perimeter using the standard AOI function within IPP. Upon the establishment of the AOI, image segmentation was executed using the threshold limits defined in Table 7.2. Selection of the HSI colour model enabled image segmentation through the thresholding of hue, saturation and intensity; however
colour segmentation can generally be achieved through thresholding of hue levels alone. The exception was found to be during thresholding of white panels, as this could not be achieved using hue values alone. It was found experimentally that saturation and intensity had to be used as an alternative. Figure 7.8 illustrates the segmentation process by the thresholding of the blue panels within the image.

![Image of segmentation process](image)

**Figure 7.8 - Image segmentation by thresholding of the blue panels within IPP**

The location of the blue panels was signified through the use of a neutral pink colour, as shown in Figure 7.8. A binary image was created by applying a mask to the AOI which converted the areas in pink to white clusters, whilst reducing the remainder of the AOI to black. A 2x2 morphological erosion filter was performed in order to remove isolated points, and the resulting binary groups measured for area and pixel coordinate centroid position using the count/size function within IPP. The filters reduce the intensity of outlying pixels by reducing the rate of brightness change within an image. The process is illustrated in Figure 7.9.
7.4.1.1 Results

At this stage it became necessary to determine panel centroid coordinates for a series of panels on view in an image. It was decided that a manual inspection of the individual panel centroid coordinates could be considered to be the standard for comparison. Although subject to inherent human error, manual inspection provides a sufficient means of determining panel centroid coordinates to an accuracy of +/- 1 pixel. Image segmentation was used to estimate the centroid coordinates of each coloured panel contained within the AOI. Table 7.3 shows a comparison of the coordinates obtained within IPP compared with panel centroid coordinates estimated by manual inspection of the image frame.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( x )</td>
<td>( y )</td>
<td>( x )</td>
</tr>
<tr>
<td>Red 01</td>
<td>196</td>
<td>192</td>
<td>197</td>
</tr>
<tr>
<td>Red 02</td>
<td>280</td>
<td>196</td>
<td>275</td>
</tr>
<tr>
<td>Green 01</td>
<td>239</td>
<td>218</td>
<td>233</td>
</tr>
<tr>
<td>Blue 01</td>
<td>240</td>
<td>166</td>
<td>236</td>
</tr>
<tr>
<td>Blue 02</td>
<td>190</td>
<td>242</td>
<td>191</td>
</tr>
<tr>
<td>Blue 03</td>
<td>262</td>
<td>284</td>
<td>262</td>
</tr>
<tr>
<td>Black 01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Black 02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>White 01</td>
<td>305</td>
<td>219</td>
<td>304</td>
</tr>
<tr>
<td>White 02</td>
<td>233</td>
<td>261</td>
<td>233</td>
</tr>
</tbody>
</table>

Table 7.3 - Panel centroid measurements for image containing prototype ball #1

Unfortunately the hue threshold limits derived for the black panels included both elements of the hue threshold ranges for green and blue. This prevented detection of the black panels, as IPP was unable to differentiate between black, green and blue panels. It was therefore decided to produce a second prototype ball with the black panels replaced by yellow panels. The colour yellow is located between red and green in the colour spectrum shown in Figure 7.4, therefore it was envisaged that the hue range for yellow would not be in conflict with any of the other colours.

The threshold limits derived for the red, green, blue and white panels produced estimations of panel centroid coordinates that were in reasonable agreement with those obtained by manual inspection of the image frame. Generally the panel centroid estimations from segmentation were accurate to within \(+/- 7\) pixels (in \(x\) and \(y\)), of the estimates from manual inspection. However, the positional error observed for the green and blue panels was increased by interference from adjoining black panels. The replacement of black panels with yellow should reduce positional error for the green and blue panels. Although care was taken to ensure that the manual estimation of the panel centroid coordinates was as accurate as possible, the inherent errors present in manual estimation (\(+/- 1\) pixel) should be given consideration.
7.4.2 OPTIMISATION OF PANEL IDENTIFICATION PROCEDURE

The feasibility study had shown that black was an unsuitable colour for segmentation, due to the hue range of the black panels being in conflict with those of the green and blue panels. Therefore a second prototype ball was manufactured, shown in Figure 7.10 and consisting of red, yellow, green, blue and white panels.

Figure 7.10 - Prototype ball #2 featuring unique arrangement of red, yellow, green, blue and white coloured panels

The colours on the first prototype ball were arbitrarily marked on the panels, however the colours on the second prototype ball were specifically marked using permanent marker pens according to the colour relationship requirements of the algorithm, as given in Table 7.1. An exploded view of the panel colour arrangement required for rotational ‘uniqueness’ is shown in Figure 7.11.

Figure 7.11 - Exploded view of panel colour assignment derived from genetic algorithm
An image of prototype ball #2 in flight obtained with the NAC 500 high-speed camera using the same procedure outlined in Section 7.4.1 is shown in Figure 7.12.

![Image of prototype ball #2](image)

**Figure 7.12 - Indoor image of prototype ball #2 obtained using NAC 500 high speed camera**

The threshold limits for the yellow panels were determined using the same procedure described in Section 7.4.1, and found to exist between hue values of 25 and 40. Crucially this range did not conflict with any of the other panel colours. The colour threshold limits for prototype ball #2 are shown in Table 7.4.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Hue</th>
<th>Saturation</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>240-5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yellow</td>
<td>25-40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Green</td>
<td>60-120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue</td>
<td>145-170</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>White</td>
<td>-</td>
<td>0-30</td>
<td>100-255</td>
</tr>
</tbody>
</table>

Table 7.4 - Threshold limits derived for coloured panels on prototype ball #2

A manual AOI was created and positioned around the ball in Figure 7.12 and image segmentation was used to calculate the centroid coordinates of each panel, as described previously in Section 7.4.1.
7.4.2.1 Results

The panel centroid coordinates estimated by image segmentation were compared with the panel centroid coordinates estimated by manual inspection of the image frame. The results are shown in Table 7.5.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>X</td>
</tr>
<tr>
<td>Red 01</td>
<td>256</td>
<td>232</td>
<td>254</td>
</tr>
<tr>
<td>Red 02</td>
<td>237</td>
<td>293</td>
<td>235</td>
</tr>
<tr>
<td>Yellow 01</td>
<td>211</td>
<td>269</td>
<td>213</td>
</tr>
<tr>
<td>Yellow 02</td>
<td>270</td>
<td>285</td>
<td>270</td>
</tr>
<tr>
<td>Green 01</td>
<td>283</td>
<td>235</td>
<td>281</td>
</tr>
<tr>
<td>Green 02</td>
<td>220</td>
<td>241</td>
<td>224</td>
</tr>
<tr>
<td>Blue 01</td>
<td>227</td>
<td>215</td>
<td>228</td>
</tr>
<tr>
<td>Blue 02</td>
<td>250</td>
<td>264</td>
<td>245</td>
</tr>
<tr>
<td>White 01</td>
<td>258</td>
<td>210</td>
<td>258</td>
</tr>
<tr>
<td>White 02</td>
<td>205</td>
<td>237</td>
<td>206</td>
</tr>
<tr>
<td>White 03</td>
<td>275</td>
<td>254</td>
<td>275</td>
</tr>
</tbody>
</table>

Table 7.5 - Panel centroid measurements for image containing prototype ball #2

The panel centroid coordinates determined by image segmentation were accurate to within +/- 5 pixels (in x and y), of the manual inspection estimates. The accuracy obtained for prototype ball #1 in comparison with the manual inspection estimates was +/- 7 pixels based on the maximum observed error. Therefore the use of prototype ball #2 appeared to reduce the difference between automated and manual centroid estimation. Table 7.6 shows a comparison of the average centroid position differences and the associated standard deviations (in both x and y) for prototype ball #1 and #2. Both average centroid position differences and standard deviation were lower for prototype ball #2, most likely due to the replacement of the black panels with yellow.
<table>
<thead>
<tr>
<th>Image Analysis</th>
<th>Average Positional Difference (pixels)</th>
<th>Standard Deviation (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>Prototype Ball #1</td>
<td>2.28</td>
<td>2.68</td>
</tr>
<tr>
<td>Prototype Ball #2</td>
<td>1.85</td>
<td>2.08</td>
</tr>
</tbody>
</table>

Table 7.6 - Analysis of panel centroid positional error for prototype ball #1 and prototype ball #2

The first two stages of preliminary testing confirmed that automatic location of coloured panels using IPP was possible. However, assuming that manual inspection of the image frame gave an accurate estimate of the panel centroid coordinates, the accuracy of the automated segmentation method could be improved upon. The use of red, yellow, green, blue and white panels was found to be the optimum colour selection for successful and un-conflicting panel segmentation. Although the generation of an AOI around the ball was carried out manually during the first two stages of testing, a new method of determining ball location would be required in order to achieve a fully automated system.

7.4.3 AUTOMATIC IDENTIFICATION OF BALL LOCATION AOI WITHIN AN IMAGE FRAME

A program of advanced testing was carried out in both indoor and outdoor conditions using an alternate image capturing system. The NAC 500 high-speed camera had originally been used to obtain a sequence of images of the prototype balls in flight. However the quality and clarity of the images obtained were questionable compared with the quality of images obtainable from digital cameras. Therefore, it was decided to experiment with a Canon XM1 digital camera running at 30 frames per second and set at a shutter speed of 1/2800s in order to obtain sharp, good quality images. The use of a slower camera reduced the number of sequential images that could be obtained in the camera field of view considerably. The NAC 500 could obtain around 20 images of the ball in flight within the field of view, whereas depending on ball velocity; only 2 or 3 images could be obtained using the Canon XM-1. However, providing the time between frames is known, 2 sequential images of a ball in flight are sufficient for the computation of initial ball velocity, elevation and spin rate.

7.4.3.1 Indoor Testing

A Canon XM1 digital camera operating at 30 frames per second was used to capture indoor images of prototype ball #2 in flight. The optimum shutter speed for sharp, good quality images was determined experimentally to be 1/2800s, with two floodlights providing sufficient additional lighting. The image resolution was set at 640 x 480 pixels and the camera positioned ‘side-on’ perpendicular to the initial ball trajectory. The video footage was later
transferred onto a PC using MGI VideoWave 4 video capturing software. Corel Photopaint software was used to identify and extract 3 image frames from each capture: 1 frame immediately before the ball came into the camera field of view, and 2 frames featuring the ball in flight within the field of view. The purpose of selecting a frame without an image of the ball was to provide a means of automatically detecting ball position within the image frame. The sequence of images obtained is shown in Figure 7.13 (the ball was moving from left to right).

Figure 7.13 - Sequence of images of prototype ball #2 obtained using Canon XM1 digital camera
7.4.3.1.1 Determination of Ball Location

Preliminary testing described in Sections 7.4.1 and 7.4.2 had shown that automatic detection of individual panel colours was possible. However, positioning of an AOI around the ball had been carried out manually, and a method of automatically determining ball location had not been attempted. In order to calculate the spatial position of a ball within an image, a ‘reference frame’ containing an image of the camera field of view immediately prior to each ball capture was obtained. The selection of a ‘reference frame’ was necessary in order to perform an image differencing operation on the 2 subsequent frames containing the ball. The image differencing function compared the ‘reference image’ and an image containing the ball and effectively eliminated aspects of the image that were indistinguishable. A new image was then created containing only aspects of the compared images that were disparate (i.e. the ball itself), as shown in Figure 7.14.

Figure 7.14 - 1st ball image undergoing arithmetic image ‘differencing (absolute)’ operation in order to identify ball location within the image frame

The ball location was identified by selecting the RGB colour model and performing segmentation on the entire image. The RGB model was used in preference to the HSI model as the RGB model provided a superior method of thresholding a coloured ball against a black background. Threshold limits of 0 - 20 for red, green and blue were used to apply a mask to the image, producing a binary image containing disparate elements of the image. The
resulting circular object corresponding to ball location was detected and measured for centroid position, area and the maximum height and width of the 'bounding square' around the object, as shown in Figure 7.15.

Figure 7.15 - Automatic identification of ball location within image frame

The measurement options within IPP were set-up to identify circular objects by imposing a limit on object area and setting roundness measurement parameters. However, the white binary objects obtained after thresholding were sometimes not completely circular; therefore an additional measurement that specified the maximum diameter along any axis around the object was selected. This measurement was required in order to generate an accurate 'bounding square' around the ball, in the event of the horizontal or vertical diameter being eroded during thresholding. Occasionally as the foot of the kicker followed through after impact with the ball, the kicking foot came into the camera field of view. This caused the presence of the foot to be detected during the thresholding process, as exemplified by the white cluster on the left hand side of the image in Figure 7.15. In order to discount the presence of the foot within the image during the measurement process, 2 additional measurement options were applied to the measurement procedure. Measurement parameters were set for the aspect ratio and radius ratio measurements within the count/size function in IPP. These measurements were utilised in order to ensure that only objects that exhibited a
reasonable degree of circularity were detected. The count/size option box within IPP showing the measurement parameters used to detect and locate circular objects is shown in Figure 7.16.

