CRANFIELD UNIVERSITY

MATTHEW CAPLE

MECHANICAL BEHAVIOUR OF NATURAL TURF SPORTS SURFACES

SCHOOL OF APPLIED SCIENCES

PhD THESIS

Supervisors: Dr Iain James and Dr Mark Bartlett
November 2011

CRANFIELD UNIVERSITY

SCHOOL OF APPLIED SCIENCES

PHD THESIS

2011

MATTHEW CAPLE

Mechanical behaviour of natural turf sports surfaces

Supervisors: Dr Iain James and Dr Mark Bartlett

November 2011

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

The understanding of the mechanical behaviour of natural turf pitches is limited, owed in part to the deficiencies in current testing devices and methodologies. This research aimed to advance the understanding of surface mechanical behaviour through *in-situ* and laboratory experiments, and via the development of new testing devices.

An impact testing device, the Dynamic Surface Tester (DST) was developed, with impacts replicating the magnitude of stress applied by athletes onto turfed surfaces during running. Developmental experiments indicated that the device was sensitive to changes in soil condition due to variations ($P<0.05$) in impact data.

The GoingStick device was implemented for use on natural turf sports pitches. Through the use of a specific calibration, the device successfully measured the range of mechanical behaviour occurring on three pitches across a playing season. The measured parameters of the device, penetration resistance and shear resistance, were linearly correlated to data measured with the established testing devices, the Clegg Impact Soil Tester (CIST; $r^2 = 0.75$) and studded disc apparatus ($r^2 = 0.88$) on these *in-situ* surfaces, and provided a more efficient means to test surfaces.

A season-long study assessing mechanical behaviour of a variety of pitches indicated that sand rootzone surfaces were more resistant to deformation and more consistent in their impact behaviour through the season than native soil pitches containing greater proportions of clay. This was attributed to the shear strength of clay soils being more dependent upon soil water content than managed sand rootzones. Temporal surface consistency may be beneficial to player performance, but surfaces that deform less in impact may increase the risk of more impact-related injuries. All data on the sand rootzones exceeded preferred values for impact hardness of the Performance Quality Standard (PQS) framework, indicating that the framework is obsolete for modern surfaces or that these surfaces are too hard.

Geostatistical techniques (variograms and interpolation) identified that three sports pitches exhibited spatially random variation in their mechanical behaviour assessed with the DST and GoingStick, and for soil water content. Impact hardness data from the third drop of the CIST were spatially related, attributed to lower variation in data as a result of flattening of the grass leaf and compaction of the thatch and soil under repeated drops. Spatial variation was generally lower on a sand rootzone pitch than native soil pitches. The presence of spatially random surface behaviour should be considered further for its effect on athlete performance and injury risk.

Grass leaves on natural turf were shown to absorb sufficient energy from single drops of low energy (2.7 J; 0.5 kg CIST) impacts compared to bare soil treatments, indicated by reducing ($P<0.05$) values of surface hardness. This effect was removed by the third drop when grass leaves were flattened and the soil was compacted. Grass leaves were shown to reinforce surfaces under repeated higher energy impacts (9.9 J; 2.25 kg CIST), preventing the soil from deforming plastically. Energy absorption from athlete-specific impacts using the DST was not dependent upon the presence of grass leaves. The results indicated that the impact behaviour of surfaces is dependent upon the stress history of the surface and the loading conditions of the impact, an important consideration when modelling athlete-surface interaction. The compressible nature of grass roots was shown to reduce the frictional properties of a sand soil in cyclic triaxial tests, increasing plastic deformation and reducing soil stiffness. Behaviour of a clay loam soil was independent of roots, attributed to the cohesive behaviour of the soil bonding the roots to the soil particles. These initial results suggest that the reduction in surface stiffness of sand soils with grass roots may provide increased energy dissipation to the athlete on contact with sand rootzone surfaces.

This research provides an important contribution to knowledge in the understanding of mechanical behaviour of natural turf pitches temporally, spatially, with the presence of grass, and in response to stresses representative of athlete loading. The new testing devices present a means to improve surface testing on pitches and expand understanding of surface behaviour in the future. Ultimately this will lead to improvements in the

management of pitches, and provide safer surfaces which also allow players to perform to a high standard.

ACKNOWLEDGEMENTS

I would like to thank the following people:

Dr Iain James and **Dr Mark Bartlett**, my PhD supervisors, for their continual and unwavering support and assistance in the project. This was very much appreciated, likewise their enthusiasm to submit the research chapters as papers.

Dr Bruce Jefferson and **Dr Jack Hannam**, for providing feedback during the project.

David Bartlett, for providing the DST and always being on call for repairs and technical support.

Mike Maher and staff at TurfTrax Group, for providing new calibrations for the GoingStick.

Richard Andrews and his team at the soil laboratories; **Ceri Llewellyn, Roy Newland, Simon Stranks, Kim Blackburn**, and the other staff at the soil dynamics laboratories for their help and guidance during practical work.

All the **research students and staff** in B42, and **Clare Humphries** for making my time at Cranfield so enjoyable.

The Gallier and Thompson clans, for keeping me sane during the three years, and helping me realise the important things in life.

My fiancée **Kel**, for putting up with me, tolerating my absence, and reminding me of who I am. And finally **my parents**, who have made me what I am.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND NOTATION

ACRONYMS

AAA	Advanced Artificial Athlete
AAB	Artificial Athlete Berlin
AAS	Artificial Athlete Stuttgart
ACL	Anterior cruciate ligament
A-MP	Main pitch at Club A
ANOVA	Analysis of variance
ASTM	American society for testing and materials
A-TP	Training pitch at Club A
B-MP	Match pitch at Club B
BW	Body weight
CIST	Clegg impact soil tester
C-MP	Match pitch at Club C
C-TP	Training pitch at Club C
D-MP	Match pitch at Club D
DPI & F	Department of primary industries and fisheries (Queensland, Australia)
DST	Dynamic Surface Tester
ET	Evapotranspiration
FIFA	Federation Internationale de Football Association
G	Soil with roots treatment
H1	GoingStick horseracing calibration 1
H2	GoingStick horseracing calibration 2
HIC	Head Injury Criterion
IDW	Inverse distance weighting
IRB	International Rugby Board
LSD	Least significant difference
MP	Match pitch
NG	Soil without roots treatment
PQS	Performance quality standard

PTM	Precision turfgrass management
RMSE	Root mean square error
SBR	Styrene butadiene rubber
SP1	GoingStick sports pitch calibration 1
STRI	Sports Turf Research Institute
TP	Training pitch

NOTATION

Cu	Undrained soil shear strength (KPa)
dz	Vertical displacement (mm)
dFz_{50}	Vertical loading rate in first 50 milliseconds of impact (kN s^{-1})
E	Young's modulus
E_{sec}	Secant modulus
E_{tan}	Tangential modulus
G	Shear modulus
g	Peak deceleration (in gravities)
K	Bulk modulus
M_{r}	Resilient modulus
M_{sec}	Secant modulus
R	Proportion of strain recovery (%)
z_{max}	Maximum depth of vertical penetration (mm)
ρ_{d}	Soil dry density (g cm^{-3})
ε	Strain
ε_a	Axial strain at the maximum axial stress
$\varepsilon_{\mathrm{rec}}$	Portion of recovered strain
σ_a^{max}	Maximum axial stress
θ_{v}	Volumetric soil water content (%)

1. INTRODUCTION

1.1 THE ROLE OF NATURAL TURF SPORTS PITCHES

Natural turf sports pitches are used globally as a surface for team sports such as football (soccer), rugby codes, Gaelic sports, lacrosse, and American football. The sports of football and rugby union are the most popular sports using these surfaces in the UK, with 2.1 million and 312,000 adults participating in these sports at least once a week respectively (Sport England, 2011). The management of these surfaces is limited by the financial and management resources available to a sports club, with the aim of surface provision arguably altering with these components.

Below the elite level of sport, where resources are often limited, Baker and Canaway (1993) have stated that the principal aim in sports pitch management is to provide a hard wearing (durable) surface that maximises a player's enjoyment of the game but minimises the risk of injury. At the elite level, income and expenditure in football is substantial: broadcasting revenue for Premier League clubs is over £2.2 billion per year; players' wages reached a total of £1.4 billion across the 92 professional football clubs in 2010/2011; over £3.5 billion has been invested by clubs in stadiums since 1991 (Deloitte, 2011). Arguably the aim of surface management at this level is to provide conditions which enhance the quality of the games played on them by allowing players to perform to their highest ability, in addition to minimising the risk of injuries. Providing surface conditions for the former maximises entertainment for spectators, and allows performance targets to be achieved e.g. winning trophies, team promotions, skills development, financial income. This was emphasised in the 1980s, where football league games played on short pile synthetic turf surfaces were considered less enjoyable by spectators than those played on the natural turf equivalent (Baker and Canaway, 1993). This was attributed to the excessive ball bounce and roll on these early generation synthetic surfaces and the reduction in aesthetic quality.

Irrespective of the level of sport, certain criteria are desired of pitches as the performance of these surfaces is critical to the nature and outcome of games. Surfaces are required to allow players to run at high speeds across the surfaces (18 - 30 km h^{-1};

Andersson et al., 2008), perform sharp changes of direction, and provide sufficient impact absorption during landing from jumps or falls encountered in contesting the ball. Surfaces are required to be flat and consistent, providing uniformity in the bounce and roll of balls, and removing the necessity for players to adapt to a changing supporting surface (Adrian and Xu, 1990).

Surface failure, be it in terms of providing inadequate safety for players, loss of player performance, or ball unpredictability, can have large consequences: loss of enjoyment, ceased participation and missed working days for amateurs; poor team performances, loss of financial income, and ending of careers at the elite level. Drawer and Fuller (2002) identified that team performance, in terms of league positions, reduced when a higher ratio of players were unavailable through injury. Additionally, it has been estimated that relegation from the English Football Premier League will result in a club losing £25 million in revenue in the first season, with this figure reaching £41 million after four years (Switzer, 2011).

The mechanical behaviour of natural turf pitches, defined as the reaction of the surface to a physical force, is an important component of the surface that governs playing quality. This behaviour is responsible for absorbing and returning impact forces, provides traction to players, and plays a role in surface durability. Certain mechanical properties of the playing surface have been recognised for their contribution to the biomechanics of athletes during locomotion, and with some cited as causal factors in the occurrence of injuries (Kerdok et al., 2002; Shorten, 2007). Injury rates are high in professional football and rugby, with 30.5 and 91 injuries respectively per 1000 playing hours in professional matches (Brooks et al., 2005; Ekstrand et al., 2006). Injury rates in football have been cited as three times higher than those in defined high-risk occupations (Hawkins and Fuller, 1999), and a professional sports club provides a unique setting for health and safety management in the workplace - The Health and Safety at Work Act 1974 requires employers to control as far as is reasonably practicable, risks to the health, safety, and welfare of employees. This is complicated by the fact that there are no regulatory standards for the mechanical performance of natural turf sports pitches, injury tolerances of the human body are not fully defined, and that determination of whether the pitch is fit to play is ultimately decided by the match referee.

Sports governing bodies, such as the Fédération Internationale de Football Association (FIFA) and the International Rugby Board (IRB) are responsible for setting and enforcing worldwide rules for football and rugby respectively. In contrast to the use of new generation artificial surfaces, governing bodies have not designated regulatory standards for the construction or performance of natural turf sports pitches, despite the performance of synthetic surfaces being based on the behaviour of 'good' natural turf pitches (FIFA, 2009; IRB, 2011). McAuliffe (2008) has suggested that it is not in the interest of governing bodies to regulate surface performance as it may limit the sports being played in parts of the world where management resources are limited. This would also be the case for surfaces susceptible to large variations in surface behaviour.

1.2 QUANTIFYING SURFACE PERFORMANCE

In-situ surface testing is the most common method to assess natural turf surfaces, in comparison to biomechanical or laboratory experiments. This type of testing allows instant quantification of surface performance at a relatively low cost, without the need to await laboratory results, prepare test specimens, or design intricate biomechanical experiments. Despite the lack of regulatory standards, the process of defining and quantifying playing quality of sports pitches has been undertaken for decades by researchers, and is driven by surface links to athlete injury and performance, the assessment of surface durability, and comparison of pitch performance over time or across facilities (Bartlett et al., 2009).

In-situ testing grew in popularity in the UK in the 1980s when a set of standards was proposed, now commonly referred to as the Performance Quality Standard (PQS) framework. This was predominantly established by researchers at the Sports Turf Research Institute (STRI; Holmes and Bell, 1986) with support from the Sports Council, although previous work by Peter Dury at Nottinghamshire County Council was attributed as providing the foundation for these objective tests (IOG, 2004). This framework outlined minimum standards for surface properties in an effort to improve the quality of natural turf pitches, and to allow comparisons of surface behaviour to synthetic turf (Baker and Bell, 1986). This testing involves categorising and benchmarking surface parameters through a combination of subjective and objective techniques, with preferred and acceptable limits evident (Bell and Holmes, 1988).

Two mechanical surface properties, impact hardness and shear resistance, are quantified under the PQS framework alongside a number of other surface parameters: grass length and density, percentage of desirable species, surface infiltration rate, surface evenness, and ball bounce and roll. Under the PQS framework, measures of surface quality are made at five defined locations across the pitch (Figure 1-1). Such is the popularity of the PQS standards and the testing methodologies, aspects of it have been adopted for use in other parts of the world such as the USA, Australia, and other parts of Europe (Chivers and Aldous, 2003; McNitt and Landschoot, 2003; Grossi et al., 2004; Magni et al., 2004). After their inception in the 1980s, a number of studies implemented the PQS framework in the ensuing years, advancing understanding of the behaviour of natural turf pitches. These studies allowed assessment of physical components of the natural turf system to be assessed: grass species (Canaway, 1984), soil textures (Baker and Isaac, 1987; Baker et al., 1988), surface constructions (Baker and Canaway, 1991), and soil amendments (Richards, 1994).