![Select Measurements](image)

**Figure 7.16 - Measurement settings required for detection and measurement of circular objects**

### 7.4.3.1.2 Coloured Panel Analysis

The calculation of ball location was the first stage of image analysis; and the second stage was the identification of the coloured panels and the determination of the centroid coordinates. The images obtained from the Canon XM1 camera had considerably different colour properties to those obtained using the NAC 500, therefore it was necessary to re-determine the thresholding limits for each panel colour using the same procedure described in Section 7.4.1. The approximate colour threshold limits for prototype ball #2 using the Canon XM1 are shown in Table 7.7. At certain ball orientations the yellow panels experienced considerable specular reflection caused by the floodlighting, therefore a saturation range of 100 - 255 was specified in order to discriminate against the white panels.
<table>
<thead>
<tr>
<th>Colour</th>
<th>Hue</th>
<th>Saturation</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>0 - 10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Yellow</td>
<td>23 - 45</td>
<td>100 - 255</td>
<td>-</td>
</tr>
<tr>
<td>Green</td>
<td>50 - 100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue</td>
<td>160 - 255</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>White</td>
<td>-</td>
<td>0 - 100</td>
<td>120 - 255</td>
</tr>
</tbody>
</table>

Table 7.7 - Threshold limits for coloured panels on prototype ball #2 using Canon XMI in indoor testing conditions

7.4.3.1.3 Results

Four ball strikes were captured indoors and three images extracted from each capture: a reference image immediately prior to impact, and two sequential images of the ball in flight. Three individual macros were written within IPP to achieve an automated image analysis process. The first macro identified the ball by RGB colour segmentation using the method described in Section 7.4.3.1.1, the second macro calculated the 'bounding square' coordinates for each ball and the third macro calculated the panel centroid coordinates using the threshold limits outlined in Section 7.4.3.1.2. The combination of the three macros in order allowed the automated location of each ball and estimation of the panel centroid coordinates. Table 7.8 shows a comparison between the ball 'bounding square' coordinates calculated using IPP, and the estimated ball 'bounding square' coordinates determined by manually creating an AOI around the ball within the image frame.
Table 7.8 - Positional difference between 'bounding square' coordinates obtained by IPP and manual inspection

<table>
<thead>
<tr>
<th>Image ID</th>
<th>Ball Location method using IPP (pixels)</th>
<th>Ball Location by Manual Inspection (pixels)</th>
<th>Positional Difference (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top Left</td>
<td>Bottom Right</td>
<td>Top Left</td>
</tr>
<tr>
<td>Image 1a</td>
<td>160, 201</td>
<td>251, 291</td>
<td>159, 200</td>
</tr>
<tr>
<td>Image 1b</td>
<td>453, 119</td>
<td>541, 207</td>
<td>451, 118</td>
</tr>
<tr>
<td>Image 2a</td>
<td>90, 223</td>
<td>185, 317</td>
<td>91, 222</td>
</tr>
<tr>
<td>Image 2b</td>
<td>398, 140</td>
<td>491, 232</td>
<td>398, 140</td>
</tr>
<tr>
<td>Image 3a</td>
<td>122, 207</td>
<td>211, 298</td>
<td>122, 208</td>
</tr>
<tr>
<td>Image 3b</td>
<td>419, 124</td>
<td>505, 212</td>
<td>417, 124</td>
</tr>
<tr>
<td>Image 4a</td>
<td>34, 233</td>
<td>132, 327</td>
<td>35, 233</td>
</tr>
<tr>
<td>Image 4b</td>
<td>375, 132</td>
<td>473, 227</td>
<td>376, 132</td>
</tr>
</tbody>
</table>

The positional differences between the 'bounding squares' generated using IPP and by manual inspection were small. Assuming that manual creation of an AOI around the ball is an accurate estimate of ball perimeter, the positional 'error' of the IPP method can be determined. The mean pixel error for the x-axis was 1.19, and the mean pixel error for the y-axis was 0.69. The largest positional error was observed in the analysis of Image 3b, with a maximum error of 3 pixels in x and y for the bottom right corner of the 'bounding square'. The coloured panel centroid coordinates for the 8 test images were analysed using the IPP calculated 'bounding square' as the AOI, and the results are given in Appendix 17. After successful application of the 3 macros, the panel centroid data along with the ball 'bounding square' coordinates were inserted into a bespoke spin analysis software tool developed by Chris Sumpter in order to determine rotational 'uniqueness' and calculate the axis of spin using the principle described in Section 7.3.3. The spin analysis software tool was based around the pattern match algorithm and was written as a Java applet so that it could be used in Internet Explorer.
The results for the four pairs of images were analysed in turn using the spin analysis tool. The software required the ‘enclosing square’ and panel centroid coordinates for each ball to be manually inserted by the user as shown in Figure 7.17. If a single unique solution was found for each ball image, the software used the algorithm to calculate the axis of spin, expressed as phi (\( \phi \)), psi (\( \psi \)) and the spin rate expressed as theta (\( \theta \)) and shown in Figure 7.18. However, if zero or multiple solutions were found for a particular image, the software was unable to calculate the spin axis and an error message was displayed. Failure to obtain a unique pattern match was generally due to accuracy errors with either ball location, or failure to identify a sufficient number of panels during the image analysis process.
Figure 7.18 - Determination of spin axis using spin analysis tool (developed by Chris Sumpter)

The results of the ball spin analysis for the four pairs of indoor test images are shown in Table 7.9.

<table>
<thead>
<tr>
<th>Image ID</th>
<th>Outcome</th>
<th>Spin Axis (deg)</th>
<th>Rotation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phi (φ)</td>
<td>Psi (ψ)</td>
</tr>
<tr>
<td>Image Set 1</td>
<td>Pass</td>
<td>-9</td>
<td>47</td>
</tr>
<tr>
<td>Image Set 2</td>
<td>Fail</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Image Set 3</td>
<td>Pass</td>
<td>-45</td>
<td>68</td>
</tr>
<tr>
<td>Image Set 4</td>
<td>Pass</td>
<td>72</td>
<td>-30</td>
</tr>
</tbody>
</table>

Table 7.9 - Velocity, elevation and spin rate results for indoor ball captures

The spin analysis software successfully identified a pattern match for 7 of the 8 ball images. However, image 2a returned zero solutions when analysed due to a failure to obtain coordinate data for a sufficient number of panels. The successful identification of the colour patterns in image sets 1, 3 and 4 enabled the calculation of the axis of spin for each ball capture. The successfully identification of 7 pattern matches from 8 ball images, gave a success rate of 88%.
7.4.3.2 Outdoor Testing

A sample of 4 impact captures were obtained on an outdoor soccer pitch in order to assess the suitability of the procedure in different lighting conditions. The equipment used was the same as used in the indoor testing described in Section 7.4.3.1, however, additional floodlighting was not required as natural light provided sufficient illumination. A sequence of images obtained outdoors is shown in Figure 7.19 (the ball was moving from right to left).

Figure 7.19 - Sequence of outdoor images of prototype ball #2 obtained using Canon XM1 digital camera
7.4.3.2.1 Determination of Ball Location

The spatial position of the ball within each image was determined using the same procedure described in Section 7.4.3.1.1. Figure 7.20 shows the ball location as a circular white object after undergoing RGB thresholding within IPP. Unlike the images obtained indoors, a significant display of white pixel 'noise' can clearly be observed in the binary image. In this case it was not possible to identify the ball location, as IPP was not able to identify the circular outline of the ball due to interference caused by the background image 'noise'.

![Figure 7.20](image)

Figure 7.20 - Binary image illustrating the problem caused by a non-static background during automatic identification of ball location

The background pixel 'noise' was caused by the movement of trees between frames in the background of the camera field of view. The tree movement was caused by high winds and some changes were made to the ball location macro in order to reduce the problems caused by background movement in an image. The arithmetic process used to eliminate the image background compared the images containing the ball with a 'reference image' obtained before the ball came into the field of view. However, the time delay between the 'reference frame' and the frames containing the ball was clearly too long and having an adverse effect on results. Disregarding the reference frame and performing the arithmetic difference comparison on the two sequential image frames containing the ball reduced the time delay to
0.03 seconds. This change minimised any movement in the background of an image, and also allowed the ball locations to be identified in a single image, reducing processing time. To further reduce the background pixel ‘noise’, a 3x3 rank filter and a 2x2 morphological erosion filter were used on the binary image in order to remove some of the isolated pixel clusters caused by the background movements. The effect of the modifications can be seen in Figure 7.21.

Figure 7.21 - Modified automatic identification of ball location in order to reduce the effect of background movement

Figure 7.21 shows the improved method of ball location identification that allows the spatial location of both balls to be determined at the same time. It was not originally possible to locate the position of the left hand ball (as shown in Figure 7.20), however, the modifications made to the macro enabled both balls to be successfully located. Clearly there is still some background ‘noise’ caused by the tree movement however, the macro modifications succeeded in reducing the extent of the ‘noise’ considerably.

7.4.3.2.2 Coloured Panel Analysis

The colour properties of the images obtained in natural light varied slightly to those obtained indoors using floodlights. Therefore it was necessary to experimentally re-determine the thresholding limits for each panel colour using the same procedure as described in
Section 7.4.1. The approximate colour threshold limits for prototype ball #2 in outdoor conditions are shown in Table 7.10.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Hue</th>
<th>Saturation</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>0 - 20 &amp; 240 - 255</td>
<td>30 - 255</td>
<td>-</td>
</tr>
<tr>
<td>Yellow</td>
<td>25 - 45</td>
<td>50 - 255</td>
<td>50 - 255</td>
</tr>
<tr>
<td>Green</td>
<td>50 - 120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Blue</td>
<td>130 - 230</td>
<td>20 - 230</td>
<td>-</td>
</tr>
<tr>
<td>White</td>
<td>-</td>
<td>0 - 50</td>
<td>120 - 255</td>
</tr>
</tbody>
</table>

Table 7.10 - Threshold limits for coloured panels on prototype ball #2 using Canon XM1 in outdoor testing conditions

Lighting conditions outdoors are extremely variable and dependent on factors such as the time of day, intensity of sunlight and amount of cloud cover. Consequently, the threshold limits for ball panels in outdoor conditions also include saturation and intensity parameters in order to further discriminate against the other colours.

7.4.3.2.3 Results

Four ball impacts were captured during outdoor testing, and the set of modified macros used to determine ball 'bounding square' and coloured panel centroid coordinates. Table 7.11 shows a comparison between the ball 'bounding square' coordinates calculated using IPP, and the estimated 'bounding square' coordinates determined by manual inspection of the image frame.
<table>
<thead>
<tr>
<th>Image ID</th>
<th>Ball Location method using IPP (pixels)</th>
<th>Ball Location by Manual Inspection (pixels)</th>
<th>Positional Difference (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top Left</td>
<td>Bottom Right</td>
<td>Top Left</td>
</tr>
<tr>
<td>Image 1a</td>
<td>406,239</td>
<td>508,335</td>
<td>407,239</td>
</tr>
<tr>
<td>Image 1b</td>
<td>49,184</td>
<td>148,280</td>
<td>50,184</td>
</tr>
<tr>
<td>Image 2a</td>
<td>467,351</td>
<td>552,434</td>
<td>467,352</td>
</tr>
<tr>
<td>Image 2b</td>
<td>134,343</td>
<td>223,433</td>
<td>134,344</td>
</tr>
<tr>
<td>Image 3a</td>
<td>283,201</td>
<td>364,277</td>
<td>284,201</td>
</tr>
<tr>
<td>Image 3b</td>
<td>1,130</td>
<td>79,209</td>
<td>0,134</td>
</tr>
<tr>
<td>Image 4a</td>
<td>510,280</td>
<td>601,366</td>
<td>511,280</td>
</tr>
<tr>
<td>Image 4b</td>
<td>164,180</td>
<td>249,266</td>
<td>164,182</td>
</tr>
</tbody>
</table>

Table 7.11 - Positional difference between 'bounding square' coordinates obtained by IPP and manual inspection

The positional difference between the 'bounding squares' generated using IPP and by manual inspection were a maximum of 3 pixels for the x-axis and 4 pixels for the y-axis. Therefore, assuming the manual inspection estimate to be accurate, the mean pixel error for the x-axis was 1.25, and the mean pixel error for the y-axis was 1.19. The mean error values are slightly higher than those obtained for the indoor captures, with the x-axis error slightly better than the y-axis possibly due to a small amount of blur in the image due to the motion of the ball. The largest positional error was observed in the analysis of image 2b, with a maximum error of 3 pixels in x and y for the bottom right corner of the 'bounding square'. The panel centroid coordinates results obtained for the 8 test images are given in Appendix 18. In order to determine rotational 'uniqueness' the panel centroid data along with the ball 'bounding square' coordinates were inserted into the spin analysis tool as described in Section 7.4.3.1.3. The ball spin analysis results for the four pairs of outdoor test images are shown in Table 7.12.
A unique colour pattern was determined for 7 out of the 8 images, giving an identical success rate to that obtained indoors. Image 2 failed to locate one of the three white panels on the ball during the segmentation process. The successful identification of the colour patterns in image sets 1, 3 and 4 enabled the calculation of the spin rate and spin axis for each ball capture.

### 7.4.4 SYSTEM ACCURACY

The accuracy of the algorithm spin measurement was assessed using a coloured ball model created within Unigraphics (UG) software, and shown in Figure 7.22. A CAD model of a spherical 32-panel soccer ball was created within UG, and red, yellow, green, blue and white colours were assigned to the exterior panels according to the arrangement detailed in Figure 7.11. The UG system was used to accurately rotate the ball through a nominated angle, about a defined axis. By comparing the spin rate and spin axis results obtained using the algorithm, with the spin rate and axis assigned to the ball within UG, it was possible to determine the system accuracy.

![Figure 7.22 - UG model of coloured ball used to assess spin measurement accuracy](image)

### Table 7.12 - Velocity, elevation and spin rate results for outdoor ball captures

<table>
<thead>
<tr>
<th>Image ID</th>
<th>Outcome</th>
<th>Spin Axis (deg)</th>
<th>Rotation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phi (φ)</td>
<td>Psi (ψ)</td>
</tr>
<tr>
<td>Image Set 1</td>
<td>Pass</td>
<td>6</td>
<td>69</td>
</tr>
<tr>
<td>Image Set 2</td>
<td>Fail</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Image Set 3</td>
<td>Pass</td>
<td>89</td>
<td>78</td>
</tr>
<tr>
<td>Image Set 4</td>
<td>Pass</td>
<td>-65</td>
<td>-70</td>
</tr>
</tbody>
</table>
A reference image of the ball model in an arbitrary orientation was obtained within UG and the model rotated 30° about an oblique spin axis (\( \varphi = 90^\circ, \psi = 45^\circ \)), in order to create a second image. The two ball images were analysed within IPP for ball ‘enclosing square’ and panel centroid coordinates using the macros described previously, and the rate and axis of spin determined using the spin analysis tool described in Section 7.4.3.1.3. A second reference image was then created for an arbitrary ball orientation, and the ball rotated 60° about an oblique spin axis (\( \varphi = 45^\circ, \psi = 45^\circ \)). The rate and axis of spin were obtained using the same procedure as described previously. The results for the two pairs of ball images are shown in Table 7.13.

<table>
<thead>
<tr>
<th>Image ID</th>
<th>Rotation (deg)</th>
<th>Spin Axis (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theta (( \theta ))</td>
<td>Phi (( \varphi ))</td>
</tr>
<tr>
<td>Image Set 1</td>
<td>31</td>
<td>88</td>
</tr>
<tr>
<td>Image Set 2</td>
<td>61</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 7.13 - Ball rotation and spin axis results for UG ball model images

The ball rotation calculated from the pattern match algorithm for the first pair of images was 31° and for the second set of images 61°. The spin axis for the first pair of images was calculated as (\( \varphi = 88^\circ, \psi = 44^\circ \)), and for the second pair of images (\( \varphi = 43^\circ, \psi = 43^\circ \)). The results demonstrate the spin measurement accuracy of the pattern match algorithm. Based on the results obtained from the UG ball model, spin measurement can be considered as being accurate to +/- 1 degree with spin axis measurement accurate to +/- 2 degrees. In terms of spin rate measurement, the results show that the system would be accurate to +/- 0.1 revs/s (6.0 rpm).

7.5 PROTOTYPE SYSTEM

The results obtained during testing using the Canon XM-1 camera system showed that an accurate automated system capable of ball velocity, elevation and spin rate measurement was attainable, and led to the development and manufacture of a prototype image capturing system. Chris Sumpter was responsible for the development and manufacture of a prototype system with a view towards potential commercialisation. The system consisted of an image capture unit connected to a laptop computer running IPP software. The image capture unit consisted of a camera, two flash units, a microphone, battery and a PCB containing control hardware. The unit could potentially be powered from the battery in order to allow testing to be carried out in the field, although the battery was limited to around 30 captures before
recharging was required. The prototype unit is shown in Figure 7.23 along with a specially manufactured soccer ball with coloured panels. A sample of 32-panel 'FIFA Approved' standard balls were specially manufactured in Pakistan to conform to the panel colour distribution outlined in Figure 7.11.

![Figure 7.23 - Prototype image capture unit mounted on tripod with specially manufactured coloured soccer ball](image)

The image capture unit was connected to a laptop via a firewire connection enabling ball images to be exported into IPP for immediate processing. A firewire repeater was added to the capture unit in order to allow the firewire connection to supply power to the camera.

### 7.5.1 IMAGE CAPTURE SYSTEM

The prototype image capture system utilised a progressive scan camera synchronised with two flash units in order to obtain two sequential images of a ball in flight. A digital colour CCD (charge coupled device) progressive scan video camera with an IEEE-1394 firewire interface was used for image capture. The camera was delivered with a software development kit (SDK) that allowed software integration, and the IEEE-1394 interface allowed images to be transferred directly to a laptop running IPP software. The camera operated at 30 frames per second and was set at a shutter speed of 1/8000s, with a gain setting of 8 dB. The camera lens had a focal length of 4mm giving a horizontal field of view of 60°. The flash units were standard commercially available units with a flash duration of 1
ms and a horizontal field of view of 60°. The battery contained within the unit was a 12v lead acid battery and the microphone was a standard commercially available condenser microphone.

The pair of flash units were incorporated into the capture unit in order to allow the system to be used both indoors and outdoors irrespective of lighting conditions. Image capture was triggered by the impact sound of a player striking the ball, prior to the ball entering the camera field of view. For normal assessment of reasonable ball velocity kicks, the ball was positioned 2m from the camera unit (in the direction of travel), and 2m from the camera lens (in the direction of view), as shown in Figure 7.24.

![Figure 7.24 - Ball impact location relative to camera unit required for normal assessment of reasonable velocity kicks](image)

The microphone detected the ball impact, and after a set time delay of 67 ms, the flash units were activated within 1 frame (33 ms) of each other in order to attain two sequential images. The delay after impact was set to 67 ms in order to ensure that the ball had travelled a suitable distance away from the foot. If the kicking foot and the ball were in close proximity within the image frame at the capture of the first image, the system could potentially fail to recognise the circular profile of the ball.

7.5.2 IMAGE ANALYSIS

The Image Pro Plus software package included a software development kit (SDK) for the development of customised IPP applications. In conjunction with the SDK, Chris Sumpter developed a customised software interface for the image capture and subsequent image analysis operations within IPP. The customised interface was created in Visual C++ and inserted into IPP as a single ‘plug-in’. The IPP ‘plug-in’ essentially consisted of 4 sections covering:
i) Communication with the camera in order to capture ball images.

ii) Image analysis macros for obtaining ball location and panel coordinate data.

iii) Algorithms for determining ball launch characteristics.

iv) Display of results on screen.

The image analysis macros used for obtaining ball location and panel coordinates within the prototype system can be found in Appendix 19. The results from a typical capture displayed within the customised IPP interface are shown in Figure 7.25. Measurements have been obtained for ball velocity, elevation, spin rate and spin axis.

![Figure 7.25 - Results displayed from a typical capture obtained using the prototype system](image)

7.5.3 COLOUR OPTIMISATION

A sample of coloured balls were manufactured for testing and the colours specifically chosen to closely match the colours originally applied by permanent marker on prototype ball #2. The precise colours used were defined using Pantone colour standards. The use of a new ball and camera system required that the ball panel thresholding limits required re-evaluation using the same procedure described in Section 7.4.1. The threshold limits for the manufactured balls along with the associated Pantone colour designations for each colour are shown in Table 7.14. The threshold limits were derived experimentally from both indoor and outdoor captures.
Table 7.14 - Threshold limits for coloured panels on specially manufactured balls using prototype image capture system

7.6 SYSTEM EVALUATION

The prototype system was evaluated extensively in a range of different locations, including sports halls, laboratories, exhibition halls and outdoor playing surfaces. During the evaluation tests the capture unit was mounted on a tripod and fixed at a height of approximately 0.4m from the floor. This section presents an evaluation of the system, describing the problems identified during testing, and potential solutions.

7.6.1 ASSESSMENT OF IMAGE CAPTURE RANGE

Ball size and illumination within the image frame diminish considerably as a ball is moved further away from the camera lens, severely restricting measurement accuracy. The camera in the prototype unit operated at a resolution of 640 x 480 pixels, therefore using trigonometry and taking into account the camera field of view, estimations for ball pixel diameter could be obtained for a range of distances from the camera, as shown in Table 7.15.

Table 7.15 - Decrease in ball pixel diameter as ball distance from camera lens is increased

Table 7.14 - Threshold limits for coloured panels on specially manufactured balls using prototype image capture system
capturing distance for consistent, accurate and successful image analysis, a series of ball images were obtained at a range of distances from the camera lens.

An experienced university standard soccer player was instructed to perform straight medium velocity instep kicks at a range of distances from the camera and the results were analysed to determine system accuracy. The distance settings were 1.0, 1.5, 2.0, 2.5 and 3.0m, and 5 captures were obtained at each setting. The tests were performed in 2 locations: an indoor laboratory, and an outdoor natural turf soccer pitch. An ISO-TECH digital light meter was used to measure lighting conditions at each location, in order to compare indoor and outdoor luminance. To obtain a reading the light meter sensor was positioned on the capture unit facing the camera field of view. The indoor laboratory produced a luminance reading of 180 lux, and the results are shown in Table 7.16. The ‘Ball Location’ column indicates the number of times the system successfully located ball position within the image frame, and the ‘Ball Spin Measurement’ column indicates the number of times the system successfully calculated ball spin. The ‘Success Rate’ column indicates the percentage of successful system captures achieved. Clearly, failure to measure ball location or rotation resulted in an unsuccessful capture.

<table>
<thead>
<tr>
<th>Distance From Camera Lens (m)</th>
<th>Ball Location Success</th>
<th>Ball Spin Measurement Success</th>
<th>Overall capture Success Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>5/5</td>
<td>0/5</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>2.5</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>3.0</td>
<td>1/5</td>
<td>1/5</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7.16 - System results for image captures obtained in an indoor laboratory

Table 7.16 shows that the system failed to measure ball spin for any of the 5 captures obtained at a distance of 1m from the camera lens. However, ball locations were successfully identified for all 5 captures. Failure to measure ball spin was due to the panel colours becoming ‘washed out’ as a result of a decrease in image saturation caused by the close proximity of the flash units. An example of an image obtained at a 1m distance is shown in Figure 7.26. The decrease in saturation did not affect detection of the red, yellow, green and blue panels, as they were thresholded by hue level and were not dependant on saturation.
However, automatic detection of the white panels by thresholding saturation and intensity levels was not possible and consequently a pattern match could not be obtained.

![Figure 7.26 - Unsuccessful calculation of spin rate due to close proximity of ball to flash units](image)

As the ball trajectory was moved further away from the camera lens, the system achieved a 100% success rate at distances of 1.5, 2.0 and 2.5m from the lens. However, the intensity of light given off by the flash units reduced with distance; therefore the ball images obtained at a distance of 3m from the camera lens were poorly illuminated as well as being small in size. Although one capture was successfully processed, the other 4 captures at 3m failed due to an inability to detect ball location. A sample image obtained indoors at a distance of 3m is shown in Figure 7.27.
The reduction in ball size within the image frame in Figure 7.27 in comparison to Figure 7.26 is notable. The small ball size coupled with the poor illumination in Figure 7.27 suggest that 2.5m is the maximum practical distance for obtaining successful and consistent indoor image captures.