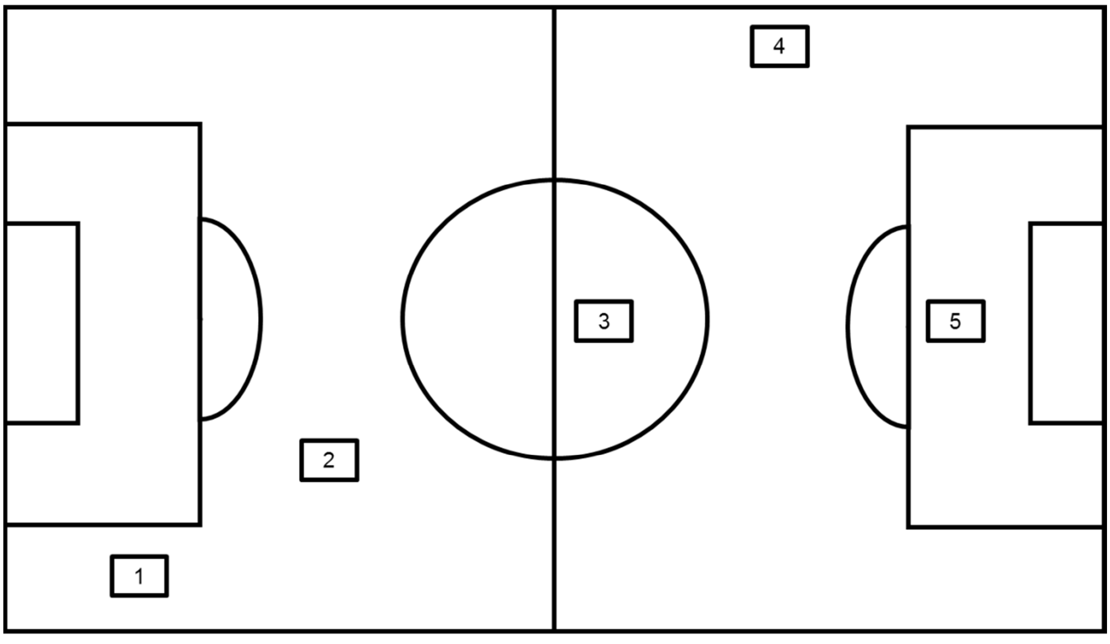

Figure 1-1 The five standard PQS pitch locations, used by Bartlett et al. (2009).

Deficiencies in the functionality and implementation of the PQS framework have been identified by Bartlett et al. (2009) in their review of the PQS framework: the validity and number of surface parameters assessed under benchmark frameworks is considered too large and requires narrowing for more efficient surface testing in the modern era; the devices used in assessing mechanical surface behaviour (impact hardness and shear resistance) are time consuming and laborious when used simultaneously, with a requirement for methodologies to be able to assess multiple parameters from single determinations. The benchmark ranges for impact hardness and shear resistance under the PQS framework were based on subjective perceptions of quality and comfort from amateur players (Bell and Holmes, 1988), and not on defined limits correlating to biomechanical or injury data. This means that the ability of the standards to define surface safety or athlete performance is limited, despite the maximum value of surface hardness used to determine whether surfaces are safe for play in Australia (Twomey et al., 2011).

The number of testing parameters used and inefficient nature of PQS methodologies is a driver behind the testing frequencies undertaken in the literature (once a month or less), and the selected number of pitch locations (five). In the development of the PQS framework, Holmes and Bell (1986) stated that pitches should be tested at six times during the playing season to assess temporal variation. Six pitch locations were also preferred for testing, as the use of 12 pitch locations in their study were not considered necessary as pitch areas were duplicated and regimes of wear could be covered by using three locations in each half of the pitch. These approaches to surface testing have remained the accepted procedure since their inception, albeit with five pitch locations now used. The adoption of this testing methodology means that behaviour of pitches between testing dates, and the behaviour of surfaces outside of these five pitch locations, is not quantified. As surface mechanical behaviour is dependent upon climatic conditions, and soil is non-homogenous and anisotropic, this methodology has limited the understanding of surface behaviour temporally and spatially.

The design, construction, and maintenance of elite level natural turf pitches have developed considerably since the inception of the PQS benchmark framework - modern elite level surfaces are considered harder with higher traction than pitches played upon 30 years ago, mirroring the increased fitness and technique levels of the modern elite player (Stiles et al., 2009; James, 2011). Benchmark testing devices and methodologies have not evolved in response to these developments. Research into the area of athlete-surface interaction has expanded rapidly in recent years, and this has prompted the development of a new type of testing device – those used to assess sports surfaces to athlete-specific loading and boundary conditions. However, the implementation of these devices on natural turf has been limited due to their lack of portability, with many devices confined to laboratory conditions or more commonly implemented on synthetic turf surfaces.

A greater understanding of the mechanical behaviour of natural turf is required, in addition to the development of testing devices and methodologies which address the deficiencies of current testing approaches. An increased understanding of surface behaviour temporally, spatially, and to athlete loading would ultimately improve the maintenance, design, and engineering of these surfaces, as well as providing insight into specific mechanisms relating to player biomechanics and injury.

1.3 PROJECT AIM AND OBJECTIVES

1.3.1 Aim

The aim of this study is to advance the understanding of surface mechanical behaviour of natural turf sports surfaces, through *in-situ* and laboratory experiments, and via the development of new testing devices.

1.3.2 Objectives

The following objectives have been defined:

1) To adapt and evaluate existing testing devices used on other natural turf surfaces for use on natural turf sports pitches. This is in order to overcome the limitations

of existing testing devices used on sports pitches and to improve understanding of biomechanical athlete-surface interaction.

2) To quantify the dynamic behaviour of *in-situ* natural turf surfaces in response to athlete-specific stresses, in order to increase understanding of surface yield and impact absorption.
3) To define the variation in mechanical behaviour of *in-situ* natural turf surfaces with time, soil texture, and soil water content, in order to understand the extent of surface variation and to evaluate data in the context of existing surface quality benchmarks.
4) To determine the spatial variation in surface mechanical behaviour of *in-situ* natural turf sports surfaces with the use of appropriate geospatial techniques, in the context of managing surfaces to provide consistent mechanical behaviour for optimum surface performance, athlete performance, and reduction of injury risk.
5) To quantify the effect of the grass plant on the dynamic behaviour of natural turf surfaces to improve understanding of soil-root interactions and the contribution of the grass leaf in surface impact absorption.
6) To evaluate surface performance data for quasi-static and dynamic sports surface testing devices, to increase understanding of natural turf stress-strain behaviour in loading by athletes and to inform recommendations for the use of these devices in surface testing.

1.4 THESIS STRUCTURE

The research chapters (3-8) in this thesis are formatted as a series of papers submitted to or published in peer-reviewed journals. Details of the focus and submission of the research chapters is summarised in Table 1-1. To facilitate thesis integration and contextualisation, some additional text is included in the chapters e.g. references to appendices or to previous chapters. The author (M. Caple) was primarily responsible for analysing data and writing the papers. The contribution of the co-authors (I. James & M. Bartlett) was that of editing of the papers and provision of advice, characteristic of their roles as supervisor to this PhD research project. All experimental work was undertaken by M. Caple.

Table 1-1 Focus and current status (at thesis submission) of the six research chapters submitted to peer-reviewed journals as papers.

Chapter	**Title**	**Journal**	**Status**
3	Development of a simplified dynamic testing device for turfed sports surfaces	*Journal of Sports Engineering and Technology*	Published
4	Technical Note - Using the GoingStick to assess pitch quality	*Journal of Sports Engineering and Technology*	Accepted
5	Mechanical behaviour of natural turf sports pitches across a season	*Sports Engineering*	Submitted
6	Spatial analysis of the mechanical behaviour of natural turf sports pitches	*Sports Engineering*	Submitted
7	The response of soils with roots to cyclic triaxial loading	*European Journal of Soil Science*	Submitted
8	The effect of grass leaf height on the impact behaviour of natural turf sports field surfaces	*Sports Technology*	Accepted

A review of the literature pertaining to this research project is presented in Chapter 2. Additional literature reviews are provided as introductory sections of each research chapter, relevant to the particular subject area.

The development and operation of the DST device is presented in Chapter 3, a new biomechanically-valid testing device for use on natural turf sports surfaces. The device is assessed for its ability to detect changes in surface condition through a controlled laboratory experiment in the Soil Dynamics Laboratory. This Chapter addresses Objective 1. The research provided a foundation for the use of the device *in-situ* in Chapter 5.

An introduction to the use of the GoingStick as a surface assessment tool on natural turf sports pitches is presented in Chapter 4. The development of the device is outlined and the potential implementation of the device is discussed, using data collected on three sports pitches over two playing seasons and within a controlled laboratory experiment. Objective 1 is addressed in this chapter.

Chapter 5 details an *in-situ* pitch study assessing the mechanical behaviour of six natural turf sports pitches over a playing season. Surface behaviour is assessed against soil texture and soil water content. The GoingStick and DST device are implemented in this study, with the Clegg Impact Soil Tester used to relate surface behaviour to an established testing device. Data are related to the PQS testing framework. This chapter addresses Objectives 1, 2, 3, and 6.

The spatial variability in the mechanical behaviour of natural turf pitches is examined in Chapter 6 using the testing devices implemented in Chapter 5. Data is collected at over 100 locations on three pitches at three dates across the playing season. Variograms and interpolation techniques are used to assess the spatial structure of the data, with the study relating to Objectives 4 and 6.

Chapter 7 assesses the contribution of grass roots to the dynamic behaviour of two sports turf soils (sand; clay loam) through the implementation of the dynamic triaxial apparatus. This chapter addresses Objective 5.

Chapter 8 details a laboratory experiment assessing the contribution of grass leaves to absorbing impacts on natural turf. Three grass heights were assessed for their potential to absorb impacting energy of drop devices and the DST device. Objectives 5 and 6 are addressed within this chapter.

A synthesis of the research chapters is presented in Chapter 9. The findings of the research are discussed contextually in respect to surface testing, athlete performance and injury, and surface management. The contributions to knowledge of the project are also highlighted, as are the research limitations and future research recommendations. Conclusions of the project are outlined in Chapter 10.

1.5 REFERENCES

Adrian, M. and Xu, D. (1990), Matching the playing field to the player, in: Schmidt, R. C., Hoerner, E. F., Milner, E. M., (eds.) *Natural and Artificial Playing Field: Characteristics and Safety Features,* American Society for Testing and Materials, Philadelphia, pp. 10-19.

Andersson, H., Ekblom, B. and Krustrup, P. (2008), Elite football on artificial turf versus natural grass: Movement patterns, technical standards, and player impressions, *Journal of Sports Sciences,* vol. 26, no. 2, pp. 113-122.

Baker, S. W. and Canaway, P. M. (1993), Concepts of playing quality: Criteria and measurement, in: Carrow, R. N., Christians, N. E. and Shearman, R. C. (eds.) *International Turfgrass Research Journal,* Intertec Publishing Corp., Kansas, pp. 172-181.

Baker, S. W. and Bell, M. J. (1986), The playing characteristics of natural turf and synthetic turf surfaces for association football, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 9-35.

Baker, S. W., Cole, A. R. and Thornton, S. L. (1988), Performance standards and the interpretation of playing quality for soccer in relation to rootzone composition, *Journal of Sports Turf Research Institute,* vol. 64, pp. 120-132.

Baker, S. W., Gibbs, R. J. and Adams, W. A. (1992), Case studies of the performance of different designs of winter games pitches. I. Playing quality and usage, *Journal of the Sports Turf Research Institute,* vol. 68, pp. 20-32.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T. and Reddin, D. B. (2005), Epidemiology of injuries in English professional rugby union: part 1 match injuries, *British Journal of Sports Medicine,* vol. 39, pp. 757-766.

Canaway, P. M. (1984), The response of Lolium perenne (Perennial Ryegrass) turf grown on sand and soil to fertiliser nitrogen III. Aspects of playability - ball bounce resilience and shear strength, *Journal of the Sports Turf Research Institute,* vol. 60, pp. 27-36.

Chivers, I. H. and Aldous, D. E. (2003), Performance monitoring of grassed playing surfaces for Australian rules football, *Journal of Turfgrass and Sports Surface Science,* vol. 79, pp. 73-80.

Deloitte (2011), *Annual review of football finance 2011*, Deloitte LLP, London.

Drawer, S. and Fuller, C. W. (2002), An economic framework for assessing the impact of injuries in professional football, *Safety Science,* vol. 40, no. 6, pp. 537-556.

Ekstrand, J., Timpka, T. and Hägglund, M. (2006), Risk of injury in elite football played on artificial turf versus natural grass: A prospective two-cohort study, *British journal of sports medicine,* vol. 40, no. 12, pp. 975-980.

FIFA (2009), *FIFA quality concept for football turf. Handbook of requirements.* FIFA, Geneva.

Grossi, N., Liu, C., Yang, M. H. and Wrigley, M. (2004), Tall fescue turf quality and soccer playing characteristics as affected by mowing height, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 319-322.

Hawkins, R. D. and Fuller, C. W. (1999), A prospective epidemiological study of injuries in four English professional football clubs, *British Journal of Sports Medicine,* vol. 33, no. 3, pp. 196-203.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

IOG (2004) *An Introduction to performance quality standards 2nd ed.,* The Institute of Groundsmanship, Milton Keynes, UK

IRB (2011), *IRB Artificial rugby turf performance specification,* IRB, Dublin.

James, I. T. (2011), Advancing natural turf to meet tomorrow's challenges, *Sports Engineering and Technology,* vol. 225, pp. 115-129.

Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G. and Herr, H. M. (2002), Energetics and mechanics of human running on surfaces of different stiffnesses, *Journal of applied physiology,* vol. 92, no. 2, pp. 469-478.

Magni, S., Volterrani, M. and Miele, S. (2004), Soccer pitches performances as affected by construction method, sand type and turfgrass mixture, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 281-285.

McAuliffe, K. W. (2008), The role of performance testing and standards in the sports turf industry: a case study approach, in: Stiel, J. C., Han, L. and Li, D. (eds.), *Proceedings of the Second International Conference on Turfgrass Management for Sports Fields*, ISHS, Leuven, pp. 391-398.