The results from the outdoor testing on a natural turf soccer pitch are shown in Table 7.17. The outdoor luminance was measured at 14,300 lux, using the ISO-TECH digital light meter. This value is considerably higher than the indoor luminance reading of 180 lux:

<table>
<thead>
<tr>
<th>Distance From Camera Lens (m)</th>
<th>Ball Location Success</th>
<th>Ball Spin Measurement Success</th>
<th>Overall capture Success Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>2.0</td>
<td>5/5</td>
<td>5/5</td>
<td>100</td>
</tr>
<tr>
<td>2.5</td>
<td>4/5</td>
<td>3/5</td>
<td>60</td>
</tr>
<tr>
<td>3.0</td>
<td>1/5</td>
<td>1/5</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7.17 - System results for image captures obtained on an outdoor soccer pitch

The outdoor images obtained 1m from the camera unit were processed successfully, unlike the indoor images obtained at the same distance. The decrease in saturation experienced in the indoor image captures does not appear as conspicuous in natural light, due
to the considerably higher luminance present in natural light. The system success rate outdoors at distances of 1.0, 1.5, and 2.0m was 100%. At a distance of 2.5m the system failed on two captures, one due to failure to determine ball location and the other due to the pattern search finding multiple solutions whilst calculating spin rate. Similar to the indoor captures, only one capture obtained at a distance of 3m was successfully processed. The other 4 captures failed to detect ball location due to the small size and poor illumination of the ball within the image frame. A sample image illustrating the poor ball illumination obtained outdoors at 3m is shown in Figure 7.28.

![Figure 7.28 - Unsuccessful determination of ball location outdoors due to poor ball illumination at a distance of 3m from the camera lens](image)

The results obtained outdoors concur with the results obtained indoors suggesting that an image depth of 2.5m is the maximum distance for successful image capture. However, only a 60% success rate was obtained outdoors at a distance of 2.5m, therefore a distance of 2m should produce the most consistent results for both indoor and outdoor conditions. Considering both sets of results together, the optimum capture range for both indoor and outdoor image capture is between 1.5 and 2.0m.

The flash units contained in the prototype capture unit were spaced 0.06m apart and were mounted facing directly forward. This arrangement means that the flash intensity in the middle of the field of view is considerably greater than the intensity around the edge of the field of view. This has implications for system accuracy, as ball images at the edges of the image frame may be undetectable due to poor illumination. If the position of the flash units was changed so that they were mounted at diverging angles away from the straight-line
forward facing position, the flash intensity across the camera field of view could become more consistent. However, this would have implications for the direction of kicking relative to the camera, as the 2 sequential images of the ball in flight would have to be obtained with the balls kicked in a fixed direction.

7.6.2 **SOUND INITIATION**

The use of ball impact sound as a capturing trigger is not ideal as it imposes restrictions on impact position in order to achieve a successful capture. The time interval between impact and the first image was fixed at 67 ms, therefore in order to obtain two sequential images of a ball within the camera field of view, the impact position is critical and dependent on ball velocity. The ball velocity results obtained from professional players detailed in Chapter 4 show that the majority of good soccer kicks are in the velocity range 12 - 33 m/s. In order to ensure that ball images were captured within the optimum image capture range of 1.5 - 2m, it was necessary to create 3 individual ‘kicking zones’ for a series of 3 ball velocity ranges. Based on the velocity measurements detailed in Chapter 4, the three velocity ranges identified were: low velocity (7.5 - 15 m/s), medium velocity (15 - 25 m/s), and high velocity (25 - 33 m/s). The impact kicking zones required for image capture at each of the three velocity ranges are illustrated in Figure 7.29. If the impact position for all three kicking zones is maintained at a distance approximately 2m from the camera lens, good quality captures and measurement consistency should be attained.
During further testing a series of problems were identified relating to the use of sound as a triggering mechanism for initiating capture. During outdoor testing the microphone could be triggered by sudden gusts of wind before the kicker had made contact with the ball. Similarly, during indoor testing, the impact sound caused by the placement of the non-kicking foot on a sports hall wooden sprung floor also triggered the microphone. In order to eliminate the occurrence of premature impact sound detection an alternative microphone with reduced sensitivity may provide a solution.

7.6.3 PRESENCE OF REFLECTIVE SURFACES

The presence of reflective surfaces within the camera field of view can have an adverse effect on system accuracy and consistency. During an image capture, the system obtains 2 sequential ball images and compares them using the 'diff. absolute' image differencing function within IPP. The function effectively creates a new image containing aspects of the 2 images that are disparate (i.e. the ball itself). However, as the two flash units are in different positions and are activated 33 ms apart, any light returned from a reflective surface in the field of view will appear in a different position in each image. In this scenario, the image differencing process will detect the position of the disparate reflected light as well as the two ball images. Should the outline of the reflective surface interact with the outline of either of the balls in the thresholded image, IPP can fail to detect the ball location, as this detection is dependant on the binary ball images appearing circular.
The image analysis problem caused by reflective surfaces is illustrated in Figure 7.30. The two images shown were obtained in an indoor sports hall, with the camera positioned approximately 6m from a wall containing exposed metalwork in the centre of the image field of view. The close proximity of the metalwork to the camera causes light emitted from the flash units to be reflected back to the camera.

![Figure 7.30 - Pair of sequential images obtained in an indoor sports hall containing reflective surfaces within the image frame](image)

The 2 images were combined using the differencing function to eliminate aspects of both images that were identical. The resultant binary image is shown in Figure 7.31, with the reflective surfaces clearly visible. In this example the presence of the reflective metal surfaces altered the circular profile of the left hand ball image and prevented automatic detection. The right hand ball image was successfully detected, as it did not interact with any of the reflected surfaces.
Automatic ball detection within an image is dependant on a binary ball profile appearing circular after thresholding; therefore the presence of reflective surfaces within the field of view can have a detrimental effect on the capability of the system to determine ball location. If the capture unit is positioned in excess of 10m from a reflective surface, the visibility of any reflective surface will be sufficiently reduced due to the limited depth of the flash units. Therefore, reflective surfaces will only pose a problem if they are in close proximity (less than 10m) to the capture unit. The failure of the image differencing process to eliminate the reflected light was due to the different positions of the flash units and the fact that they were activated 33 ms apart. If a single flash unit were used to illuminate both images, the light reflected in each image would potentially be more analogous, and could therefore be eliminated during the image differencing process. However, image quality is essential to the accuracy of the system and it is questionable if a single flash unit would be able to provide sufficient quality images.

7.6.4 IMAGE SHADOW EFFECTS

During testing of the prototype system, image captures obtained in close proximity to a background wall generally failed due to the presence of shadow. Light generated from the flash units can create considerable ball shadow against a coloured background, although if the
background wall is black, ball shadow will generally not be visible at any distance. Experimental testing has shown that images obtained with the camera positioned in excess of 8m from a wall, do not experience the effects of ball shadow, due to the limited illumination depth of the flash units. However, should the camera be positioned within 8m of a coloured background wall, the system will generally be unable to accurately ascertain ball location.

The problem of ball shadow is illustrated in Figure 7.32. The two images shown were obtained indoors, with the camera positioned approximately 5m from a beige coloured wall.

![Figure 7.32 - Pair of sequential images obtained indoors containing ball shadow projected on background](image)

The 2 images were combined using the differencing function to eliminate aspects of both images that were identical. The new image was then thresholded giving the resultant binary image is shown in Figure 7.33. Unfortunately, the ball shadow is in a different position in each image; therefore as the image differencing process combined the disparate parts of each image into a new image, the shadow was included. During the thresholding process the shadow merged with each ball resulting in the 2 binary ball objects appearing distorted. Despite the distortion, the binary objects were successfully identified based on their circular nature, however the inaccurate 'bounding square' coordinates obtained resulted in incorrect measurements of ball velocity and spin rate.
Figure 7.33 - Binary image illustrating ball location inaccuracy due to presence of shadow on background

The presence of shadow has a damaging effect on the capability of the system to accurately measure ball location. Without accurate measurement of ball location, the system will be unable to accurately measure ball velocity, elevation and spin rate. Shadow is generated if the captures are obtained in close proximity to a coloured wall in a dark environment; therefore in outdoor conditions shadow is generally not a problem. In order to eliminate the effects of shadow care must be taken to ensure that the camera is not positioned in close proximity to a coloured background. Alternatively, if image capturing must take place in close proximity to a wall, covering the wall with a black material will eradicate shadow visibility and allow for accurate ball location measurement. Further work is required in order to identify shadow removal techniques that could be used to eliminate the presence of shadow in images.

7.6.5 SUMMARY

Testing showed that the optimum image capturing distance for successful ball image analysis is at a distance of 1.5 - 2.0m from the camera. However, the use of impact sound as a capture trigger imposed limitations on ball impact position, as the impact location was dependent on ball velocity. Therefore it was necessary to specify three different impact positions based on low, medium and high kick velocity ranges. Furthermore, the microphone
used for impact detection was found to be sensitive to sudden gusts of wind in outdoor testing conditions. Therefore, an alternative microphone with reduced sensitivity may be necessary to eliminate premature impact sound detection.

Extensive field testing of the system in a range of different locations has shown that further work is required to eliminate system failures caused by reflective surfaces and ball shadow. The problems associated with ball shadow and reflective surfaces are only evident if the wall/reflective surfaces are in close proximity to the camera (less than 8m for shadow, less than 10m for reflective surfaces). Therefore providing that the wall/reflective surfaces are located at a distance in excess of 10m from the camera, they will not be visible within the image frame due to the limited range of the flash units. If a wall is in close proximity to the capture unit, covering the wall and any exposed reflective surfaces with a black material will allow successful measurements can be obtained.

7.7 CONCLUSION

An image analysis system has been developed that can automatically measure soccer ball velocity, spin rate, spin axis and launch elevation. The system utilises Image Pro Plus software to locate and analyse a pair of sequential ball images captured during flight using a video camera synchronised with flash photography. In order to calculate spin rate, 5 colours were assigned to the panels of an 32-panel icosadodecahedron structure soccer ball, providing a unique total surface marking scheme for any given ball orientation. A genetic algorithm was used to determine the specific orientation of the ball in each image and calculate the associated rotation. The unique arrangement of coloured panels around the ball enables the determination of spin rate to an accuracy of 1 degree, and spin axis to an accuracy of 2 degrees, validated using a CAD model of the coloured ball.

Extensive testing showed that the system was capable of successfully measuring initial ball launch characteristics in a range of different lighting conditions, although further work is required to eliminate system failures caused by reflective surfaces and ball shadow. As far as the author is aware, the system is the only automatic soccer ball performance measurement system in existence capable of measuring 3D spin. The system could be used for the assessment of velocity and spin rate as part of a dynamic ball testing program.
CHAPTER 8

RECOMMENDATIONS FOR FURTHER WORK

The work conducted in this study has developed new knowledge concerned with the performance of soccer balls and presented new tools and techniques for the assessment of ball performance. However, time constraints have prevented the development of a complete range of dynamic testing procedures, and this chapter discusses further work required for the development of a comprehensive ball testing program.

8.1 AERODYNAMIC SOCCER BALL PERFORMANCE TESTING

One of the important factors affecting soccer ball flight performance is that of aerodynamic forces. The determination of drag ($C_D$) and lift ($C_L$) coefficients for soccer balls is essential for the understanding and prediction of soccer ball flight characteristics. Although there have been numerous aerodynamics studies on smooth spheres and other spherical sports balls, published data on the aerodynamic forces of soccer balls is negligible. Accurate determination of $C_D$ and $C_L$ for soccer balls would enable ball trajectory models to be developed in conjunction with ball velocity, elevation and spin rate data. Studies by Carré et al. (2002) and Bray and Kerwin (2003) estimated $C_D$ and $C_L$ for soccer balls experimentally using equations of motions derived from trajectory analysis, however wind tunnel analysis could provide a more detailed assessment.

A wind tunnel could be used to calculate the aerodynamic forces acting on stationary and spinning soccer balls. The ball velocity data obtained from elite players in Section 4.6 indicates that the tunnel used would have to be capable of flow speeds in the range 0 - 35 m/s. In order to evaluate aerodynamic performance of spinning balls it would be necessary to design and manufacture a bespoke rig capable of rotating test balls at the required spin rates, whilst not adversely affecting the flow stream through the tunnel. The spin rate data obtained from elite players in Section 4.6 shows that the rig would have to be capable of ball rotation in the range 0 - 14 revs/s. The rig would be attached to a balance used to directly measure the aerodynamic forces acting on the ball (lift and drag). Successful determination of
$C_d$ and $C_l$ for soccer balls with different surface characteristics would enable an improved understanding of soccer ball aerodynamics and the potential development of accurate trajectory models.

Ball types featuring different panel designs and exterior surface characteristics could be assessed in order to determine the aerodynamic effects of ball design and construction. Changing the surface of a ball so that it is considerably rougher in appearance could affect ball aerodynamic properties considerably. This is because a rougher surface will result in reduced drag and higher velocities as the transition at critical Reynolds number is induced earlier. Wind tunnel testing could be used to set appropriate aerodynamic standards for soccer balls.

### 8.2 SOCCER BALL FRICTIONAL INTERACTION

Changes made to the surface characteristics of soccer balls can have a significant effect on the frictional characteristics of the ball as well as the aerodynamic properties. An increase in surface roughness will cause an increase in the coefficient of friction at impact with the contacting surface, and result in increased spin (Asai and Akatsuka, 1998). It is claimed that the adidas Predator soccer boot has a higher coefficient of friction than other soccer boots due to the addition of raised rubber 'fins' located on the upper of the boot. Theoretically, this should allow the generation of increased spin, although no scientific data has been published in support of this theory. Further work into soccer ball frictional characteristics could result in an improved understanding of the interaction between the soccer ball and the boot during impact.

The frictional interaction of the ball with surfaces such as grass, artificial turf, boots and gloves are additional important considerations in soccer. The interaction is dependent on the playing conditions, as the coefficient of friction is significantly reduced in wet conditions. Time constraints prevented investigation of the frictional characteristics of soccer balls as part of the present study; however the development of a specific test for friction assessment is recommended as further work. The coefficient of friction of soccer balls could be determined using a simple pendulum technique. The ball would be held in an appropriate fixture at the end of a swinging arm and raised to an angle of 90° before being allowed to swing freely. As the pendulum was swung the ball surface would come into contact with a test surface and the rebound angle would be recorded. The coefficient of friction can be determined from the ratio of the rebound angle to the 90° release angle. The technique would require extensive development and the manufacture of an appropriate testing rig, however it
could provide a sufficient means of comparing the frictional characteristics of ball surfaces. Unfortunately the impact velocities would be relatively slow and friction is affected by velocity.

In principle, a soccer ball exhibiting a high degree of surface roughness could result in increased spin due to the increased coefficient of friction, and increased flight velocity due to the transition between laminar and turbulent flow regimes occurring earlier. A ball capable of increased spin and velocity would doubtless prove very popular with free kick takers looking to manipulate the flight of the ball to their advantage. However, it is unlikely goalkeepers would reciprocate these feelings, as they are likely to favour a ball that is predictable and consistent during its flight towards goal. In the interests of the game therefore, frictional characteristics along with aerodynamic forces may require standardisation.

8.3 MEASUREMENT OF OUT OF BALANCE FORCES IN SOCCER BALLS

The soccer ball out of balance measurement technique developed as part of this study could be used for a dynamic performance test on ball balance. However, further work would be required before it would be suitable for inclusion within a comprehensive testing program.

8.3.1 DEVELOPMENT OF ENHANCED BALL FIXTURE FOR MEASUREMENT OF OUT OF BALANCE

The out of balance assessment method described in detail in Chapter 5 utilised a specially manufactured fixture to attach to the standard spindle interface on a vertical balancing machine. The purpose of the fixture was to secure test balls in a fixed orientation and prevent the balls from moving whilst the spindle was rotated. It was essential that the fixture was rigid as any vibration within the fixture could distort the measurements obtained; therefore a fixed size fixture appropriate for 'FIFA Approved' sized balls was manufactured. The limitation with the fixture was that balls had to be loaded into the fixture in a deflated state, and re-inflated to a pressure sufficient to prevent movement. Due to variations in ball diameter, the pressure required to prevent movement varied considerably across the range of test balls. Consequently, it was not possible to maintain a constant ball pressure during testing and results could have been adversely affected. Furthermore, the fixture consisted of a four pronged frame attached to a retaining ring which caused the balls to experience deformation whilst held in the fixture. The extent of the ball deformation could also have had an adverse effect on the results obtained.

If the vertical balancing machine method of unbalance measurement were to be employed as a dynamic ball performance test, the fixture design would need further
consideration. It would be essential that test balls are held secure, whilst ensuring that the balls are not significantly deformed whilst being held. In addition, potential new fixture designs should have the capability to measure unbalance at any pressure across the FIFA stipulated range of 69 - 103 kPa (10 - 15 psi).

8.3.2 THE ABILITY OF ELITE PLAYERS TO PERCEIVE BALL UNBALANCE

The ability of elite players to perceive differences between balls exhibiting varying degrees of unbalance was assessed using elite players. The testing was carried out using professional players from 2 FA Premiership clubs and is described in detail in Section 5.7. Unfortunately, testing at each club was carried out on different playing surfaces: a ‘rubber-crumble’ artificial pitch at Aston Villa FC and natural grass at Leicester City FC. The interaction of the ball along the playing surface was critical to the short passing test; and the use of different surfaces may have had a detrimental effect on the overall consistency of the results. The variations in playing surface will not have had an adverse effect on the long passing test results, as the ball was assessed whilst airborne. The results obtained from these tests were not found to be significant, however, repeating the tests using a group of 16 players on a consistent surface may lead to different results. It would be recommended that an artificial surface be used for any future tests as ball bounce and roll properties are generally more consistent.

Furthermore, the difference in the magnitude of unbalance within the three balls selected for player testing was not evenly balanced. Therefore, the subjects found it difficult to differentiate between 2 of the test balls in the ball performance tests. It is recommended that the testing be repeated using a FIFA Approved standard ball featuring an unbalanced mass of around 10 g, together with two other identical balls featuring unbalanced masses of 15 and 20 g respectively.

8.4 DEVELOPMENT OF SOCCER BALL PERFORMANCE MEASUREMENT SYSTEM

The automated soccer ball performance measurement system concept was successfully implemented and a prototype image capture and analysis system was developed. However, time constraints prevented a complete investigation into some of the image capture problems identified during testing.

8.4.1 FLASH UNIT CONFIGURATION

The prototype image capture system utilised 2 flash units located either side of the camera, spaced 0.06m apart. The use of different flash units for the illumination of each ball image led to potential system failure if reflective surfaces were present within the camera field.
of view and in close proximity to the camera. The use of 2 flash units caused light returned to
the camera from reflective surfaces to occur in different positions within an image frame as
described in detail in Section 7.63. System failure would occur if the position of reflective
surfaces coincided with the position of either ball within the image frame. The ball images
were located based on their circular appearance therefore; the presence of background
reflective surfaces could distort the circular appearance of the ball images and prevent
automatic detection.

Replacement of the 2 flash units with a single flash unit could reduce system failure due
to the presence of reflective surfaces considerably. A single flash unit would have to provide
sufficient illumination within the camera field of view, and be capable of a long duration flash
or successive flashes 33 ms apart. The use of a single flash unit should ensure that the light
present on reflective surfaces occurs in the same position within each image frame. The
image differencing process should then be able to eliminate the image backgrounds and
successfully identify the ball locations. The single flash unit could be positioned directly
above or below the camera, or even incorporated around the camera lens in an annular
arrangement. Further work would be required to determine the optimum flash arrangement
for successful image capture.

8.4.2 INCORPORATION OF SHADOW REMOVAL TECHNIQUE

The use of flash photography generated background shadow in images obtained in close
proximity to a background wall, as described in Section 7.6.4. Although ball shadow was
generally not visible against a black background, or if the capture unit was moved a suitable
distance away from a wall, the presence of shadow prevented accurate identification of ball
location. The presence of shadow is a common problem in imaging applications, and a
search of existing solutions for shadow removal may lead to identification of a suitable
method that could be incorporated into the image analysis procedure. Alternatively, it may be
possible to develop a new technique for shadow removal within IPP that could be
incorporated into the system as a macro. Further investigation is required to assess the
validity of existing shadow removal applications, or to develop a new technique.

8.4.3 DEVELOPMENT OF ALTERNATIVE BALL CAPTURE TRIGGER

The existing prototype system is triggered by the sound generated by the foot during
impact with the ball. However, the use of sound as a trigger imposes limitations on the
position the ball must be struck from in order to achieve a successful capture. Section 7.6.2
showed that three different impact positions were required for three different ball velocities
ranges (low, medium and high). The practical limitations of the current sound measurement technique necessitate the development of an improved method of triggering ball capture. Further work should investigate possible alternatives for triggering ball capture as the ball comes into the camera field of view.

The inclusion of a laser within the capture unit could be used to trigger capture at the instant the ball enters the camera field of view. The camera field of view is 60° and a laser beam would have to be emitted at an angle less than 30° from the straight line direction of the camera in order to trigger as the ball came into the field of view. The limitation of a laser beam trigger is that a separate laser receiver would be required in order to detect the instant at which the beam is broken by the ball. Other potential solutions include the use of infrared or ultrasound, as these methods would not require an additional receiver unit. Further investigation would be required in order to determine the validity of these solutions and generate other possibilities.

8.4.4 POST IMPACT TRAJECTORY MODEL

The soccer ball performance measurement system provides accurate instantaneous measurement of ball velocity, elevation, spin rate and spin axis. The measurements are computed from images obtained over the period 67 - 100 ms after impact with a ball and therefore reasonably represent the initial launch characteristics. In order to predict the behaviour of the ball over the course of its intended trajectory it would be necessary to develop a trajectory model. Ball trajectory models are typically created using the aerodynamic lift and drag force equations described in Section 2.2, together with standard impact equations of motion.

The essential measurements required for the simulation of a ball trajectory model are those obtained by the system (velocity, spin rate and elevation at launch), and \( C_D \) and \( C_L \) values for soccer balls across a range of spin rates and velocities. Aerodynamic wind tunnel testing as described in Section 9.1 would need to develop accurate determination of \( C_D \) and \( C_L \) values, enabling the development of a suitable trajectory model. The trajectory model could be displayed graphically in order to provide system users with visual feedback on the likely trajectory of their kicks. This graphical representation could be incorporated into the existing system alongside the measurements for velocity and spin currently obtained.

8.5 POTENTIAL DEVELOPMENT OF AN INSTRUMENTED SOCCER BALL

Contemporary live television coverage of many sports now includes virtual replays of ball tracking and trajectory prediction. Television coverage of sports such as baseball, cricket
and tennis all utilise ball trajectory systems. The potential development of a soccer ball tracking system using wireless technologies is already being investigated by a number of companies. It is envisaged that microchips placed within a ball could be utilised to emit a continuous electromagnetic wave signal which could be detected by a series of receivers positioned around a soccer stadium. It is claimed that the receivers could determine the 3D position of the microchip and therefore enable measurements to be obtained for ball velocity and even spin rate.

However, systems of this type are currently still in development and the potential accuracy remains to be established. Calculation of velocity may be attainable with a single microchip positioned at the geometric centre of the ball, however calculation of spin rate and spin axis would most likely require the incorporation of an array of sensors positioned within the ball. The inclusion of additional components to a soccer ball would likely have a detrimental effect on ball unbalance and moment of inertia, and the deformation experienced by the ball during impact with a foot or goalposts has the potential to damage the sensors. In order to accommodate this deformation and reduce the risk of damage, the mounting of the microchip within the ball would need careful consideration. Further work would be required to establish the accuracy of instrumented soccer balls and to determine the effect of additional components on ball dynamic properties.
An evaluation of the FIFA rules regarding dynamic ball performance has revealed that the rules need to be reconsidered in the light of new design and manufacture methods and modern player capability. This thesis describes new measurement techniques and instrumentation that could be utilised to assess the dynamic performance characteristics of soccer balls.

The sphericity measurement of soccer balls has been investigated in order to develop a more consistent and accurate method than that currently employed by FIFA. The sphericity measurement of soccer balls was deemed important because of the detrimental effect poor sphericity can have on ball performance consistency. The new measurement procedure was devised using a CMM to obtain 3D coordinates of the ball panel centroids. Computer software fitted a least mean squares sphere approximation to the coordinate data allowing automatic calculation of ball sphericity and ball diameter. Test results showed that this method of sphericity assessment is more consistent and representative than the existing FIFA method. The improvement in measurement consistency obtained using the least mean squares approximation to a sphere method is such that the FIFA specification may require reconsideration.

The performance playing parameters of soccer balls were identified through extensive professional player testing. High-speed cameras were used to measure the kicking capabilities of 25 elite players drawn from 5 professional clubs. Ball velocities in the range 13.5 - 33.1 m/s were recorded for three different kick types (full power kick, instep swerve kick and outstep swerve kick). Spin rates were measured in the range 2.6 - 13.9 revs/s for two kick types (instep swerve kick and outstep swerve kick), although typically in the range 6 - 10 revs/s. The data gathered in the study was used as a benchmark to suggest appropriate limiting standards for ball velocity and spin rate. It was suggested that initial ball velocity for highest quality balls in a controlled test should not exceed 31.5 m/s (70 mph), and initial spin
rate should not exceed 12.5 revs/s (750 rpm). Furthermore, the data was used to define and simulate a common spin rate of 6.67 revs/s (400 rpm) for the assessment of ball out of balance using the vertical balancing machine.

The concept of unbalance was investigated and a method of measuring the position and magnitude of out of balance forces within soccer balls was developed using a vertical balancing machine. To measure unbalance test balls were held within a bespoke fixture secured to the balancing machine spindle and rotated at 6.7 revs/s (400 rpm). For an accurate measurement of unbalance it was essential that the point of unbalance was positioned on the ball equator, at 90° to the axis of rotation. The system measurement accuracy was shown to be +/- 0.17 g, which was validated by using additional masses attached to existing balls. Ball unbalance measurements in the range 6 - 13 g were obtained for samples of 4 ‘FIFA Approved’ soccer balls, confirming that unbalance is a common feature within top class soccer balls, and therefore a significant area for improvement. The position of unbalance in all of the sample balls was found to be in close proximity to the valve. In light of these results, it is hoped that FIFA may consider a ball unbalance test that imposes an unbalance limit of 10 g for FIFA Approved standard balls.