McNitt, A. S. and Landschoot, P. J. (2003), Effects of soil reinforcing materials on the surface hardness, soil bulk density, and water content of a sand root zone, *Crop Science,* vol. 43, no. 3, pp. 957-966.

Richards, C. W. (1994), The effects of mesh element inclusion on soil physical properties of turfgrass rootzones, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 110-118.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Sport England (2011), *Active People 5,* Sport England, London.

Stiles, V. H., James, I. T., Dixon, S. J. and Guisasola, I. N. (2009), Natural turf surfaces: The case for continued research, *Sports Medicine,* vol. 39, no. 1, pp. 65-84.

Switzer, A. (2011), The cost of relegation from the Premier League, *The Telegraph,* May 23rd 2011, Issue 1034.

Twomey, D. M., Otaga, L. and Saunders, N. (2011), Challenges in the development of standards for synthetic turf for Australian football and cricket, *Journal of Sports Engineering and Technology,* vol. 225, pp. 93-101.

2. LITERATURE REVIEW

2.1 THE ROLE OF SPORTS SURFACES IN ATHLETE PERFORMANCE AND INJURY

A number of relationships have been drawn between the mechanical behaviour of sports surfaces and athlete biomechanics and injury. The two most important characteristics of sports surfaces relating to athlete-surface interaction are behaviour during impact, and the horizontal behaviour relating to the grip of shoes on the surface (Stiles et al., 2009). The dynamic stress-strain behaviour of sports surfaces is an important consideration for athlete-surface impacts such as those occurring in falls or during running and landing, and for impacts occurring from balls. During impact, energy is transferred from the impacting object (athlete's shoes, balls) to the surface, and the ratio of returned energy is dependent upon the material properties of the surface. The path of energy flow can be partly dissipated as heat, but more prominently retained or dissipated in strain or plastic deformation, or rebounded to the impacting object through material stiffness (Davidson et al., 2009).

The absorption and return of impact energy contributes to athletic performance (Baroud et al., 1999). It is considered that athletes perform movements more efficiently on stiffer surfaces which deform less and return energy to the athlete faster (greater rate of loading) and in greater magnitudes (Stefanyshyn and Nigg, 2003). Ball bounce has also been shown to be higher on stiffer surfaces compared to those that deform on impact (Bell and Holmes, 1988). When athletes run on surfaces that deform, ground contact times are increased as the surface deforms under the foot, resulting in a reduction in the stride length and running speed achieved (McMahon and Greene, 1978). Increased surface deformation on contact can result in larger athlete energy requirements in performing movements and lead to muscle fatigue as a result of a decrease in the efficiency of work done by muscles (Lejeune et al., 1998; Millet et al., 2006). McMahon and Greene (1979) showed that the stiffest surfaces do not always produce the fastest running speeds, as an intermediate track compliance which was tuned to comply with the mechanical properties of the human runner produced optimum running speeds. Stafilidis and Arampatzis (2007) stated that unless the deformation of the surface is sufficient enough to affect the leg mechanics of the athlete, energy return and performance will not be influenced. This was shown in the sprint times of athletes not being affected by variation in stiffness (5500, 2200, and 550 kN m^{-1}) of three surfaces.

The magnitude and rate of loading of impact forces returned by sports surfaces is regarded as a potential cause of injury. Large peak forces and rates of loading returned by stiff surfaces increase the shock that is placed on the human body when impact with the surface is made, and this is believed to place an athlete at a greater risk of injuries such as knee osteoarthritis and stress fractures, and head injuries such as concussion (Grimston et al., 1991; Dura et al., 1999; Butler et al., 2003; Shorten, 2003). Stiff sports surfaces have also been cited as a potential for overuse injuries such as shin splints and Achilles tendinitis as a result of a combination of large impact forces and repetition in impact (James et al., 1978; Ekstrand and Nigg, 1989; Reilly and Borrie, 1992). In contrast to stiff surfaces, deformable sports surfaces dissipate energy and extend impact forces over a longer ground contact time, reducing the rate of loading and the subsequent risk of impact-related injuries (Davidson et al., 2009).

The increased magnitude and rate of loading of impact forces provided by stiff surfaces leads to compensatory adjustments by athletes when contacting the surfaces to reduce the loads absorbed by the body, such as a reduction in leg stiffness, reduction in heel velocity, and increase in joint flexion when running and landing (Dura et al., 1999; Kerdok et al., 2002; Dixon et al., 2005). These compensatory adjustments are not afforded by the player when they contact the surface accidently i.e. in head impacts or falls, and therefore surfaces are required to provide a sufficient degree of impact absorption for player safety. In rugby, overuse injuries are less frequent and injuries tend to be more traumatic as a result of impacts from players or with the ground (Milburn and Barry, 1998). Lüthje et al. (1996) also showed that 74% of injuries in football were as a result of physical contact with opposing players when contesting the ball (i.e. not directly surface related).

Traction is an important sport surface property, allowing athletes to perform movements such as a changing the direction of running (cutting manoeuvres) and forefoot push-offs

(Verhelst et al., 2009). Friction is defined as the resisting force acting between two contacting surfaces (Dixon et al., 1999), which is applicable to sports surfaces and the soles of sports shoes during athlete movements. On sports surfaces, there are two components of friction which are relevant for athlete traction: ‘force-locking connections’ relevant to the properties of the contacting surfaces to provide friction, dominant in flat-soled shoes on synthetic sports surfaces such as tennis; ‘form-locking connections’ provided by spikes or studs of shoes, which is dominant on natural turf pitches where studs penetrate into the surface (Stucke et al., 1984). It is universally accepted that hypothetical limits of traction exist for sports surfaces, although these are not fully defined with biomechanical or injury data (Chivers, 2008a). Insufficient traction forces between surfaces and shoes during athletic movement result in excessive horizontal movement, reducing the performance of players and can cause players to slip or fall. Conversely, a degree of shoe movement is required to allow stresses to be applied to the athlete over a greater time period, as injuries such as anterior cruciate ligament (ACL) tears in the knee have been linked to situations where the rotation of the shoe on the surface is restricted and excessive rotational force is applied to ligaments (Torg and Quedenfeld, 1974; Lambson et al., 1996; Orchard et al., 2005).

It is evident that a compromise is sought in the performance of sports surfaces: surfaces that deform sufficiently to provide protection against injury, but provide sufficient energy return for ball bounce and player performance; surfaces that provide sufficient traction to prevent players slipping, but do not expose players to excessive injury risks associated with excessive levels of traction. Although maximising player performance and reducing the risk of injury is idealistic for sports surfaces, providing optimum conditions for both of these components is not considered to be achievable, as they are not considered to be positively correlated past a certain point (Kolitzus, 1984). Explanations for injury and performance are often considered to be too simplistic, generic, or idealistic: although ACL tears can be attributed to foot fixation on the surface, Shorten (2007) considered that 71% of this type of injury in a study of American football players was not attributed to this mechanism. This leaves uncertainty as to whether the playing surface is a causal or contributory factor in injury occurrence. The biomechanical conditions leading to specific types of injuries, and the tolerances of internal structures are not fully defined yet (Villwock et al., 2009b; Grund and Senner, 2010). Owing to these issues, it is clear that a better understanding of sports surface behaviour relating to specific biomechanical movements and injury occurrences is required.

2.2 NATURAL TURF MECHANICAL BEHAVIOUR

2.2.1 Definitions and Mechanisms

Mechanical behaviour of natural turf describes the reaction of the surface in response to a physical force. Behaviour is often quantified in terms of ‘stiffness’ ‘strength’, and ‘hardness’, with all of these parameters providing an indication of the resistance of the surface to deformation. Natural turf mechanical behaviour should be referred to within a soil mechanics context, due to the soil component of the system largely determining surface behaviour (James, 2011).

Hooke’s law dictates that for elastic solids, the strain induced is proportional to the level of stress applied - the material returns to its original shape immediately after the stress is removed. In contrast, materials that exhibit plasticity deform under stress, but this deformed shape is retained (Hillel, 1998). Soil is a non-Hookean material in that the stress-strain relationship is non-linear and behaviour does not adhere to idealistic models i.e. elastic or plastic (Craig, 2004). Despite this, it is convenient to approximate elastic-plastic behaviour over a limited stress range in numerous applications: soil is considered to display elastic properties when stressed until a yield point is reached, an increase in stress beyond the yield point will cause the soil to exhibit permanent plastic behaviour (Wulfsohn and Adams, 2002). This behaviour is shown graphically in Figure 2-1 (left), with an elastic stage (A-B), a limited recoverable range (B-C), leading to a plastic yield point (C). In reality, elastic behaviour of soil is low (around 1% of strain), and both elastic and plastic strain occurs during loading. The magnitude of these is dependent upon properties of the soil, the characteristics of the applied stress, and the previous stress history of the soil (Brown et al., 1975; Wood, 1980; O'Reilly and Brown, 1991; Karg and Haegeman, 2009).

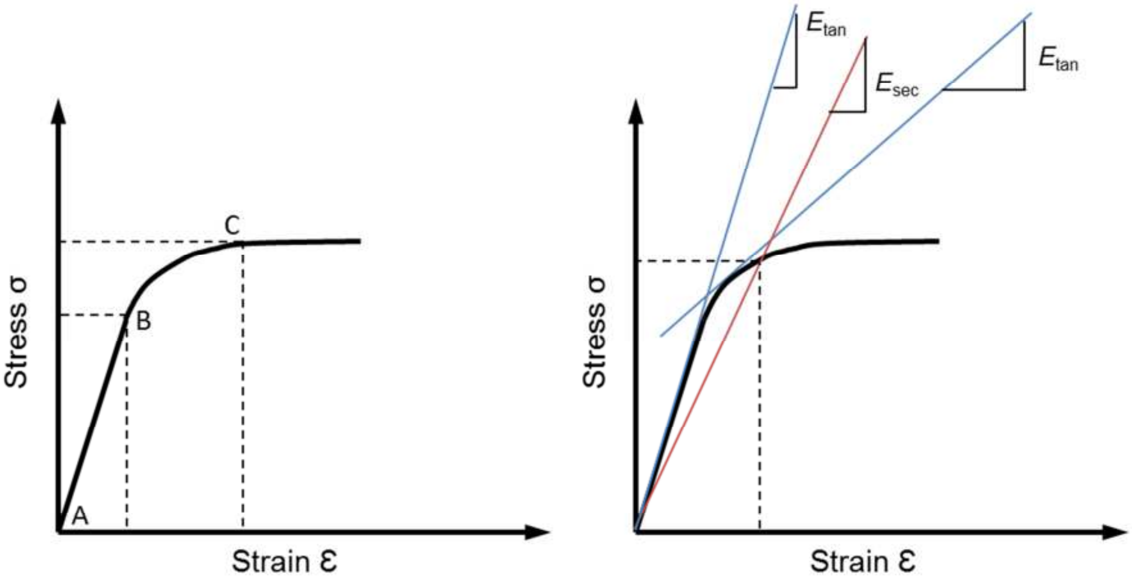

Figure 2-1 Left: Graph outlining theoretical soil behaviour - between points A and B elastic strain occurs where strain is equal to the stress applied; B to C some plastic strain occurs that is not fully recoverable; after point C perfectly plastic behaviour occurs where strain is constant for the level of stress applied; Right: examples of tangential moduli (blue lines) for different points on the stress strain curve, and secant moduli (red line) for the position on the curve indicated by the black dashed lines, adapted from Whitlow (2001).

Stiffness is used as an indicator of the stress-strain behaviour of soil, defining the level of strain exhibited for a certain level of stress. Soil stiffness is typically quantified in terms of moduli, determined from the slopes of stress-strain loading curves. Depending on the orientation of stress application and parameters recorded, stiffness can be presented by Young's modulus (E), bulk modulus (K), and shear modulus (G). As soil behaviour is non-linear (Figure 2-1), it is also common to define soil stiffness from stress-strain curves as either the tangent modulus (E_{tan}) which varies from point to point in the stress-strain curve, or secant modulus (E_{sec}), defined as the ratio of difference in stress to the corresponding strain (Whitlow, 2001; Figure 2-1 right). Although an important surface property, the small strain measurements associated with stiffness and elasticity (<1%) means quantification of this parameter within natural turf systems has been limited to laboratory analysis using sophisticated soil analytical equipment such as the triaxial testing apparatus (Guisasola et al., 2010a,b). The domination of plastic behaviour in natural turf mechanical behaviour means it is more common to determine properties such as strength and hardness on *in-situ* surfaces.

Strength of soil relates to plastic yield behaviour, and is fundamentally described as the ability of the soil body to resist stresses without experiencing plastic failure. Strength in soils is caused by inter-particle resistance provided by friction and cohesion, and failure results in soil undergoing a change in volume or shape as particles slide or roll over each other. This failure may be in terms of sliding movements on shear slip surfaces, common in dry brittle soils, or internal particle flow common in soils with greater water content (Whitlow, 2001). Strength values are theoretically described by the maximum stress a soil can withstand prior to failure, although in practice it is quantified as the minimum stress that causes failure (Hillel, 1998).

The term 'hardness' is used ambiguously in the literature, and often interchangeably with 'strength'. Similar to strength, hardness of natural turf refers to the resistance of the soil to plastic deformation. More specifically, it is defined as the resistance of the surface either to plastic deformation when impacted (impact hardness), or the resistance of the surface to penetration (penetration hardness; Bartlett, 1999). In *in-situ* surface testing, this surface property is quantified in terms of peak deceleration of a vertically dropped flat-faced missile (Clegg, 1980), or resistance to a probe being forced into the surface (Orchard, 2001) respectively. In this respect, surface hardness is also reliant upon the presence of thatch in the turf (a layer of decomposing fibrous plant material and organic matter lying above the soil profile), and in the case of the former, grass leaves on the surface. Hardness has been used more contextually in the literature to relate to the ratio of energy absorption a player might receive when impacting the surface, and the resistance of the surface to stud penetration (Norton et al., 2001; Clarke et al., 2010).