The effect of out of balance forces on dynamic ball performance was assessed in a study composed of two parts. In the first part, a pneumatically driven ‘pendulum’ type kicking leg was used as a launch platform to assess the effect of ball unbalance and orientation on ball flight characteristics. The results showed that the presence of unbalance in soccer balls can have an adverse effect on ball launch trajectory consistency; although it does not significant affect initial launch velocity. The extent to which the ball flight trajectory is affected depends on the magnitude of the unbalance force and the position of unbalance at impact. The detrimental effect of unbalance on trajectory consistency supports the introduction of a ball unbalance test and associated limiting standards in order to improve ball performance consistency.

In the second part of the study, the ability of elite players to perceive ball unbalance was assessed using a group of 16 professional players. The subjects were instructed to perform 2 different types of kick using 3 balls exhibiting varying degrees of unbalance, although identical in appearance. The subjects were asked to rank the 3 balls in order of preference. Analysis of the ranking data showed that the subjects were generally able to identify the ball containing the largest unbalanced mass (24.25 g), yet were unable to distinguish between the other two balls containing smaller unbalanced masses. Although no statistically significant
correlation was found within the data, the ability of the majority of subjects to identify the ball containing the largest unbalanced mass suggests that unbalance does have an effect of ball performance.

An automated system capable of accurately measuring the dynamic flight characteristics of soccer balls was developed. The measurement procedure was entirely automated and therefore not subject to human digitising error. A range of image processing techniques were employed to analyse a pair of sequential images of a ball in flight, and additional software was developed to obtain measurements for initial ball velocity, 3D spin rate and elevation to a high degree of accuracy. In order to calculate spin rate, 5 colours were assigned to the panels of a 32-panel soccer ball, providing a unique total surface marking scheme for any given ball orientation. A prototype system was manufactured and extensive testing showed that the system was capable of successfully measuring initial ball launch characteristics in a range of different lighting conditions. However, reflective surfaces and light coloured backgrounds that are in close proximity to the camera can prevent successful image capture and further work is required to eliminate these problems. The system could be used for the assessment of velocity and spin rate as part of a dynamic ball testing program.

The ability to accurately measure soccer ball flight performance parameters is essential for the development of limiting standards, and to assess the effect of manufacturing inconsistencies such as poor sphericity and ball out of balance on dynamic ball performance. If used in conjunction with a consistent ball launch platform, the system could allow accurate comparison of different ball types and constructions, as well as the establishment of limiting standards for ball velocity and spin rate. A robot leg such as that described in Chapter 6 could be employed as a ball-launching device for the assessment of ball flight characteristics.

This research study has successfully developed methods and instrumentation for some of the important dynamic ball flight performance factors. The work could be used as the foundation for the development of a dynamic testing program, for soccer ball performance standardisation and evaluation. However, further work is required to develop a comprehensive set of test procedures that encompass impact characteristics and other ball performance considerations.
REFERENCES


BS 2953 (1999). Mechanical vibration - Balancing machines - Description and evaluation.


BS 6740 (1987). Determining departures from roundness by measuring variations in radius.


Neilson, P.J. and Jones, R. (2003b). Dynamic soccer ball performance measurement. 5th World Congress of Science and Football, April 11-15; Lisbon, Portugal.


APPENDICES
## Appendix 1 - Range of Ball Panel Designs Currently Available

<table>
<thead>
<tr>
<th>Ball Name</th>
<th>Manufacturer</th>
<th>Panel Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-1000</td>
<td>Brine, USA</td>
<td>6</td>
</tr>
<tr>
<td>World Platinum</td>
<td>Penalty, Brazil</td>
<td>12</td>
</tr>
<tr>
<td>PT-13</td>
<td>Uhlsport, Germany</td>
<td>13</td>
</tr>
<tr>
<td>Classique 18</td>
<td>Patrick, France</td>
<td>18</td>
</tr>
<tr>
<td>P20</td>
<td>Nike, USA</td>
<td>20</td>
</tr>
<tr>
<td>Atlantis</td>
<td>Brine, USA</td>
<td>24</td>
</tr>
<tr>
<td>ISO</td>
<td>Mitre, UK</td>
<td>26</td>
</tr>
<tr>
<td>Fevernova</td>
<td>adidas, Germany</td>
<td>32</td>
</tr>
<tr>
<td>Prototype Ball</td>
<td>Puma, Germany</td>
<td>42</td>
</tr>
<tr>
<td>Coppa</td>
<td>Puma, Germany</td>
<td>52</td>
</tr>
</tbody>
</table>
### APPENDIX 2 - OVERVIEW OF FIFA TEST CRITERIA FOR SOCCER BALLS

#### OUTDOOR

<table>
<thead>
<tr>
<th>Test</th>
<th>FIFA Inspected</th>
<th>FIFA Approved</th>
<th>Ball Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>410 - 450 grams</td>
<td>420 - 445 grams</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Circumference</td>
<td>68 - 70 cm</td>
<td>68.5 - 69.5 cm</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Sphericity %</td>
<td>Max. 2</td>
<td>Max. 1.5</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Loss of Pressure %</td>
<td>Max. 25</td>
<td>Max. 20</td>
<td>1.0 bar</td>
</tr>
<tr>
<td>Water Absorption %</td>
<td>Max. 15</td>
<td>Max. 10</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Rebound at 20°C</td>
<td>115 - 165 cm</td>
<td>120 - 165 cm</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Rebound at 5°C</td>
<td>Min. 110 cm</td>
<td>Min. 1200 cm</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>High/low rebound diff</td>
<td>Max. 10 cm</td>
<td>Max. 10 cm</td>
<td>0.8 bar</td>
</tr>
<tr>
<td><strong>Shape &amp; size retention test (after 2000 impacts)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seams and valve</td>
<td>-</td>
<td>Undamaged</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Increase in circumference</td>
<td>-</td>
<td>Max. 1.5 cm</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Deviation in sphericity %</td>
<td>-</td>
<td>Max. 1.5</td>
<td>0.8 bar</td>
</tr>
<tr>
<td>Change in pressure (bar)</td>
<td>-</td>
<td>Max. 0.1</td>
<td>0.8 bar</td>
</tr>
</tbody>
</table>

#### INDOOR

<table>
<thead>
<tr>
<th>Test</th>
<th>FIFA Inspected</th>
<th>FIFA Approved</th>
<th>Ball Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>400 - 440 grams</td>
<td>410 - 430 grams</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Circumference</td>
<td>62 - 64 cm</td>
<td>62.5 - 63.5 cm</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Sphericity %</td>
<td>Max. 2</td>
<td>Max. 1.5</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Loss of Pressure %</td>
<td>Max. 25</td>
<td>Max. 20</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Balance</td>
<td>Max. 7.5°</td>
<td>Max. 5°</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Rebound</td>
<td>50 - 65 cm</td>
<td>55 - 65 cm</td>
<td>0.6 bar</td>
</tr>
<tr>
<td><strong>Shape &amp; size retention test (after 2000 impacts)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seams and valve</td>
<td>-</td>
<td>Undamaged</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Increase in circumference</td>
<td>-</td>
<td>Max. 1.0 cm</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Deviation in sphericity %</td>
<td>-</td>
<td>Max. 1.5</td>
<td>0.6 bar</td>
</tr>
<tr>
<td>Change in pressure (bar)</td>
<td>-</td>
<td>Max. 0.1</td>
<td>0.6 bar</td>
</tr>
</tbody>
</table>

All tests bar one are conducted at room temperature (approx 20°C) and 65% humidity. The only exception is the rebound test for outdoor balls (measured at 20 and 5°C).
A sphere is specified by its centre \((x_o, y_o, z_o)\) and radius \(r_o\). Any point on the sphere surface satisfies the equation 
\[(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2 = r^2.\]

**Initial estimates for centre and radius**

Choice of a minimizing function

A minimizing function has to be identified to obtain an initial estimate for the centre and radius. Consider the function 
\[f_1 = r - r_i\]

Where \(r_i = \sqrt{(x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2}.\)

Differentiating this function with respect to \(x_o, y_o, z_o\) and \(r_o\) will result in equations which are difficult to solve.

Therefore, consider the function 
\[f_2 = r_i^2 - r^2.\]

This function can be written as 
\[f_2 = (r_i - r)(r_i + r) \approx 2r(r_i - r)\], since \(r_i + r\) can be approximated as \(2r_i\).

Differentiating this function with respect to \(x_o, y_o, z_o\) and \(r_o\) will obtain initial estimates of centre and radius.

Thus the minimizing function to obtain initial estimates for a sphere is:

\[f = r_i^2 - r^2.\]

Expanding \(f = r_i^2 - r^2\), we get

\[f = (x_i - x_o)^2 + (y_i - y_o)^2 + (z_i - z_o)^2 - r^2 = -(2x_i x_o + 2y_i y_o + 2z_i z_o) + p + (x_i^2 + y_i^2 + z_i^2)\]

Where \(p = (x_o^2 + y_o^2 + z_o^2) - r^2.\) The variable \(p\) is introduced to make the equation linear.

The above set of equations for \(n\) set of data points are now represented in matrix form.

\[
\begin{pmatrix}
-2x_1 & -2y_1 & -2z_1 & 1 \\
-2x_2 & -2y_2 & -2z_2 & 1 \\
\vdots & \vdots & \vdots & \vdots \\
-2x_n & -2y_n & -2z_n & 1
\end{pmatrix}
\begin{pmatrix}
x_o \\
y_o \\
z_o \\
p
\end{pmatrix}
\begin{pmatrix}
x_1^2 + y_1^2 + z_1^2 \\
x_2^2 + y_2^2 + z_2^2 \\
\vdots \\
x_n^2 + y_n^2 + z_n^2
\end{pmatrix}
= \begin{pmatrix}
f_1 \\
f_2 \\
\vdots \\
f_n
\end{pmatrix}
\]

For a least square solution, \(f_i = 0\). Introduce matrix notation,
We have \( AP - B = 0 \) and can solve this equation in least square sense to obtain \( P \). This means that \( P \) satisfies the equation \( A^T AP = A^T B \). The initial estimates for \( x_0, y_0, z_0 \) and \( p \) are obtained from the above solution for \( P \). The initial estimate for the radius \( r \) can be obtained from the relation \( p = (x_0^2 + y_0^2 + z_0^2) - r^2 \).

**Gauss Newton method**

After obtaining the initial estimates for the centre and radius \( r \), the Gauss Newton method is used to arrive at the final values for centre and radius.

The minimizing function is given by \( d_i = r_i - r \)

Where \( r_i = \sqrt{(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2} \)

1. Building the Jacobian matrix

\[
J = \begin{pmatrix}
\frac{\partial d_1}{\partial x_o} & \frac{\partial d_1}{\partial y_o} & \frac{\partial d_1}{\partial z_o} & \frac{\partial d_1}{\partial r_n} \\
\frac{\partial d_2}{\partial x_o} & \frac{\partial d_2}{\partial y_o} & \frac{\partial d_2}{\partial z_o} & \frac{\partial d_2}{\partial r_n} \\
\vdots & \vdots & \vdots & \vdots \\
\frac{\partial d_n}{\partial x_o} & \frac{\partial d_n}{\partial y_o} & \frac{\partial d_n}{\partial z_o} & \frac{\partial d_n}{\partial r_n}
\end{pmatrix}
\]

The elements of the Jacobian matrix are given by

\[
\begin{align*}
\frac{\partial d_1}{\partial x_o} &= -(x_1 - x_o) \\
\frac{\partial d_1}{\partial y_o} &= -(y_1 - y_o) \\
\frac{\partial d_1}{\partial z_o} &= -(z_1 - z_o) \\
\frac{\partial d_1}{\partial r} &= -1 \\
\frac{\partial d_2}{\partial x_o} &= -(x_2 - x_o) \\
\frac{\partial d_2}{\partial y_o} &= -(y_2 - y_o) \\
\frac{\partial d_2}{\partial z_o} &= -(z_2 - z_o) \\
\frac{\partial d_2}{\partial r} &= -1 \\
\vdots & \vdots \\
\frac{\partial d_n}{\partial x_o} &= -(x_n - x_o) \\
\frac{\partial d_n}{\partial y_o} &= -(y_n - y_o) \\
\frac{\partial d_n}{\partial z_o} &= -(z_n - z_o) \\
\frac{\partial d_n}{\partial r} &= -1
\end{align*}
\]

Evaluating various components of the Jacobian and substituting in the matrix, we get

\[
J = \begin{pmatrix}
\frac{\partial d_1}{\partial x_o} & \frac{\partial d_1}{\partial y_o} & \frac{\partial d_1}{\partial z_o} & \frac{\partial d_1}{\partial r_n} \\
\frac{\partial d_2}{\partial x_o} & \frac{\partial d_2}{\partial y_o} & \frac{\partial d_2}{\partial z_o} & \frac{\partial d_2}{\partial r_n} \\
\vdots & \vdots & \vdots & \vdots \\
\frac{\partial d_n}{\partial x_o} & \frac{\partial d_n}{\partial y_o} & \frac{\partial d_n}{\partial z_o} & \frac{\partial d_n}{\partial r_n}
\end{pmatrix}
\]

2. To solve the linear least square system \( J^T \hat{P} = -d \)
\[ P = \begin{pmatrix}
  p_{x_0} \\
  p_{y_0} \\
  p_{z_0} \\
  p_r
\end{pmatrix} \]

Where

3. Increment parameters according to

\[
\begin{align*}
  x_o &= x_o + p_{x_o} ; \\
  y_o &= y_o + p_{y_o} ; \\
  z_o &= z_o + p_{z_o} ; \\
  r_o &= r_o + p_r ;
\end{align*}
\]

4. Convergence condition

Repeat steps till algorithm has converged. The convergence condition is given by

\[ g = J^T d \] is a minimum.

(Bui and Kamaraj, 2001)
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<thead>
<tr>
<th>Ball Name</th>
<th>Manufacturer</th>
<th>Panel Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestra Silverstream</td>
<td>adidas, Germany</td>
<td>32</td>
</tr>
<tr>
<td>(Official ball of Euro 2000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimax</td>
<td>Mitre, UK</td>
<td>26</td>
</tr>
<tr>
<td>(Official ball of the FA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premiereship 1996-2000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geo Merlin</td>
<td>Nike, USA</td>
<td>32</td>
</tr>
<tr>
<td>(Official ball of the FA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premiereship 2000-2002)</td>
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<tr>
<td>Cellertor</td>
<td>Puma, Germany</td>
<td>32</td>
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<tr>
<td>(Puma premier ball 2000/2001)</td>
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<td></td>
</tr>
<tr>
<td>Shudoh</td>
<td>Puma, Germany</td>
<td>32</td>
</tr>
<tr>
<td>(Puma premier ball 2001/2002)</td>
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</tr>
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<td>King SL</td>
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<td>(Puma premier ball 1999/2000)</td>
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### APPENDIX 5 - BALL SPHERICITY RESULTS USING CMM METHOD

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<th>Diameter (mm)</th>
<th>Sphericity (mm)</th>
<th>Sphericity (%)</th>
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### APPENDIX 6 - BALL SPHERICITY RESULTS USING FIFA METHOD

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# APPENDIX 7 - SOCCER BALL PERFORMANCE TEST SUBJECT DATA SHEET

## PLAYER DATA

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## TESTING CONDITIONS

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### APPENDIX 8 - SOCCER BALL PERFORMANCE TEST SUBJECT DETAILS

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<th>Weight (kg)</th>
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<th>Team</th>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Fevernova</td>
<td>adidas, Germany</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>(Official ball of 2002 World Cup)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>ISO</td>
<td>Mitre, UK</td>
<td>26</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>(Official ball of the FA Cup 2000-2003)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Geo Merlin</td>
<td>Nike, USA</td>
<td>32</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Official ball of the FA Premiership 2000-2002)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shudoh</td>
<td>Puma, Germany</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Puma premier ball 2001/2002)</td>
<td></td>
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## APPENDIX 10 - UNBALANCE MEASUREMENT FOR TEST BALLS

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Av. Unbalance (g)</th>
<th>Unbalance Range (g)</th>
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<tbody>
<tr>
<td>adidas Fevemova 1</td>
<td>10.10</td>
<td>10.07 - 10.14</td>
</tr>
<tr>
<td>adidas Fevemova 2</td>
<td>8.62</td>
<td>8.23 - 8.93</td>
</tr>
<tr>
<td>adidas Fevemova 3</td>
<td>9.42</td>
<td>9.29 - 9.64</td>
</tr>
<tr>
<td>adidas Fevemova 4</td>
<td>10.49</td>
<td>10.21 - 10.8</td>
</tr>
<tr>
<td>Mitre ISO 1</td>
<td>7.92</td>
<td>7.81 - 8.03</td>
</tr>
<tr>
<td>Mitre ISO 2</td>
<td>8.08</td>
<td>8.01 - 8.20</td>
</tr>
<tr>
<td>Mitre ISO 3</td>
<td>10.25</td>
<td>10.20 - 10.27</td>
</tr>
<tr>
<td>Mitre ISO 4</td>
<td>8.98</td>
<td>8.81 - 9.16</td>
</tr>
<tr>
<td>Nike Geo Merlin 1</td>
<td>6.48</td>
<td>6.27 - 6.62</td>
</tr>
<tr>
<td>Nike Geo Merlin 2</td>
<td>6.11</td>
<td>6.04 - 6.14</td>
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<td>Nike Geo Merlin 3</td>
<td>9.65</td>
<td>9.43 - 9.78</td>
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<tr>
<td>Nike Geo Merlin 4</td>
<td>10.53</td>
<td>10.48 - 10.57</td>
</tr>
<tr>
<td>Puma Shudoh 1</td>
<td>8.82</td>
<td>8.74 - 8.89</td>
</tr>
<tr>
<td>Puma Shudoh 2</td>
<td>12.77</td>
<td>12.51 - 12.90</td>
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<tr>
<td>Puma Shudoh 3</td>
<td>7.34</td>
<td>7.21 - 7.45</td>
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<tr>
<td>Puma Shudoh 4</td>
<td>9.88</td>
<td>9.80 - 9.95</td>
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APPENDIX 11 - UNBALANCE MEASUREMENT FOR BALLS WITH ADDITIONAL MASS INSERTED

<table>
<thead>
<tr>
<th>Additional Mass</th>
<th>Ball ID</th>
<th>Unbalance (g)</th>
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<tr>
<td>2.5</td>
<td>A</td>
<td>16.24</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>15.11</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>14.80</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>18.26</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>19.74</td>
</tr>
<tr>
<td>5.0</td>
<td>A</td>
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<tr>
<td></td>
<td>B</td>
<td>15.70</td>
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<tr>
<td></td>
<td>C</td>
<td>18.06</td>
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<tr>
<td></td>
<td>D</td>
<td>22.44</td>
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<tr>
<td></td>
<td>E</td>
<td>17.69</td>
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<td>7.5</td>
<td>A</td>
<td>15.07</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>15.78</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>19.81</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>17.69</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>20.27</td>
</tr>
<tr>
<td>10.0</td>
<td>A</td>
<td>20.01</td>
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<tr>
<td></td>
<td>B</td>
<td>18.01</td>
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<tr>
<td></td>
<td>C</td>
<td>21.86</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>14.76</td>
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<tr>
<td></td>
<td>E</td>
<td>19.73</td>
</tr>
<tr>
<td>12.5</td>
<td>A</td>
<td>24.25</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>18.29</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>20.54</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>20.03</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>21.30</td>
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<tr>
<td>15.0</td>
<td>A</td>
<td>22.57</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>21.83</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>22.32</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>22.55</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>17.26</td>
</tr>
</tbody>
</table>
## SHORT PASSING TEST

Rank the balls 1-3 in order of unbalance? A score of 1 being the best, and 3 being the worst in terms of unbalance.

**Ball Order:**

<table>
<thead>
<tr>
<th></th>
<th>Ball 1</th>
<th>Ball 2</th>
<th>Ball 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking Order</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## LONG PASSING TEST

Rank the balls 1-3 in order of unbalance? A score of 1 being the best, and 3 being the worst in terms of unbalance.

**Ball Order:**

<table>
<thead>
<tr>
<th></th>
<th>Ball 1</th>
<th>Ball 2</th>
<th>Ball 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strike 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
## APPENDIX 13 - BALL UNBALANCE TEST SUBJECT DETAILS

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Position</th>
<th>Team</th>
<th>Size</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bewers, Jonathan</td>
<td>20</td>
<td>1.75</td>
<td>70</td>
<td>Midfield</td>
<td>Aston Villa</td>
<td>9</td>
<td>Right</td>
</tr>
<tr>
<td>Butcher, Aarran</td>
<td>17</td>
<td>1.85</td>
<td>76</td>
<td>Midfield</td>
<td>Leicester City</td>
<td>9.5</td>
<td>Right</td>
</tr>
<tr>
<td>Cooke, Stephen</td>
<td>20</td>
<td>1.75</td>
<td>64</td>
<td>Midfield</td>
<td>Aston Villa</td>
<td>7</td>
<td>Right</td>
</tr>
<tr>
<td>Deen, Ahmed</td>
<td>17</td>
<td>1.75</td>
<td>70</td>
<td>Midfield</td>
<td>Leicester City</td>
<td>7.5</td>
<td>Left</td>
</tr>
<tr>
<td>Doyle, Jamie</td>
<td>17</td>
<td>1.70</td>
<td>58</td>
<td>Midfield</td>
<td>Leicester City</td>
<td>7</td>
<td>Right</td>
</tr>
<tr>
<td>Husbands, Michael</td>
<td>18</td>
<td>1.78</td>
<td>72</td>
<td>Forward</td>
<td>Aston Villa</td>
<td>8</td>
<td>Right</td>
</tr>
<tr>
<td>Hylton, Leon</td>
<td>20</td>
<td>1.71</td>
<td>77</td>
<td>Defender</td>
<td>Aston Villa</td>
<td>8.5</td>
<td>Left</td>
</tr>
<tr>
<td>Jackman, Danny</td>
<td>20</td>
<td>1.65</td>
<td>64</td>
<td>Defender</td>
<td>Aston Villa</td>
<td>7</td>
<td>Left</td>
</tr>
<tr>
<td>Matthews, Nick</td>
<td>17</td>
<td>1.83</td>
<td>83</td>
<td>Defender</td>
<td>Leicester City</td>
<td>11</td>
<td>Right</td>
</tr>
<tr>
<td>McAnallen, Connor</td>
<td>17</td>
<td>1.78</td>
<td>65</td>
<td>Defender</td>
<td>Leicester City</td>
<td>8</td>
<td>Right</td>
</tr>
<tr>
<td>McGavigan, Ryan</td>
<td>17</td>
<td>1.75</td>
<td>70</td>
<td>Midfield</td>
<td>Leicester City</td>
<td>8</td>
<td>Left</td>
</tr>
<tr>
<td>Myhill, Boaz</td>
<td>20</td>
<td>1.91</td>
<td>95</td>
<td>Goalkeeper</td>
<td>Aston Villa</td>
<td>9</td>
<td>Right</td>
</tr>
<tr>
<td>O'Grady, Chris</td>
<td>17</td>
<td>1.85</td>
<td>83</td>
<td>Forward</td>
<td>Leicester City</td>
<td>11</td>
<td>Right</td>
</tr>
<tr>
<td>O'Shea, Colin</td>
<td>17</td>
<td>1.78</td>
<td>71</td>
<td>Defender</td>
<td>Leicester City</td>
<td>9</td>
<td>Right</td>
</tr>
<tr>
<td>Pecora, Antoni</td>
<td>17</td>
<td>1.88</td>
<td>86</td>
<td>Goalkeeper</td>
<td>Aston Villa</td>
<td>9</td>
<td>Right</td>
</tr>
<tr>
<td>Ridgewell, Liam</td>
<td>18</td>
<td>1.85</td>
<td>72</td>
<td>Defender</td>
<td>Aston Villa</td>
<td>9.5</td>
<td>Left</td>
</tr>
</tbody>
</table>
APPENDIX 14 - KENDALL’S COEFFICIENT OF CONCORDANCE W

The Kendall's coefficient of concordance (W) is a non-parametric test used to determine the degree of association among k sets of rankings. To perform the test, the data is arranged into a k x N table, where N is the number of entries to be ranked and k is the number of judges assigning ranks. The sum of ranks for each entry (Ri) is calculated and the squared values of each of the sums determined (Ri^2). Providing there are no ties or the proportion of ties is small, W can be calculated using the following equation:

\[
W = \frac{\sum_{i=1}^{k} (\bar{R}_i - \bar{R})^2}{N(N^2 - 1)/12}
\]

If the proportion of ties among the N ranks is large, the following equation can be used to determine W:

\[
W = \frac{12\sum R_i^2 - 3N(N+1)^2}{N(N^2 - 1) - (\sum T_i)/k}
\]

The Kendall's coefficient of concordance ranges from 0 (no agreement) to 1 (complete agreement) (Siegel and Castellan, 1988).
APPENDIX 15 - THE WILCOXON SIGNED RANKS TEST