2.2.2 Loading of Natural Turf Sports Surfaces

The most common forms of loading that a natural turf surface receives are vertical compression loading and horizontal shearing forces. The elastic-plastic behaviour of soil determines the dynamic behaviour of natural turf surfaces during impact. Energy is dissipated and absorbed by the natural turf surface through the plasticity of the soil. This is important for reducing peak forces, increasing ground contact time for players, and providing a reduced risk of impact-related injury. The stiffness (and elastic) behaviour of soil is related to the return of impacting energy which is important for players to perform athletic movements efficiently, and for ball bounce. Traction on natural turf is provided by horizontal shear resistance of the surface in response to the shearing movement of studs in the turf. As stud length is typically ≤15 mm, the shear resistance of the surface at this depth is reliant upon the behaviour of the soil (shear strength), grass roots (tensile strength and adhesion to particles), thatch, and the combined behaviour of all of these components. Three defined orientations of shearing stress are applied to the turf by shoes with studs during athletic movements: rotational, translational (linear), and lateral. At present rotational traction is the most popular orientation quantified on sports surfaces, as links between excessive rotational traction (shear resistance) of shoes and foot fixation injuries have been made (Lambson et al., 1996). Moreover, surfaces that are very hard (high yield stress) will not allow studs to penetrate fully into the surface when athletes contact the surface with their shoes. This reduced stud penetration has the effect of reducing traction as less surface area of studs and shoe sole is in contact with the turf (Kirk, 2007). Lateral and translational traction is quantified more commonly for their relation to athlete performance, in movements such as 180° turns and forefoot push-offs respectively (Carré et al., 2007; Verhelst et al., 2009; Meyer et al., 2010). Insufficient shear resistance of the turf during these movements result in excessive horizontal movement of the studs and boot through the turf, defined by soil particles sliding over each other in shear failure, and can result in players slipping.

When an athlete's foot impacts the surface during running, it is moving downward at a high velocity (*ca.* 1.10 m s^{-1} when athletes run at a forward velocity of 4 m s^{-1}; Nigg et al., 1987). During impact, the foot decelerates rapidly towards zero velocity, with the rate of deceleration sensitive to the mechanical behaviour of the surface (plasticity; stiffness). Zero velocity of the foot is reached by the surface applying an equal and opposite force onto the foot, termed the ground reaction force. Figure 2-2 (left) illustrates both vertical and horizontal force-time profile of athlete footstrike when running on natural turf surfaces at a forward velocity of 3.83 m s^{-1} (Guisasola et al., 2010a). Three distinct stages of impact are identified: a peak impact stage (A) is present during heelstrike, followed by the rolling motion of the foot which produces an increase in force applied until a peak active force is generated during midstance (B), and finally a take-off stage where vertical force reduces and peak horizontal force is applied (C) during unloading. The right side of Figure 2-2 illustrates the orientation of applied force by the athletes at these three stages. Most notable is that the force applied by the athlete during peak impact and active forces are predominantly in the vertical direction, but a rotation of principle stress occurs where rearward horizontal and vertical loading dominates leading to foot take-off. These complex movements and rotation of principal stress axes means that shear stresses between particles (and subsequent failure) occurs in a variety of orientations and loading rates, and also highlights the difficulty in replicating the loading of athletes through the development of mechanical devices.

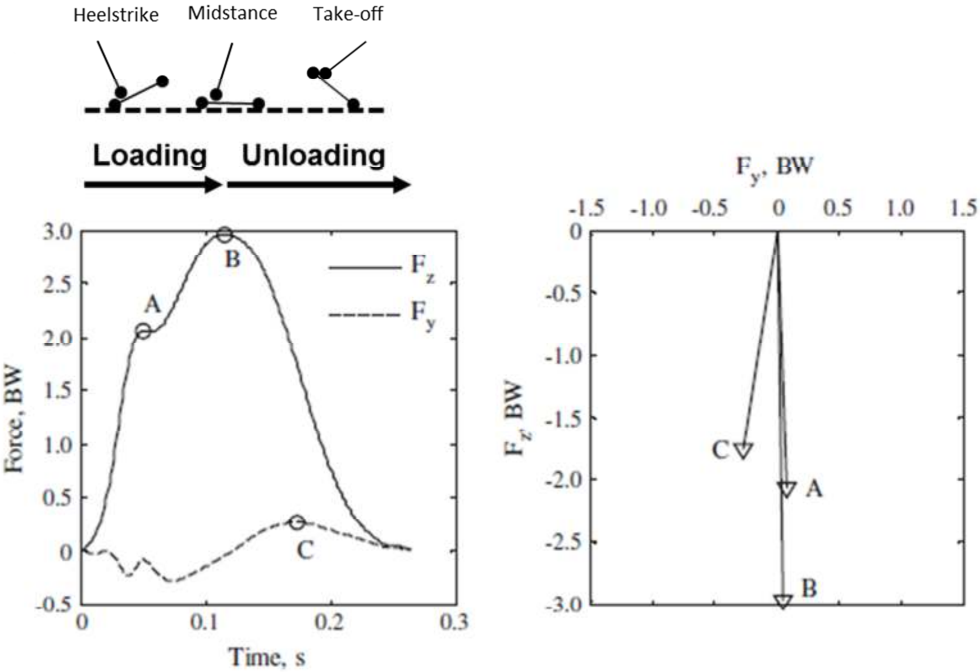

Figure 2-2 Example of rotation of forces applied within athlete footstrike during running, Left: Vertical (F_z) and horizontal (F_y) ground reaction force-time profiles, with schematic pictation of stages and foot angles; Right: Ground reaction forces in the *z:y* plane for three points – A peak impact (F_z), B peak active (F_z), C peak active (F_y). Adapted from Guisasola et al., (2010a).

An important aspect in quantifying the stress-strain behaviour of natural turf is the strain rate applied. Strain rate is defined as the rate of deformation per unit of time, and is a function of the magnitude of the load applied and the rate of loading (Karmakar and

Kushawa, 2005). The non-linearity of soil stress-strain behaviour can result in an increase in the stiffness and resistance to failure exhibited when an increased strain rate is applied (Brandon et al., 1986; Shao and Xie, 2002; Guisasola et al., 2010b), thus affecting the ratio of elastic and plastic behaviour exhibited. Guisasola et al. (2010b) showed that loading (secant) and recovery (resilient) stiffness modulus and recovery of strain was increased in 'dynamic' cyclic triaxial tests of a sand and clay loam soil when the loading rate of stress application was increased from 0.6 to 5.7 kN s^{-1}. These dynamic loading rates are in comparison to 'quasi-static' rates of $5x10^{-4}$ kN s^{-1} in another study (Guisasola et al., 2010a). When dynamic loading rates are applied, soil does not have time to produce plastic deformation and dissipate pore pressures that is characteristic of quasi-static tests (O'Reilly and Brown, 1991). These loading conditions are defined as undrained, as the deformation of the soil mass relates to the stiffness of both the pore water and the soil solids and the degree of saturation with respect to water (Whitlow, 2001). Within athlete loading on sports surfaces (Figure 2-2), the strain rate of stress application is dependent upon a number of factors such as the material response, mass of the athlete, running style, acceleration/velocity of the athlete, footwear, and the biomechanical movement being performed (Nigg et al., 1987; Nilsson and Thorstensson, 1989; Smith et al., 2004; Guisasola, 2008). Generally, as running velocity increases, the rate and magnitude of force application by athletes onto sports surfaces also increases: vertical force magnitudes can reach up to 3.3 BW (bodyweights) when sprinting (Girard et al., 2011), or up to 5.5 BW when landing from a vertical jump (Fritz and Peikenkamp, 2003). The magnitude of horizontal force applied during the impact and midstance phases of footstrike also increases with an increase in running velocity (Nilsson and Thorstensson, 1989), and also during stopping movements when large horizontal braking forces are applied.

Surface durability of natural turf pitches relates to the ability of the surface to withstand excessive failure when loaded repeatedly under the wear associated from play i.e. compression and/or shear forces. Withstanding these wear-related effects enables measured mechanical properties (surface hardness and shear resistance) to maintain minimum standards under benchmark testing and increase the carrying capacity of the surface (more games permitted during a playing season; Baker and Gibbs, 1989).

Viscosity, a time dependent soil property, is also important for surface durability: energy is dissipated through deformation during loading, with this property allowing soil to regain a ratio of its original shape. Viscosity is time-dependent and does not influence the return of energy for players or balls associated with soil stiffness or elasticity (Muir Wood, 1991). In the Guisasola et al. (2010b) study, two soils (sand, clay loam) were subjected to repetitive dynamic compression under stresses modelled from athletes running on natural turf. It was shown that the behaviour of the soil was dependent upon the stress history of the soil, as early cycles were dominated by viscoplastic behaviour (where energy is dissipated through hysteretic strain) and later cycles by viscoelastic behaviour (where recovery of strain dominates). The latter behaviour was caused by the soil being compacted, increasing density and optimally orientating particles and resulting in greater soil resilience. This behaviour was linked to the effect of wear from play on turf pitches, where certain areas of the pitch are compressed repeatedly and mechanical behaviour can vary.

2.2.3 Biomechanical and Injury Variations Related to Mechanical Behaviour

The theoretical relationships between surface behaviour and athlete performance are often assessed through biomechanical experiments. Athlete-centric measurement systems such as force platforms or pressure insoles are used in these experiments to measure biomechanical parameters such as peak impact and active forces, rates of loading, ground contact times, and peak deceleration when athletes run or land on the surface (Dura et al., 1999; Dixon et al., 2000; Tillman et al., 2002; Dixon et al., 2005; Stiles and Dixon, 2007; Tessutti et al., 2010). Although less common, some studies measure the behaviour of the surface during these interactions (McMahon and Greene, 1979; Kerdok et al., 2002).

Biomechanical studies are rarely performed on natural turf owing to the sensitivity of test equipment or practicality of the testing procedures to be implemented outdoors. This is confounded by replication requirements and repeatability constraints of experimentation with natural turf in laboratory conditions, and the difficulty in extrapolating data to *in-situ* natural turf pitch properties (Stiles et al., 2007). This has restricted the frequency of these types of studies in the literature, limiting the understanding of athlete-surface interaction on this surface type. Only a limited number of studies performed in biomechanics laboratories (Dixon et al., 2008; Stiles et al., 2011) have been reported, while more studies have been performed outdoors, often assessing biomechanical response differences between natural and synthetic surfaces. Eils et al. (2004) found little differences for vertical in-shoe pressure measurements between a natural turf surface and red cinder surface when athletes ran on them. The traction properties were not considered in this study, which may have indicated differences between surfaces in greater magnitude than vertical loading. Ford et al. (2006) found no differences in running performance (sprint times) between a natural turf and third generation synthetic turf surface, although peak pressures in-shoe were higher in forefoot and midfoot regions on the synthetic surface. The authors hypothesised that this loading explained faster running times noted in previous studies on synthetic turf compared to natural turf, although findings may also explain the greater non-contact injury rates associated with synthetic turf. Two other studies by Clarke et al. (2010) and Kirk (2007), assessed stud patterns, shoes, and comfort on a natural turf and third generation synthetic surface, but much analysis was dedicated to the performance of the shoes rather than between surfaces. All of these studies did not characterise the construction/soil texture or mechanical behaviour of the natural turf surfaces adequately, typically labelling the surfaces ‘grass’ or ‘natural turf’. This lack of characterisation makes comparison of natural turf properties to athlete biomechanics difficult.

Out of the above mentioned studies, only those by Dixon et al. (2008) and Stiles et al. (2011) considered the effect of the natural turf surface mechanical behaviour on athlete biomechanics, as well as providing characterisation of the surface. In the Dixon et al. (2008) study, athletes ran on a sandy loam soil (no grass) with pressure sensors within shoes and in the soil at depths of 100 mm, 200 mm, and 350 mm. It was shown that a reduction in dry density from 1.59 g cm^{-3} to 1.46 g cm^{-3} of the soil (effectively reducing soil strength) resulted in a significant reduction of in-shoe heel pressure for athletes, although peak forces and loading rates were not found to vary within the surface. This behaviour was attributed to the maintenance of peak forces by the athlete across surfaces to maintain running performance, but the reduced heel loading indicated that the more compliant surface (1.46 g cm^{-3}) provided more cushioning to the athlete. It was also shown that the peak loading rate was two orders of magnitude greater at 100 mm than 200 mm depth, indicating athlete-surface interaction effects are most critical in the first 100 mm depth of the soil.

In the Stiles et al. (2011) study, athletes ran on trays of a sand, sandy loam, and clay loam turf surface (with grass) in the laboratory, with force platforms positioned below the turf. Results indicated that peak loading rate was greater on the sand surface, but peak forces remained similar across surfaces. During turning movements, impact velocities were significantly lower for the 5th metatarsal phalangeal joint (MTP; equivalent to heel velocity) on the clay loam surface than the sandy loam surface, with the former characterised as having greater impact hardness by an objective surface testing device. The loading rate difference in surface behaviour was determined in the Guisasola et al. (2010b) study assessing the dynamic compression behaviour of the sand and clay loam soils. Behaviour was explained by the increased stiffness modulus of the sand soils, a result of lower soil deformation during loading compared to the clay loam soil. The lower MTP velocity on the clay loam was attributed to the athlete producing adaptations during turning movements to reduce forefoot loading (Stiles et al., 2011). These two biomechanical studies undertaken on natural turf materials proved that the properties of natural turf surfaces can affect the support and biomechanics of athletes when loading the surface, and that these aspects can be dependent upon soil texture and soil physical condition. A greater understanding of the behaviour of *in-situ* surfaces to athlete loading and the potential affect it has on surface-related injuries is required, such as the increased stiffness and rates of loading provided by sand rootzone surfaces.

An early-season bias of injury has been identified in pitch-based sports played on natural turf, with increased hardness of the pitch at the beginning of the season cited as a contributory factor in these injuries (Alsop et al., 2000; Garraway et al., 2000; Orchard, 2001; Orchard, 2002). This notion has often been proposed without objectively quantifying surface condition. Integrated studies by Orchard (2001) and Takemura et al. (2007) quantified surface hardness of rugby pitches objectively and simultaneously with athlete injury data. Trends between ground hardness and injury rate were evident but were not significant. In Orchard's study, there was a significant trend towards softer grounds as the season progressed, coupled with a significant trend towards a reduction in ACL injury risk. It is evidence such as this that has led researchers to speculate that the relationship between stage of season and injury rate is more likely caused by extrinsic variables such as surface condition on natural turf, rather than intrinsic variables such as player fitness or fatigue (Chivers, 2008a).