The Wilcoxon signed ranks test is the non-parametric equivalent of a paired $t$-test and evaluates both the magnitude as well as the direction of the difference between pairs of data. To perform the test, the magnitudes of the differences $|d_i|$ between each pair of data $(x_i, y_i)$ are ranked in order of size with the smallest magnitude of difference receiving a rank of 1. If any pair of values is equal, they are dropped from the analysis and the sample size reduced accordingly. Then, to indicate whether the ranks arose from a positive or a negative $d_i$, the sign of the difference is affixed to each rank. If there is no difference between the variables $X$ and $Y$ some of the ranks with a large magnitude would come from positive values of $d_i$, when $x_i$ is considerably bigger than $y_i$, and others would come from negative values of $d_i$ when $y_i$ is considerably greater than $x_i$, and therefore the sum of the positive ranks $T^+$ would be expected to be approximately the same as the sum of the negative ranks $T$. If $T^+$ is very much different from $T$ then it would indicate that there is a difference between the two variables. The probability $p$ of the value of $T^+$ occurring when there is no difference between the variables can be calculated and if it falls below the chosen level of significance then the variables can be considered to be different at that level of significance (Siegel and Castellan, 1988).
APPENDIX 16 - FLOW CHART OF GENETIC ALGORITHM

START

1. Generate Panel Mesh
2. Set initial colour count
3. Generate random distribution of colours

A

- Adjoining colours?
  - NO
  - YES

B

- Rotation violation?
  - NO
  - YES

C

- Unique pattern?
  - NO
  - YES

Store result

Reduce colour count
### APPENDIX 17 - PANEL CENTROID COORDINATES FOR INDOOR IMAGES

<table>
<thead>
<tr>
<th>Panel ID</th>
<th>Image 1a</th>
<th>Image 1b</th>
<th>Image 2a</th>
<th>Image 2b</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>204,250</td>
<td>489,159</td>
<td>151,302</td>
<td>452,150</td>
</tr>
<tr>
<td>2</td>
<td>184,266</td>
<td>467,168</td>
<td>109,275</td>
<td>475,172</td>
</tr>
<tr>
<td>3</td>
<td>199,219</td>
<td>500,135</td>
<td>135,232</td>
<td>426,163</td>
</tr>
<tr>
<td>4</td>
<td>225,230</td>
<td>511,181</td>
<td>159,276</td>
<td>407,185</td>
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<tr>
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<td>213,271</td>
<td>514,153</td>
<td>155,275</td>
<td>451,172</td>
</tr>
<tr>
<td>6</td>
<td>177,238</td>
<td>482,182</td>
<td>130,285</td>
<td>439,218</td>
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<tr>
<td>7</td>
<td>230,250</td>
<td></td>
<td></td>
<td>459,198</td>
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<table>
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<th>Image 3a</th>
<th>Image 3b</th>
<th>Image 4a</th>
<th>Image 4b</th>
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</thead>
<tbody>
<tr>
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<td>484,182</td>
<td>84,291</td>
<td>403,186</td>
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<tr>
<td>2</td>
<td>149,274</td>
<td>464,137</td>
<td>126,275</td>
<td>452,166</td>
</tr>
<tr>
<td>3</td>
<td>170,263</td>
<td>463,166</td>
<td>56,283</td>
<td>389,159</td>
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<tr>
<td>4</td>
<td>161,219</td>
<td>486,156</td>
<td>105,257</td>
<td>438,141</td>
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<tr>
<td>5</td>
<td>198,261</td>
<td>457,191</td>
<td>94,317</td>
<td>454,196</td>
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<tr>
<td>6</td>
<td>150,242</td>
<td>440,150</td>
<td>74,262</td>
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<td>180,236</td>
<td>433,173</td>
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<td></td>
<td>88,244</td>
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</table>
## APPENDIX 18 - PANEL CENTROID COORDINATES FOR OUTDOOR IMAGES

### Image ID

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<th>Image 2b</th>
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<td>110,203</td>
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<td>86,252</td>
<td>481,413</td>
<td>191,416</td>
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<td>57,217</td>
<td>523,408</td>
<td>159,379</td>
</tr>
<tr>
<td>9</td>
<td>459,244</td>
<td>99,225</td>
<td>519,379</td>
<td>200,365</td>
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<tr>
<td>10</td>
<td>424,271</td>
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<td>476,386</td>
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<td>479,292</td>
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</table>

### Image ID

<table>
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<th>Panel ID</th>
<th>Image 3a</th>
<th>Image 3b</th>
<th>Image 4a</th>
<th>Image 4b</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>345,240</td>
<td>70,167</td>
<td>573,304</td>
<td>222,248</td>
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<tr>
<td>2</td>
<td>306,223</td>
<td>38,140</td>
<td>543,341</td>
<td>203,202</td>
</tr>
<tr>
<td>3</td>
<td>321,242</td>
<td>30,181</td>
<td>547,295</td>
<td>229,203</td>
</tr>
<tr>
<td>4</td>
<td>346,219</td>
<td>33,157</td>
<td>573,334</td>
<td>183,199</td>
</tr>
<tr>
<td>5</td>
<td>298,246</td>
<td>51,197</td>
<td>521,342</td>
<td>197,246</td>
</tr>
<tr>
<td>6</td>
<td>322,207</td>
<td>16,150</td>
<td>527,318</td>
<td>169,219</td>
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<td>7</td>
<td>334,262</td>
<td>54,174</td>
<td>552,314</td>
<td>215,225</td>
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<tr>
<td>8</td>
<td>307,260</td>
<td>12,171</td>
<td>590,317</td>
<td>176,239</td>
</tr>
<tr>
<td>9</td>
<td>328,220</td>
<td>55,149</td>
<td></td>
<td>185,219</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td>237,224</td>
</tr>
</tbody>
</table>
Determination of Ball Location

Sub Ball_Location()
    ret = IpSegShow(1)
    ret = IpSegSetAttr(COLORMODEL, CM_RGB)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(2)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(1)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegSetAttr(CHANNEL, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegSetRange(0, 0, 20)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegSetAttr(CHANNEL, 1)
    ret = IpSegSetRange(1, 0, 20)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegSetAttr(CHANNEL, 2)
    ret = IpSegSetRange(2, 0, 20)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(2)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(1)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegSetAttr(CHANNEL, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(1)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegSetAttr(CHannel, 0)
    ret = IpSegPreview(ALL_B_W)
    ret = IpSegShow(1)
    ret = IpSegCreateMask(5, 0, 1)
    ret = IpSegShow(0)
    ret = IpLutSetAttr(LUT_CONTRAST, -2)
    ret = IpBlbShow(1)
    ret = IpBlbLoadSetting("c:\IPWin4\QuinSpin\ball_location_settings.env")
    ret = IpBlbCount()
    ret = IpBlbUpdate(0)
    ret = IpBlbShowData(1)
    ret = IpBlbSaveData("c:\IPWin4\QuinSpin\original results\ball_location.xls", S_DATA + S_HEADER)
End Sub
Determination of Ball Enclosing Square

Sub Enclosing_Rectangle()
    Dim numobj%
    ' get rid of out-of-range or hidden objects
    ret = IpBlbUpdate(4)
    ' get number of objects
    ret = IpBlbGet(GETNUMOBJ, 0, 0, numobj)
    If numobj = 0 Then
        IpMacroStop("Please count objects first", MS_MODAL)
        Exit Sub
    End If

    Dim bounds As RECT
    Dim i%
    ' show output window
    Debug.Print "Left, top, right, bottom:
    For i = 0 To numobj - 1
        ret = IpBlbGet(GETBOUNDS, i, 0, bounds)
        Debug.Print Str$(bounds.Left) & Str$(bounds.top) & Str$(bounds.Right) & Str$(bounds.bottom)
    Next i
    ret = IpOutputSave("h:\files\lu\football\IpDev\enclosing_rectangle.txt", 0)
End Sub

Determination of Coloured Panel Centroid Coordinates

Sub Colour_Analysis()
    ret = IpAoiCreateEllipse(ipRect)
    ipRect.Left = 372
    ipRect.top = 139
    ipRect.Right = 481
    ipRect.bottom = 252
    ret = IpAoiCreateEllipse(ipRect)
    ret = IpMacroStop("Define Ball Boundary", 0)
    ret = IpSegShow(1)
    ret = IpSegSetAttr(COLORMODEL, CM_HSI)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegSetAttr(CHANNEL, 0)
    ret = IpSegPreview(ALL_C_1)
    ret = IpSegShow(2)
    ret = IpSegSetAttr(SETCURSEL, 0)
    ret = IpSegPreview(ALL_C_1)
    ret = IpSegShow(1)
    ret = IpSegSetAttr(SETCURSEL, 0)
```c
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(2)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(SEGCLR_RED, 255)
ret = IpSegSetAttr(SEGCLR_GREEN, 0)
ret = IpSegSetAttr(SEGCLR_BLUE, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(O, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegSetRange(1, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegSetRange(0, 0, 10)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpBlbShow(1)
ret = IpBlbLoadSetting("c:\IPWin4\QuinSpin\panel_colour_settings.env")
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 0)
```
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 1)
ret = IpBlbCount()
ret = IpBlbUpdate(0)
ret = IpBlbShowData(1)
ret = IpBlbSaveData("c:\IPWin4\QuinSpin\original results\redpanels.xls",
    S_DATA+S_HEADER)
ret = IpSegShow(0)
ret = IpBlbShow(0)
ret = IpWsReload

ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(2)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegSetRange(1, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegSetRange(0, 0, 45)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(0, 25, 45)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegSetRange(1, 100, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegCreateMask(5, 0, 1)
ret = IpFltErode(MORPHO_2x2SQUARE, 1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpBlbShow(1)
ret = IpBlbLoadSetting("\c:\IPWin4\QuinSpin\panel_colour_settings.env")
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 0)
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 1)
ret = IpBlbCount()
ret = IpBlbUpdate(0)
ret = IpBlbShowData(1)
ret = IpBlbSaveData("\c:\IPWin4\QuinSpin\original results\yellowpanels.xls", S_DATA+S_HEADER)
ret = IpSegShow(0)
ret = IpBlbShow(0)
ret = IpWsRload

ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(2)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegSetRange(1, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegSetRange(0, 0, 100)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegCreateMask(5, 0, 1)
ret = IpFltErode(MORPHO_2x2SQUARE, 1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegCreateMask(5, 0, 1)
ret = IpFltErode(MORPHO_2x2SQUARE, 1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpBlbShow(1)
ret = IpBlbLoadSetting("c:\IPWin4\QuinSpin\panel_colour_settings.env")
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 0)
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 1)
ret = IpBlbCount()
ret = IpBlbUpdate(0)
ret = IpBlbShowData(1)
ret = IpBlbSaveData("c:\IPWin4\QuinSpin\original results\greenpanels.xls", S_DATA+S_HEADER)
ret = IpSegShow(0)
ret = IpBlbShow(0)
ret = IpWsReload

ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(2)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHannel, 1)
ret = IpSegSetRange(1, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHannel, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpBlbLoadSetting("c:\IPWin4\QuinSpin\panel_colours_settings.env")
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 0)
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 1)
ret = IpBlbCount()
ret = IpBlbUpdate(0)
ret = IpBlbShowData(1)
ret = IpBlbSaveData("c:\IPWin4\QuinSpin\original results\bluepanels.xls", S_DATA+S_HEADER)
ret = IpSegShow(0)
ret = IpBlbShow(0)
ret = IpWsReload

ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHannel, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(2)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetRange(0, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 1)
ret = IpSegSetRange(1, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHANNEL, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegSetAttr(CHannel, 2)
ret = IpSegSetRange(2, 0, 255)
ret = IpSegPreview(ALL_C_T)
ret = IpSegCreateMask(5, 0, 1)
ret = IpFltErode(MORPHO_2x2SQUARE, 1)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegShow(1)
ret = IpSegSetAttr(SETCURSEL, 0)
ret = IpSegSetAttr(CHANNEL, 0)
ret = IpSegPreview(ALL_C_T)
ret = IpSegCreateMask(5, 0, 1)
ret = IpBlbShow(1)
ret = IpBlbLoadSetting("c:\IPWin4\QuinSpin\panel_colour_settings.env")
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 0)
ret = IpBlbSetAttr(BLOB_AUTORANGE, 1)
ret = IpBlbSetAttr(BLOB_BRIGHTOBJ, 1)
ret = IpBlbCountO
ret = IpBlbUpdate(O)
ret = IpBlbShowData(1)
ret = IpBlbSaveData("c:\IPWin4\QuinSpin\original results\whitepanels.xls", 
S_DATA+S_HEADER)
ret = IpSegShow(O)
ret = IpBlbShow(O)
ret = IpWsReload

End Sub