Norton et al. (2001) showed that Australian football game speeds quantified via video analysis were significantly related to objective measures of ground hardness. It was hypothesised that these faster game speeds resulted in a greater number and more forceful collisions between athletes, which may equate to a greater incidence of injuries on hard surfaces. Significant trends between injury rates and surface mechanical behaviour cannot be found currently in the literature. Attaining these links is complicated by the vast number of risk and contributory factors in the occurrence of injuries, which makes quantifying them all impossible in a single study (Walker, 2007). It seems intuitive to suggest that a better understanding of surface behaviour throughout the playing season, such as the approach undertaken in the aforementioned integrated studies, may provide an indication of the specific mechanisms that cause surface-related injuries.

Orchard et al. (2005) showed Australian football pitches with perennial ryegrass (*Lolium perenne*) turf were found to produce less anterior cruciate ligament (ACL) injuries for players than pitches with Bermuda grass turf (*Cynodon dactylon*). This was considered to be due to the plant growth habit and reduced thatch accumulation of the former reducing traction of the surface and ultimately providing a safer surface. It must be considered that ryegrass and Bermuda grass are cool and warm season grasses respectively, and the data in the study may be affected by the drier climates (and potentially harder ground) that is present at the facilities containing Bermuda grass swards. Moreover, as the definition of 'safe' traction levels have not been fully defined, the recommendation of grass species on pitches to produce safer surfaces is not currently possible.

2.3 MECHANICAL BEHAVIOUR AND SURFACE COMPOSITION

Although understanding of the interactions of athletes and natural turf surfaces is limited, more is known on the mechanical behaviour of natural turf and its relation to physical surface properties, as a consequence of historical data providing a foundation for knowledge.

2.3.1 Surface Construction and Soil Texture

The construction profile and soil texture evident within a natural turf pitch largely influences the mechanical behaviour of the surface. A range of surface constructions are evident for natural turf pitches, and selection is largely determined by the financial and management resources of the sports club. The most basic are surfaces managed on native soils, characteristic of amateur and community level facilities. Soils in these pitches are often dominated by large proportions of clay and silt. At the other end of the spectrum are engineered sand rootzones evident at the elite level. These surfaces consist of 300 mm depth of sand rootzone overlying gravel layers and piped drainage. The use of sand rootzones is restricted to the elite level of sport as a consequence of large initial constructions costs, and continual maintenance costs incurred by the requirements of supplementary irrigation and fertiliser applications (Baker and Canaway, 1991b). Invariably there are intermediate construction profiles between the two outlined: combinations of various piped drainage, mole ploughing, sand amelioration of surface layers, and sand slitting (Pool, 1994; James et al., 2007; James, 2011). Figure 2-3 provides examples of the soil texture of a range of different natural turf sports surfaces in the UK and around the world.

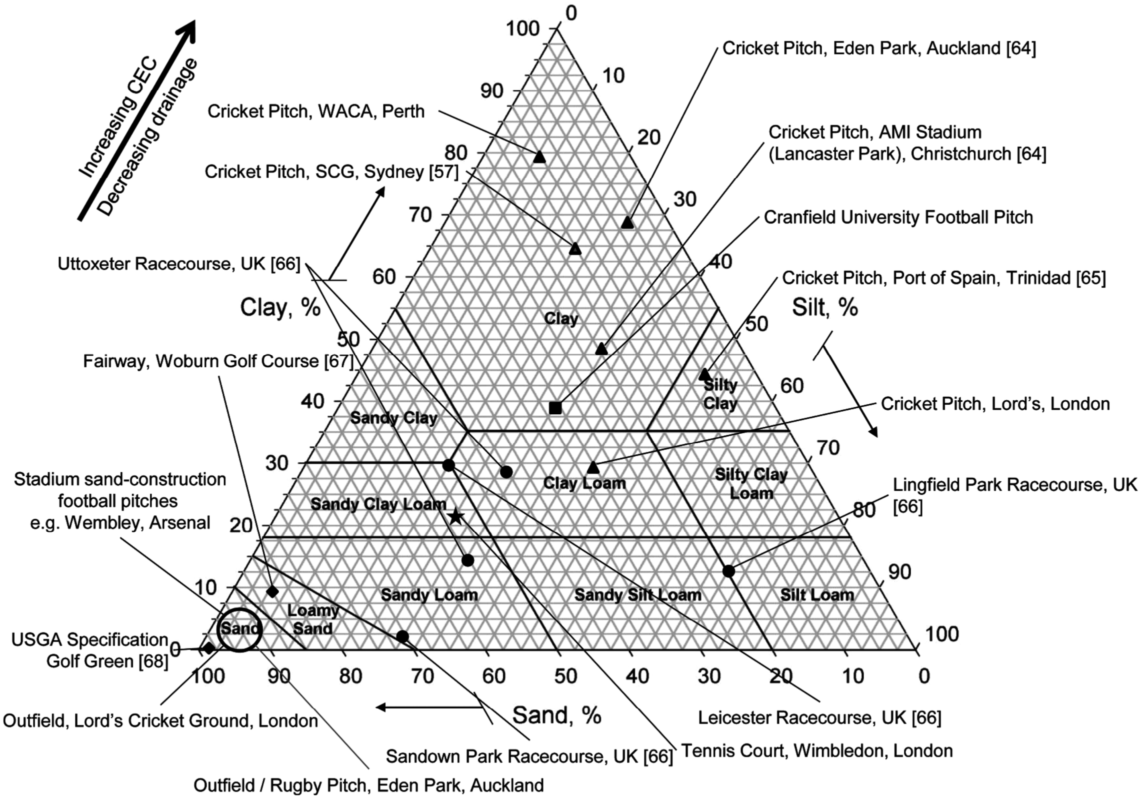

Figure 2-3 Examples of soils used in various natural turf sports surfaces in the UK and around the world. Presented in James (2011).

Sand is used in the construction of natural turf pitches where possible, owing to its greater infiltration and hydraulic conductivity, and strength characteristics that are less sensitive to water content (Baker, 2004; Guisasola et al., 2010a). Modern sand rootzones are typically reinforced with synthetic materials to improve the strength of these surfaces (Spring and Baker, 2006). This is in response to a reduction in surface strength when grass cover is lost on sand surfaces without reinforcement (Baker and Isaac, 1987). It is recognised that there are two broad categories of reinforcement – materials such as backings that form a horizontal layer at or near the surface of the turf, and reinforcement fibres that are mixed or stitched into the surface (Baker, 1997). The latter type of reinforcement is currently more commonly used in the UK. One popular construction type consists of polypropylene/polyurethane fibres (around 0.1 mm diameter; 35 mm length; around 0.3% by weight) mixed into the sand rootzone – 'Fibresand'. More recently, the Desso GrassMaster System has been introduced, consisting of larger synthetic strands stitched vertically into the surface to a depth of 200 mm (Figure 2-4). This surface construction has gained popularity due to a perceived superiority in turf shear resistance in stadium pitches, although this has not been confirmed with objective scientific studies.

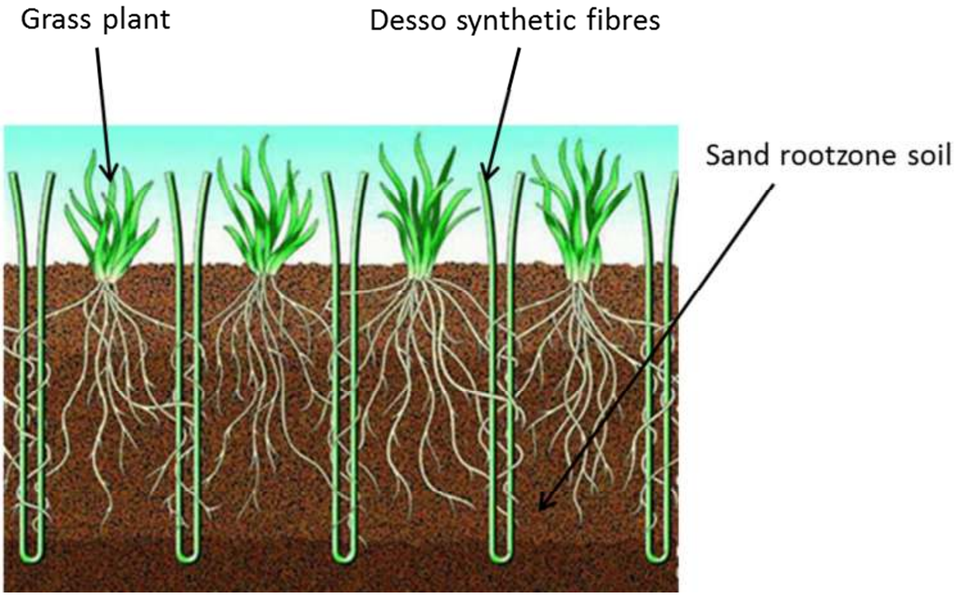

Figure 2-4 Profile of a Desso GrassMaster System surface construction. Source: greenpeopleme.com.

The ability of soil to retain water is inversely proportional to pore radius. Pore sizes are related to soil particle size, with clay soils (<0.002 mm particle size) containing a greater ratio of micropores than sand soils (2 - 0.063 mm particle size) which contain larger proportions of macropores. The greater particle surface area and mineralogy (electrostatically charged faces) of clay particles allows increased adsorption of water in these soils than sand soils. This water is held more tightly and at greater water content than sand soils at the same tension. Soil pore sizes also influence the conductivity of water through the soil, as water drains more quickly through the larger pores in sandy soil. Differences in hydraulic conductivity for sand and clay soils can be five orders of magnitude (10^{-4} m s^{-1} compared to 10^{-9} m s^{-1}; Hillel, 1998). In a comparison of infiltration rates of various pitch surface constructions, Baker and Canaway (1991b) showed that a piped drained native soil pitch exhibited rates as low as 0.5 mm h^{-1} after one year of simulated wear, compared to 157 mm h^{-1} for a sand rootzone construction. The low infiltration rates of the former construction meant that soils remained saturated for longer periods and caused surface water to be recorded on 60% of days during the playing season. This rendered the surface unplayable, and this surface behaviour is a key component behind the selection of sand soil in the construction of natural turf pitches.

Soil water content influences the resistance of soil to plastic deformation. In clayey soils, strength is provided by cohesion, which is a result of bonding the soil internally through electro-static (van der Waals) forces between particles. As water content increases, the bonds between particles within the soil are weakened and forced apart (Marshall and Holmes, 1988). This increases the susceptibility to produce plastic failure in soil as shear resistance of the soil is reduced. Plastic deformation is more prominent in cohesive soils (clay and silt-dominated soils), as plasticity is dependent upon the consistency of the soil – its physical state characteristic at a given water content (Whitlow, 2001). The plasticity index of these soils is the numerical difference between the plastic and liquid states of the soil. The plastic limit is defined as the point at which there is sufficient water in the soil to allow particles to slide past each other without internal cracks appearing, and for the soil to behave like a plastic material (Gulhati and Datta, 2005). The inert mineralogy of sand soil means the resistance to shear between particles is provided by frictional forces and the soil does not exhibit plasticity and cohesion. These forces build up when sand grains are forced to slide, rotate, or roll against each other (Bell, 2000). When sand soils are moist (but not saturated, i.e. field capacity), tension forces are built up in the water between particles and in pores, providing an apparent cohesion in the soil, increasing shear resistance of the soil mass. This apparent cohesion is removed when the soil is very dry or saturated, where particles can slide past each other more easily (Powrie, 2009).

Cohesive and frictional properties between soil particles are increased as soil density increases, caused by greater particle contact area and the optimal arrangement of particles that increases the shear resistance of the bulk soil. The effect of water content and dry density on the strength of two soils (clay loam, sand) evident in natural turf pitches was recently demonstrated by Guisasola et al., (2010a) in quasi-static triaxial compression tests. The shear strength of the sand soil was shown to be less sensitive to moisture content than the clay loam. The strength of the latter was shown to reduce when water content increased as a result of a reduction in cohesive properties. In the dynamic compression experiment (Guisasola et al., 2010b), it was also shown that the clay soil was more susceptible to plastic deformation than the sand soil at the same saturation ratio.

The inputs of water into the soil on natural turf systems are provided by rainfall and irrigation, while the outputs are provided by drainage (infiltration and hydraulic conductivity), and evapotranspiration (ET, the combined effects of evaporation from the soil surface and the loss of water through the plant via transpiration). The contribution of these components to soil water content has resulted in shear resistance and hardness of natural turf pitches being negatively correlated to rainfall and positively correlated with ET (Baker and Canaway, 1991a; Takemura et al., 2007). The increase in strength provided by apparent cohesion when sand soils are moist means that sand rootzone soils are ideally managed within a narrow range of soil water content. Managing these soils within a specific range of water content is aided by the hydraulic conductivity and water release characteristics preventing the soil from remaining at saturation for long periods after heavy rainfall, and through the application of supplementary water through irrigation preventing the soil drying out. In comparison, the reduced conductivity of clay-dominated soils, and their ability to retain greater water at the same tension, means these soils remain saturated for longer and water content of the soil remains closer to the plastic limit for longer after heavy rainfall.

2.3.2 Temporal and Spatial Variations in Mechanical Behaviour

Although a degree of temporal variation in mechanical behaviour is welcomed in certain natural turf-based sports to provide challenge to the player i.e. cricket and golf (James, 2011), temporal variation in mechanical behaviour of natural turf pitches is not desirable for the modern elite level football pitch. Surfaces are required to be consistent across the season, allowing certain player skills and team tactics to be performed, i.e. short fast passing, which has become standard in the elite level of football in recent years. Consistent provision of surfaces that allow for this type of football is demanded by television audiences and spectators.

Temporal variation in mechanical behaviour of natural turf pitches has been identified using the PQS framework (Holmes and Bell, 1986; Baker and Isaac, 1987; Bell and Holmes, 1988; Baker and Gibbs, 1989; Baker, 1991; Baker and Canaway, 1991a; Baker et al., 1992; Baker and Richards, 1995). Within these studies, pitches containing clay-dominated soils were shown to exhibit lower shear resistance and hardness in the winter periods of the season. This is linked to the soil water balance of the pitch, as rainfall is often higher and ET is lower in these periods, meaning soil water accumulates in these slow draining soils and plastic behaviour of the soil dominates. As a result, the surface mechanical behaviour can fall below minimum benchmarks for surface performance (Baker and Gibbs, 1989; Baker, 1991). This behaviour is contributed to by the accumulated effects of wear from sporting play creating an uneven surface, reducing the grass cover, and smearing the surface of clay soils. The latter acts in sealing the surface and reducing infiltration rates of the soil further, increasing the susceptibility to waterlogging and creates a viscous cycle that can only be halted with surface renovation. This behaviour in winter months was a key component in the development of the PQS framework and instigated the development of usage levels for pitch constructions: maximum usage for a pipe-drained naturally poor draining clay soil pitch was suggested as less than 50 games per season, while a sand rootzone pitch was considered to withstand up to 180 (Baker et al., 1992).

The range of temporal variation in pitch mechanical properties (shear resistance, hardness) was also shown to be greater on clay-dominated soils than sand soils in the aforementioned studies. As well as reducing shear strength when soil water increases, the shrink-swell behaviour exhibited by some clay soils (mainly those containing montmorillonite) causes the density of the soil to increase and the surface to become hard when the soil dries. This phenomenon is paramount in the management of cricket wickets in order to increase the pace and bounce of the surface, with the superior binding strength of clay soils utilised for these ball-surface interactions (Shipton, 2008; Figure 2-3). Clay soils on natural turf pitches can get very dry during periods of low rainfall, and this has been shown to produce surface conditions that are considered too hard - impact hardness exceeding PQS benchmark limits (Baker and Isaac, 1987). Temporal behaviour of clay-dominated natural turf pitches is often inevitable as a result of the reduction in shear strength as the soil water increases and the lack of management resources that are often evident at these facilities e.g. limited irrigation resources to prevent soils becoming hard. These facilities commonly demand intensive use of surfaces and are often lacking in financial resources to allow for the construction and maintenance of sand rootzone surfaces, with this situation a key component behind the adoption of synthetic turf surfaces at community and amateur facilities (Stiles et al., 2009).

Use of the PQS framework to quantify behaviour of natural turf pitches advanced the understanding of surface mechanical behaviour across the sporting season. However, the modern elite level football pitch has evolved since the PQS framework was developed in the 1980s, as a result of improvements to surface maintenance and construction techniques (Baker, 2004). Stiles et al. (2009) have postulated that these surfaces have become harder with higher traction that mirrors fitness improvements to the modern player. The behaviour of these modern surfaces requires quantifying, particularly in relation to PQS standards, as comprehensive studies have not been performed for 20 years. The resolution of testing within previous temporal studies, often at monthly intervals or less often (Baker and Gibbs, 1989; Baker, 1991; Baker and Canaway, 1991b; Baker et al., 2007), is also an area which can be improved. As surface behaviour can be sensitive to rainfall and ET rates, it is intuitive to suggest that the performance of the surface could vary on a weekly or even daily basis, requiring data to be collected at a higher resolution.

Spatial consistency in mechanical behaviour on natural turf pitches is important for predictable ball bounce and for players when contacting the surface. Spatial variation in surface mechanical properties such as surface hardness and shear resistance is detrimental to the quality and enjoyment of the game as it may cause players to slip or fall. The requirement for biomechanical adaption within locomotion caused by variation in surface condition has been cited as an injury risk in horses on natural turf (Stover, 2003), and it may be that this risk factor is present for human athletes. Meyers (2010) suggested surface inconsistency was a causal mechanism in injury occurrence on natural turf sports surfaces in wet weather, in comparison to more consistent synthetic surfaces where fewer injuries were reported, although this was not confirmed with quantitative evidence.

The mechanical behaviour of natural turf pitches was shown to vary spatially in early PQS studies undertaken by researchers at the STRI (Baker and Bell, 1986; Holmes and Bell, 1986; Bell and Holmes, 1988; McClements and Baker, 1994), and more recently by Kirby and Spells (2006). Data were collected at between 3-12 locations across the pitches (such as outlined in Figure 1-1), comparing areas such as goalmouths, central areas, and wings. This testing strategy was used as it was considered to provide representative data from the main areas of the pitch, and representative of different intensities of wear from play. It was shown that mechanical behaviour differed in central areas of the pitch that were subjected to higher concentrations of wear. Patterns of wear on football pitches are concentrated in a diamond pattern, extending out from one goalmouth to the halfway line and tapering towards the opposite goal (Holmes and Bell, 1986). Central pitch areas were found to be harder under impact but had lower horizontal shear resistance, attributed to rootzone compaction (from repetitive compression forces) increasing the density of the soil, and lower grass cover reducing the horizontal strength of the turf respectively (Holmes and Bell, 1986; Bell and Holmes, 1988). These measures of quality were taken at a variety of times within the season, and it should be noted that the mechanical properties would be dependent upon the properties of the soil i.e. water content, at the time of testing: reduction in grass cover may have reduced strength in highly worn areas, but an increase in soil compaction and surface strength in these areas may increase shear resistance values recorded (subject to surface penetration of the testing equipment); surface hardness may be increased in worn areas as a result of the compacted soil drying out, or being saturated and less easy to compress.

As with temporal variation, the magnitude of spatial variation was found to be lower on sand rootzone pitches, in comparison to clay-dominated pitches. The increased susceptibility of clay pitches to plastic deformation and shear failure with an increase in water content means that mechanical behaviour varies with the intensity of sporting wear. This is in comparison to sand soils that exhibit greater resistance to shear failure with variation in water content and produce greater resistance to the effects of wear from play. Rugby pitches were also considered to exhibit less spatial variation in mechanical behaviour than football pitches, owing to the more evenly distributed playing patterns in this sport (McClements and Baker, 1994).

The aforementioned spatial studies were limited by the number of test locations that were selected across the pitch (≤12). Miller (2004) and Freeland et al. (2008) used interpolation to map impact hardness data from 80 and 77 locations respectively across the pitch to produce surface maps. This technique allows the whole pitch to be assessed in more detail, characterising unsampled areas of the pitch located between test locations. In Miller's study variograms were used, which characterise the structure and nature of sampled data: determination of whether the data is spatial dependent (variance is related to distance), the range of evident spatial dependency, and the error in data (Webster and Oliver, 2007). Using this technique, it was shown that a native clay-dominated pitch was around 50% more spatially variable than a sand rootzone surface, assessed seven times over a two-year period. Both of these studies showed the potential that using geostatistical techniques such as variograms and interpolation can provide to analyse the spatial structure of sports pitches, but the evaluation of the identified spatial variation and methodologies implemented was brief. A review of the literature indicates that the implementation of these geostatistical techniques on natural turf sports surfaces is rare: only studies by Carrow et al. (2010) and Krum et al. (2010) have been found on other sports surfaces, which used interpolation to map soil water content and penetration resistance of golf fairways. The difficulty and time consuming nature of data collection on a large scale, in addition to the requirement for specialist software and expertise, is a reason why these techniques are under-utilised. In the studies by Carrow et al. and Krum et al., a vehicle-mounted sensor unit was used. Developing this method of data acquisition increases initial set-up costs but would ultimately reducing operating costs when collecting data on large areas such as golf fairways.

2.3.3 The Grass Plant

The grass plant plays an important role in the performance of the natural turf pitch. Grass species on pitches are predominantly selected for their resistance to wear and tolerance to shade characteristics, important within stadium environments (Canaway, 1981; Newell et al., 1999). Grass leaves are managed at specific heights relevant to the playing characteristics of the particular sport: around 18 - 25 mm for football, optimising ball bounce and roll; heights of around 50 mm for rugby, where ball bounce is less important than the absorption of impacts (Baker and Canaway, 1991a; McClements and Baker, 1994; Mooney and Baker, 2000).

The increased shear strength provided by vegetation roots in soil is well established, including in natural turf applications (Adams and Jones, 1979). Roots of the grass plant increase the strength of soil by adhering to soil particles and aggregates, producing a composite material. When soils are subjected to shear forces, roots provide increased resistance to failure as axial tensile forces are built up as the root is stretched (De Baets et al., 2008). This mechanism allows soils with plant roots to exhibit greater shear displacements before failure compared to soils without roots (Comino and Druetta, 2010; Guisasola et al., 2010a). A positive relationship is evident between strength of soils and root density and mass, attributed to the greater number of roots providing greater root-particle adherence and resultant reinforcement (Adams and Jones, 1979; Tengbeh, 1993).

The increased horizontal shear resistance provided by roots in turf surfaces is important in the provision of sufficient traction to players with studded footwear. Research by Canaway (1975), McNitt et al. (1997), and McNitt et al. (2004) has shown that different grass species can provide different traction characteristics, attributed to differing root and growth structures (lateral and bunched), and the variation in thatch production of the grass swards. The increase in soil strength provided by roots in turf pitches is also important for surface durability, as the grass plant prevents the soil from divoting under the horizontal shearing effects encountered in wear from play (Li et al., 2009). The effect of grass roots to increase strength is further increased in reinforced sand rootzone surfaces, as roots bind around the reinforcing material as well as the sand particles to produce a stronger composite (Spring and Baker, 2006; Figure 2-4).

In assessing the effect of the grass plant in the dynamic behaviour of natural turf surfaces, research has been dominated by quantifying the effect of grass leaves in absorbing impacts. The results in the literature are conflicting. The presence of grass has been found to absorb some energy of impacting missiles before impact with the soil is made (indicated by reduced hardness) in comparison to soil without grass (Rogers III and Waddington, 1989; McClements and Baker, 1994). The effect of grass leaf height has also been studied. Grossi et al. (2004) showed ball rebound heights and surface hardness was negatively correlated with grass leaf height in the range 10 - 25 mm. In contrast to these findings, a study by Mooney and Baker (2000) found that surface hardness is independent of grass leaf height (18 - 30 mm); Zebarth and Sheard (1985) found that peak deceleration of an impacting device was independent of grass leaf height in the range 30 - 150 mm. Many studies assessing the effect of grass leaves to impact are limited by the experimental design applied in the studies, where established grass swards of different leaf height are assessed for differences in impact behaviour. Variation in root structure can potentially contribute to the impact behaviour of the turf surface, as roots often grow proportionally to above ground leaves (Liu and Huang, 2002; Issoufou et al., 2008). This creates uncertainty as to the relative contributions of leaves and roots in attributing to the impact performance of surfaces. A more comprehensive description of the role of the grass plant in influencing the dynamic behaviour of sports turf soils is required (Guisasola et al., 2010b). This is both in terms of the effect of the grass leaves in absorbing impacts above ground, and the effect that roots have on the dynamic behaviour of soils i.e. stiffness and elasticity. No research can be found that considers these components separately.

2.4 SURFACE TESTING DEVICES

Surface testing of pitches with mechanical devices provides a means to immediately assess *in-situ* surface properties without the requirement to wait for subsequent results or plan testing methodologies, typical of laboratory or biomechanical analysis. There are a number of testing devices in existence, each with their strengths and weaknesses. A review of the literature indicates that devices can be categorised into two broad categories: 1) devices that provide an insight into general surface condition, and 2) devices that aim to replicate or provide insight into athlete-surface interaction.

2.4.1 Category 1 Devices

Devices evident within this category characteristically provide surface data that is informative yet not specifically applicable to athlete-surface interaction. These devices are typically used to benchmark surfaces or to compare data across facilities or over time. Some devices within this category were originally developed for use in other industries but adopted for use on natural turf due to their time and cost efficiency in implementation.

2.4.1.1 Vertical Drop Devices

Vertical drop devices aim to quantify the behaviour of the turf surfaces to a falling missile. The Clegg Impact Soil Tester (CIST; Clegg, 1976) is the most commonly used drop device, and quantifies impact hardness of the turf surface. It was originally developed to assess the hardness of pavement foundations but it has been adopted for quantification of sports surfaces. The device consists of a cylindrical missile of either 0.5 kg or 2.25 kg with an integrated accelerometer that is dropped from a fixed height (0.55 m and 0.45 m respectively) through a vertical guide tube (Figure 2-5). The missile is typically dropped repeatedly on the surface (up to four times). The peak deceleration of the missile after impact with the surface is recorded in gravities (g), with a higher value equating to harder surface. Lower peak deceleration values are as a result of longer ground contact times predominantly due to greater plastic displacements (Rogers III and Waddington, 1990; Baker et al., 2007).

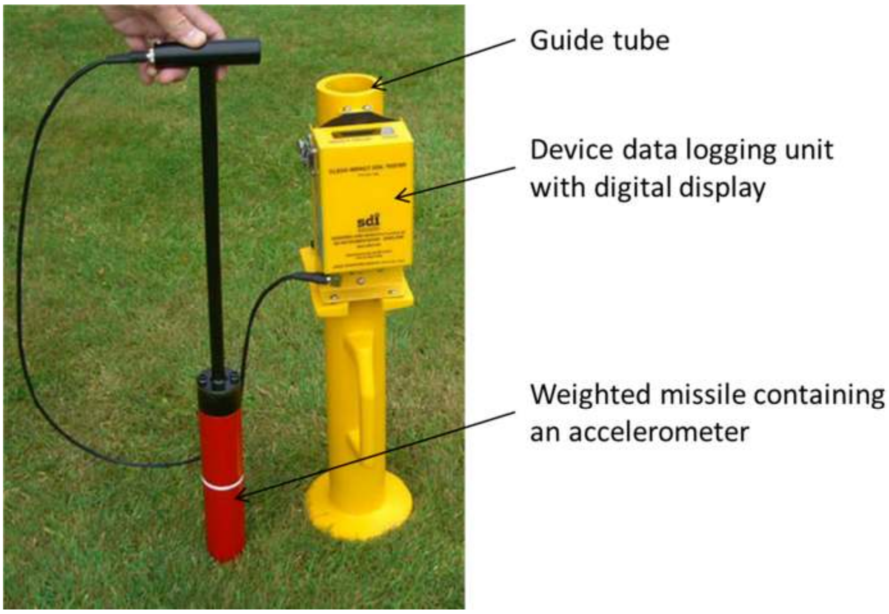

Figure 2-5 The 2.25 kg CIST device, which provides a measure of the peak deceleration of a dropped missile after contact with the surface.

The 0.5 kg CIST missile was used as standard in early PQS studies in the UK (Canaway, 1985; Bell and Holmes, 1988), while the 2.25 kg CIST missile is now more commonly used. The 2.25 kg missile is regarded to be less susceptible to the effects of grass leaves and data is less variable than the 0.5 kg missile (Rogers III and Waddington, 1989; Baker et al., 2007). The selection of drop number used for surface characterisation has varied in the literature - researchers have reported using the first, third, and fourth drops (Gibbs et al. 2000; Chivers and Aldous, 2003). Many authors have not reported drop numbers, and this was evident in early PQS studies undertaken by researchers at the STRI. The contrasting selection of drop number used for surface characterisation makes it difficult to compare data across studies, as turf surfaces become harder due to the compaction of soil (increase in density and orientation of particles) under repeated drops (Twomey et al., 2011a). A consensus needs to be reached for this aspect when using the device.

The CIST is a popular testing tool due to its reliability, relative affordability, portability, and provision of data that is easily interpreted (Baker and Canaway, 1993). The device is used alongside the studded disc apparatus to quantify mechanical behaviour of pitches under the PQS framework, and is also used in the ASTM F1702 standard for assessing impact absorption for natural turf in the USA (Bell and Holmes, 1988; American Society for Testing and Materials, 2000a). 'Acceptable' and 'preferred' benchmark ranges are evident for impact hardness of natural turf pitches assessed with the CIST (Table 2-1). These were initially devised for football and rugby through the correlation of data to player perceptions of comfort and traction (Bell and Holmes, 1988). This procedure has since been performed for Australian football surfaces (Aldous et al., 2005). The upper limit of surface hardness detailed by Chivers and Aldous (2003) is used to define whether surfaces are safe for play in Australian football – pitches exceeding the maximum value (120 g) are closed (Twomey et al., 2011a). Although this strategy can be argued to be in the interests of the players by preventing injuries that may occur as a result of playing on harder surfaces, the benchmark limits are not based on any defined injury data or tolerances in the human body, and should not be used to gauge whether surfaces are safe for play on this basis.

Table 2-1 Performance Quality Standard benchmark ranges for the two mechanical parameters assessed under the PQS framework: peak deceleration (2.25 kg CIST) and peak torque resistance (shear resistance; studded disc apparatus). Football and rugby limits are taken from Bell and Holmes (1988), McClements and Baker (1994), and Baker et al. (2007), using a drop height of 0.45 m for the 2.25 kg CIST; Australian football limits taken from Chivers and Aldous (2003), who used a drop height of 0.3 m for the 2.25 kg CIST.

	Peak deceleration (g)	**Peak torque resistance (Nm)**
Football		
Acceptable	35-120	≥20
Preferred	45-90	≥30
Rugby		
Acceptable	30-110	≥25
Preferred	40-70	≥35
Australian Football		
Unacceptably low	<30	<20
Preferred	70-89	40-55
Unacceptably high	>120	>75

The non-linear stress-strain behaviour of natural turf means that in order to assess specific impacts occurring on these surfaces, the loading conditions (magnitude and loading rate of the force, contact time) need to be replicated. Previous research has shown that the mass, drop heights, and shape of drop missiles all influence peak deceleration data and the ranking of sports surfaces (Nigg and Yeadon, 1987; Nigg, 1990; Shorten, 2003). Data from the CIST are often used to relate the potential cushioning an athlete may experience during contact with the surface. A number of studies have highlighted that the loading conditions of the CIST are not consistent with those of an athlete and devices cannot be used for this purpose (Nigg and Yeadon, 1987; Nigg, 1990; Young and Fleming, 2007). The CIST applies impact forces over very short contact times, typically *ca.* 7.9 ms on natural turf surfaces for the 2.25 kg missile (Rogers III and Waddington, 1990). From the data presented in the Rogers II and Waddington study, the strain rates applied by the 0.5 kg and 2.25 kg missiles are calculated as up to 1333 mm s^{-1} and 1257 mm s^{-1}. In comparison, the duration of loading by athlete footstrike when running on natural turf at 3.83 m s^{-1} has been shown to be more than 15 times longer at 120 ms (Stiles et al., 2011). Despite not replicating athlete impacts, the peak forces of the 0.5 kg missile and balls have been shown to correlate on sports surfaces (Fleming et al., 2004), while peak deceleration values and ball rebound heights have also been correlated (Bell and Holmes, 1988), indicating that the lighter device may provide an indication of surface behaviour relating to ball impacts.

Although the CIST devices only provide one surface parameter (peak deceleration), determination of other impact parameters has also been performed with the use of the device by logging acceleration data over time. These parameters have included impact time, time to peak deceleration, force, and displacement (Bregar and Moyer, 1990; Rogers and Waddington, 1990; Carré and Haake, 2004). Carré and Haake (2004) found that synthetic surfaces used for cricket were considered to ‘play’ similarly (coefficient of restitution) despite variations in peak deceleration data, and suggested that this variable alone is not sufficient to characterise surfaces. This view was shared by Rogers and Waddington (1990), who concluded that both peak deceleration and time increments such as total and peak impact times should be used when comparing between turfed and bare soil treatments, where effects of the grass leaf were shown in impact. Despite these findings, this approach to surface testing is not regularly performed, presumably as it decreases the portability and efficiency of using the CIST device and the difficulty in data capture.

The F355-A drop device is used under the ASTM F1936 standard for assessing natural and synthetic American football fields and has a heavier mass (9.1 kg) and larger face diameter (128 mm) than the CIST. The loading conditions of the device replicate the head accelerations of American football players impacting the surface (American Society for Testing and Materials, 2000b), although the contact shape is not replicated (Shorten, 2003). Implementation of devices to assess the risk of head injury on sports surfaces is under-utilised, particularly on natural turf. Defined tolerances to the head have been proposed and test devices developed that replicate human head impacts in the automotive and playground manufacturing industries, such as the Severity Index (SI) and Head Injury Criterion (HIC; Shorten, 2003). Theobald et al. (2010) assessed head injury risk of an elite level natural turf pitch against six types of synthetic surfaces. The natural turf pitch was not characterised for surface construction in the study, but it was presumably a sand rootzone. It was found that the natural turf surface performed similarly to the artificial surfaces, although the risk was considered greater in a central location of the pitch that was subjected to greater intensity of play (as a result of soil compaction). It was concluded that the risk of head injury may be greater on natural turf pitches that are not as intensively managed as the surface assessed (presumably referring to hard clay pitches), and that synthetic turf offers a more consistent level of safety. This area requires further consideration with greater quantification of head injury risk on natural turf.

2.4.1.2 Penetrometer Devices

Penetrometers are commonly used in agricultural and civil engineering research to provide an objective measure of soil strength (Mulqueen et al., 1977). Their use has been transferred for assessing surface condition of natural turf sports surfaces, and results are used to quantify surface penetration hardness (Orchard, 2001). Two types of penetrometer have been used in natural turf pitch testing, the cone penetrometer and the French dynamic drop-type penetrometer. Cone penetrometers can vary in composition, but invariably consist of a cone tip on a shaft that is pushed into the soil at a constant rate (typically 20 mm s^{-1}). The resistance of the soil to the probe is measured, with data often presented in terms of stress or energy (Hillel, 1998; Figure 2-6). Data is either logged manually or automatically, depending on the sophistication of the device. The depth the probe can be pushed into the soil depends on the length of the probe and the hardness of the soil, and no standard protocol has been established for testing depth on natural turf. Although affected by compression ahead of the probe and metal-soil friction, the cone penetrometer provides an indirect measure of soil shear strength, as the soil is required to fail to allow the rod to continue its downward movement into the soil (Marshall and Holmes, 1988). This failure may be in terms of separation of the soil, shear failure, plastic flow, or compression (Hillel, 1998), with shear deformation dominant at the soil surface, leading to a predominant combination of shear and compression at depths 3-5 times the diameter of the probe (Angers and Larney, 2008).

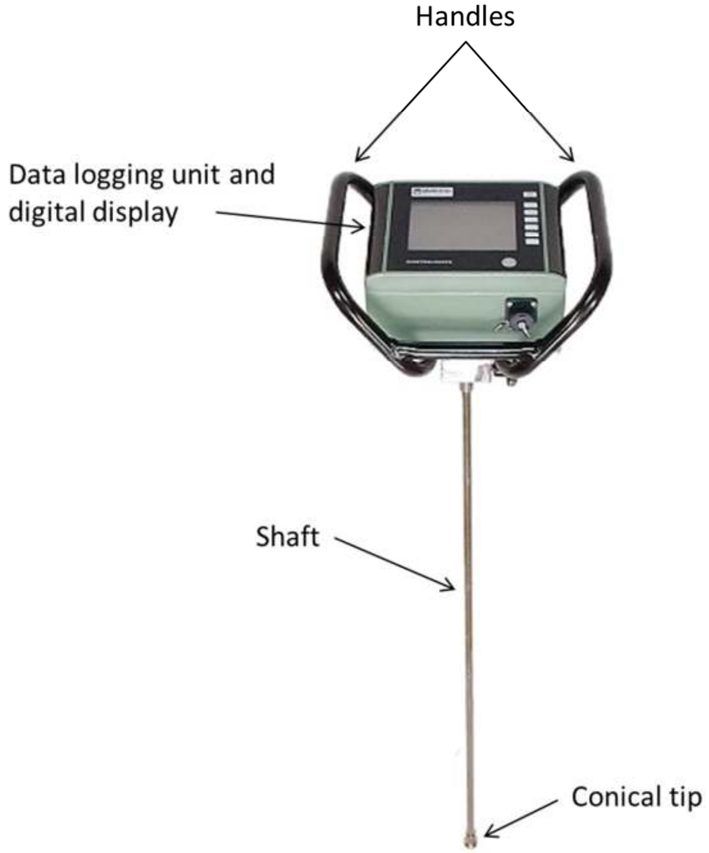

Figure 2-6 A cone penetrometer, used to assess penetration resistance of soil or natural turf.

Cone penetrometers have been used in the studies of Takemura et al. (2007), who assessed penetration hardness of rugby pitches in New Zealand (to a depth of 50 mm), and Holmes and Bell (1986) who assessed football pitches to a 20 mm depth. Holmes and Bell, in assessing devices for use in the subsequent PQS framework, rejected the future use of cone penetrometers along with three other test methodologies on pitches (shear vanes, football deceleration test, and a modified traction device). Although no specific reason was provided for the rejection of the penetrometer, all four were omitted as they were regarded as either unreliable for use *in-situ,* or that data was strongly correlated to parameters measured by other devices. Considering the Pearson correlation coefficient data in the study, the penetrometer was significantly linearly correlated ($P<0.01$) to ball bounce and the shear vane. Use of cone penetrometers on sports pitches in the UK since this study has not been found.

The French drop-type penetrometer measures penetration distance of a square section rod of 1 cm^2 when it is forced into the surface through the momentum of a 1 kg mass dropped from a height of 1 m (Chivers, 2008b). This type of penetrometer invariably stresses the surface at a faster rate than the cone penetrometer, and is a popular testing device for use in Australia and New Zealand on natural turf sports pitches and racetracks (Murphy et al., 1996; Orchard, 2001; Orchard et al., 2005). Orchard (2001) considered it a better tool for assessing the hardness of natural turf soil than the CIST devices as they penetrate the thatch layer of the turf, and are not sensitive to grass leaf length. In comparison to the CIST, data from this device has been shown to be correlated more strongly to race times on horse racing tracks, suggesting the hardness of the surface measured by the penetrometer provides a better insight into the potential energy return and subsequent athletic performance of horses (Murphy et al., 1996).

Like the CIST, penetrometer devices are easy to use, relatively affordable, portable, and provide data that is easily interpreted - penetration depth has been used as an indicator to benchmark surfaces in Australian football (Orchard, 2001). A disadvantage of the device, again similar to deficiencies of the CIST device, is that the function of the devices (a probe penetrating the soil) does not replicate interactions of players or balls impacting the surface, which are dominated by compression and horizontal shear forces.

However, it should be considered that the use of drop-type penetrometers could be modified to assess the ratio of stud penetration achievable for shoes if loading of an athlete was replicated in the falling mass.

2.4.1.3 Devices Quantifying Horizontal Shear Resistance

The studded disc apparatus is the most popular *in-situ* testing device assessing horizontal shear resistance of surfaces. The term ‘shear resistance’ is more commonly replaced as ‘traction’ when considering the measurable parameter of the device. The device was originally outlined by Canaway (1975), and further developed by Canaway and Bell (1986). This device is implemented under the PQS framework and under FIFA and IRB testing of synthetic turf (FIFA, 2009b; IRB, 2011). The studded disc consists of a studded circular plate loaded with 40 kg of mass on a central shaft. The disc contains six studs (15 mm length). During operation, the device is dropped from a standard height of 60 mm to allow the studs to penetrate fully into the surface. A torque wrench is used to rotate the shaft and disc through the turf, with peak torque used to provide a measure of shear resistance of the turf (Figure 2-7).

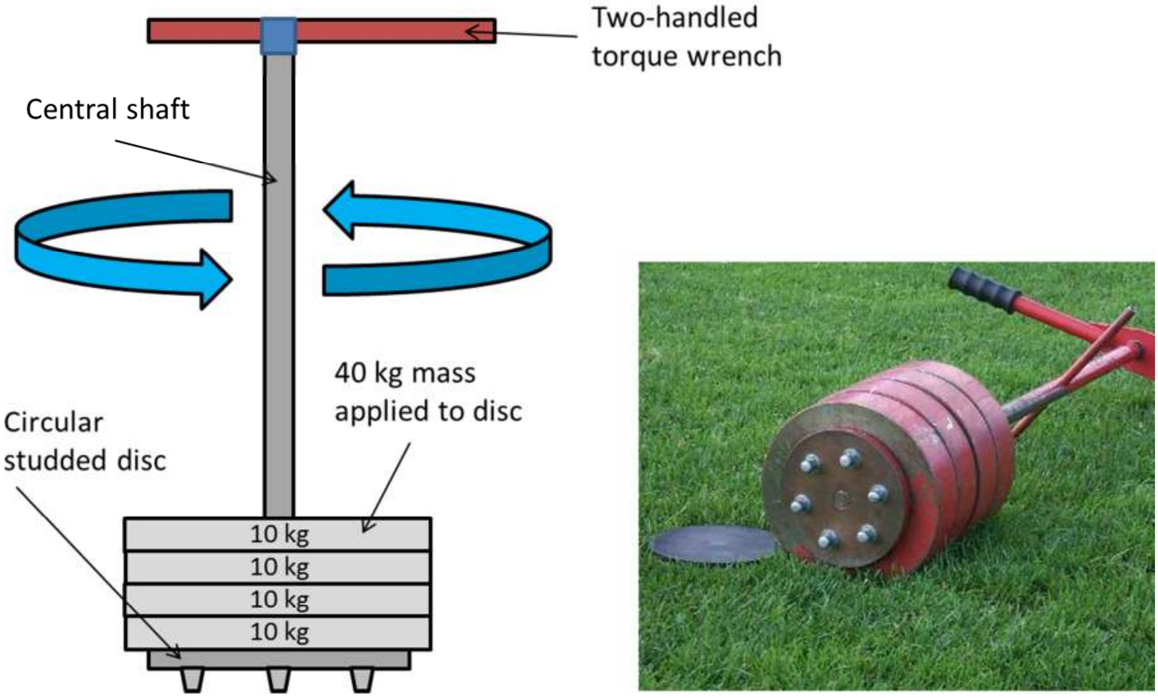

Figure 2-7 Left: A schematic diagram of the studded disc apparatus, a device to assess rotational shear resistance of surfaces under a normal load of 40 kg; Right: an apparatus on its side prior to being used on a pitch, with the stud configuration evident.

Benchmark limits for horizontal shear resistance using the studded disc apparatus under the PQS framework are presented in Table 2-1. No upper limits are evident for football and rugby, as the primary aim in surface management in the 1980s when the standards were developed was to achieve surfaces with sufficient traction, thus little regard was given for the notion that excessive surface traction could contribute to injuries. Similar to the CIST, these limits for traction were proposed on player perceptions of desirable traction (Bell and Holmes, 1988; Aldous et al., 2005), and not on biomechanical data.

Some variants of the studded disc apparatus have been developed for use on natural turf. The DPI & F Turf Tester (Roche et al., 2008) was developed to increase the reliability of testing with the apparatus by automating the drop of the equipment onto the turf and the rotation of the shaft at a set speed, minimising the error that can occur when using this equipment (Twomey et al., 2011b). The device also quantifies torque with respect to displacement, to produce profiles of measurements. Chivers (2008b) recognised the benefit of providing profiles of torque when using the studded disc, and added tilt sensors to the apparatus to determine the resistance of the turf at not only soil failure but at different degrees of rotation. This data was considered important for understanding the occurrence of ACL injuries, as greater torque at lower degrees of rotation may increase the risk of injury. The device was used to successfully indicate that peak torque provided by the turf on the studs generally occurred at around 30° of rotation, although differences between grass species were shown. After 45° of rotation, torque values decrease as the studs reach the trench provided by the stud ahead of them in rotation.

The studded disc and variants outlined above must all be considered to provide general indicators of horizontal surface shear resistance. Although the studded disc and variants measure the forces applied to studs from the turf, the boundary conditions (configuration of studs, materials of plates/studs) and the loading conditions (orientation, rate and magnitude of stress) evident for the testing devices do not represent movements of athletes and cannot be used to accurately predict traction. Representation of these conditions was regarded as paramount by Nigg (1990) to provide accurate readings of traction on sports surfaces. The use of these devices is also hindered by the requirement of using 40 kg of weights as normal force during operation which is required to be transported across a pitch, meaning testing with the device is laborious and time consuming.

A shear vane has been used to assess torsional shear resistance of natural turf: Stiles et al. (2011) quantified the shear resistance of turf trays in a biomechanical study; Holmes and Bell (1986) used the device in an early PQS study; Rogers III and Waddington (1990) used the device to quantify the effects of management practices on surface mechanical behaviour. The device consists of a rod with a four-bladed vane which is pushed into the soil and rotated (Figure 2-8a). The torque required to induce shear failure within the cylinder of soil created by the edge of the blades is presented as a measure of undrained soil shear strength (BS1377-9:1990). The depth of the surface profile assessed is variable with the size of blades used: blades 33 mm in length were used in the Stiles et al. study; Holmes and Bell used 32 mm long blades. Shear vanes are popularly used in agricultural and other soil industries because of their ease of use, and they arguably provide a more efficient and less labour-intensive means to quantify rotational shear resistance on natural turf than the studded disc apparatus. It is not known why this device has not been used more often in the assessment of natural turf, although Holmes and Bell (1986) disregarded it for future use under PQS testing, presumably as data was not linearly correlated with the studded disc apparatus and it was more preferential to use a device with studs. The lack of correlation is presumably because of the different shearing depths of the devices, the variation in normal forces applied and the configuration of the shearing components.

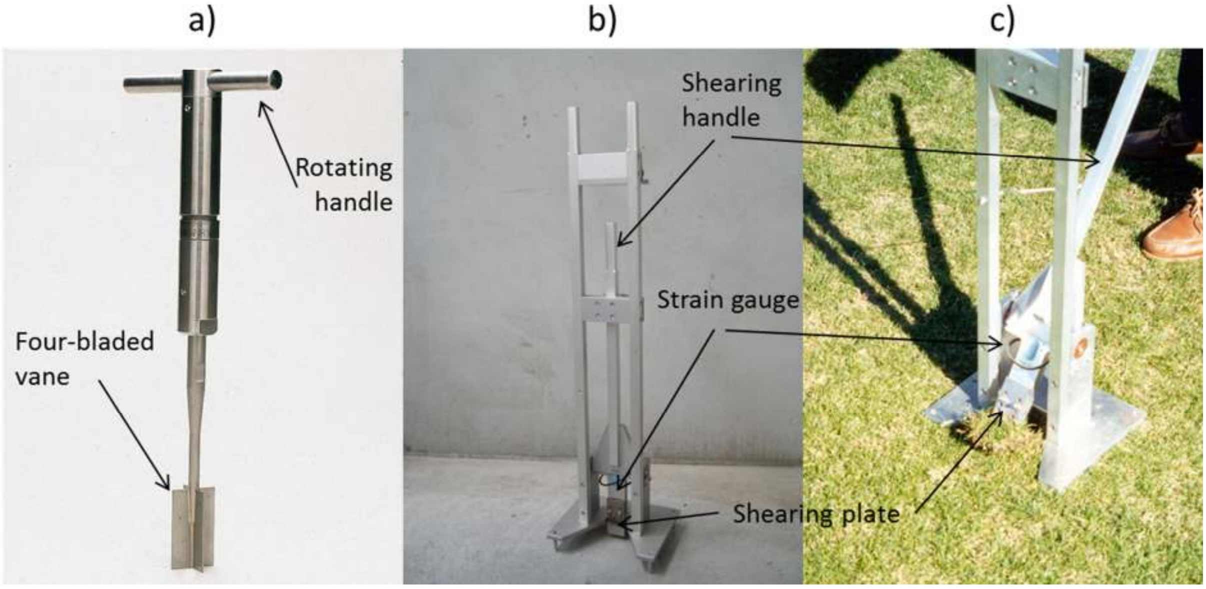

Figure 2-8 a) soil shear vane, a device consisting of a four-bladed vane that is rotated when pushed into soil to provide a measure of undrained soil shear strength; b) the Clegg Turf Shear Tester, a device measuring the translational shear resistance of turf; c) the Clegg Turf Shear Tester in operation on natural turf.

As well as rotational shear resistance, translational shear resistance is measured on natural turf as it is dominant in biomechanical ‘stopping’ movements, and forefoot push-offs (Carré et al., 2007). The Clegg Turf Shear Tester is a device providing measurements of this property, yet it falls within Category 1 of surface devices as it does not replicate athlete-specific loading or boundary conditions. An adjustable shearing plate (50 mm wide by 10 – 50 mm deep) is inserted into the turf, and the maximum translational shearing force measured when a handle is pulled back is presented in Nm, recorded with a strain gauge (Figure 2-8b,c). The pivoting motion of the device lifts the turf as well as shearing it horizontally, and the device can be regarded as measuring the resistance of the turf to divoting (Sherratt et al., 2005). This device has been used in the studies by Chivers and Aldous (2003), and by Sherratt et al. (2005) in assessing biomass accumulation on turf playing quality. Further implementation of the device cannot be found in academic studies, which has limited the objective evaluation of the device.

The studded disc apparatus remains the most popular device to assess horizontal shear resistance of natural turf sports pitches, as no other device has been universally accepted. The inefficiency of using the device mean a more lightweight and portable means to assess shear resistance is required if data is to be collected at a higher temporal and spatial resolution.

2.4.2 Category 2 Devices

Testing devices that provide generic data (Category 1) are useful for surface classification and benchmarking, and surface condition can be correlated against injury occurrences with device data. However, they do not evaluate the specific surface mechanisms involved in athlete performance or injury. The difficult and time consuming nature of biomechanical testing on natural turf means that quantification of athlete-surface interaction through the implementation of mechanical testing devices is often desirable. In order to achieve this, *in-situ* surface parameters such as the ratio of dissipated/returned energy under athlete-specific impact stresses and shoe-surface traction forces relating to specific athlete movements are required to be quantified. Testing devices that assess these parameters have been developed for use on sports surfaces. However, no mechanical device currently provides a comprehensive replication of athlete-surface interaction, as the complex nature of athlete loading onto the surface (Figure 2-2) is difficult to replicate (Nigg, 1990). Devices within this category of testing usually aim to replicate a certain aspect of athlete loading e.g. replication of specific boundary conditions, rotational angles, joint and foot positions, and magnitude and rate of stress applications. Some devices also aim to specifically replicate loading conditions that are thought to lead to injuries and therefore can potentially investigate injury risk on surfaces.

2.4.2.1 Simulating Player-Surface Impacts

This type of device aims to quantify the potential impact absorption athletes may receive when impacting sports surfaces. Artificial Athlete devices are commonly used on synthetic sports turf surfaces and polymeric running tracks to assess surfaces to specific vertical athlete impact forces and their durations during running. The Artificial Athlete Berlin (AAB; Figure 2-9) has been used under FIFA and IRB guidelines for synthetic sports pitches (FIFA, 2009b; IRB, 2011). The device consists of a 20 kg mass which is released from a height of 55 mm onto a spring (stiffness 2000 kN m^{-1}). The spring is positioned upon a metal test foot (70 mm diameter) and the compliance of the spring provides an appropriate contact time of the test foot onto the surface (typically 30 - 50 ms; Fleming and Young, 2006). The cushioning (energy dissipation) the sports surface provides is presented as a ratio of force reduction in comparison to concrete (Dixon et al., 1999). The Stuttgart version of this device (AAS) is similar in principle to the AAB but measures surface deflection when the weight is dropped from 120 mm onto a spring with stiffness 40 N m^{-1}, via displacement sensors. FIFA stipulate force reduction should be in the range 60 - 70% when using the AAB and surface deflection between 4-8 mm when using the AAS for surfaces to meet the two-star synthetic turf accreditation (FIFA, 2009a). An updated version of these devices has also recently been included in the IRB testing of synthetic turf, the Advanced Artificial Athlete (AAA), which aims to measure both force reduction and deflection through the inclusion of an accelerometer instead of a load cell (Young and Fleming, 2007; IRB, 2011).

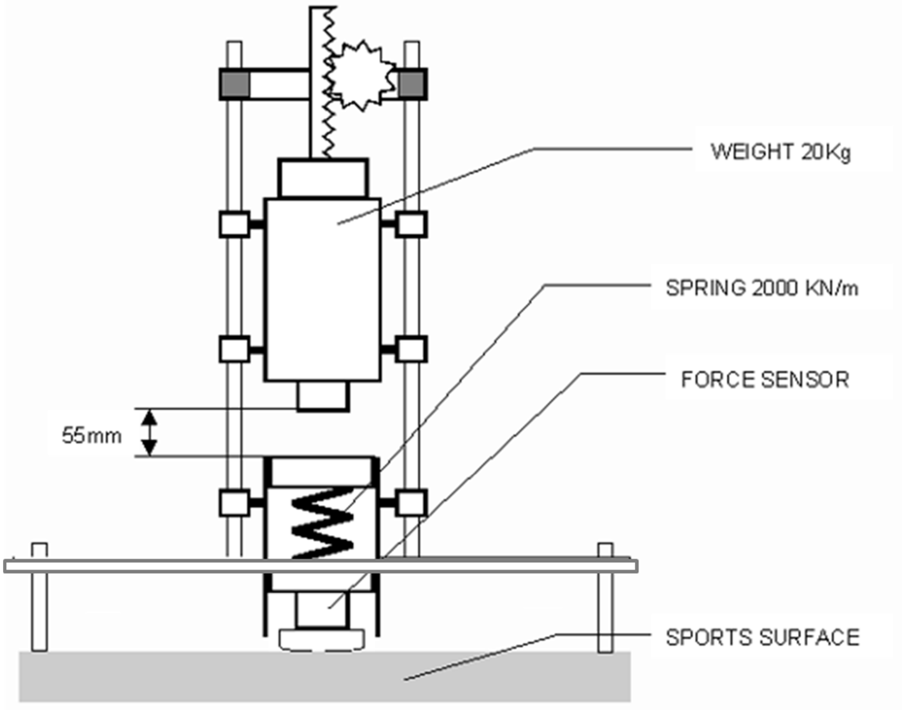

Figure 2-9 A schematic diagram outlining the main components of the Artificial Athlete Berlin (AAB).

Due to the fixed energy nature of the AAB, the peak force applied (and measured) on the surface is dependent on surface stiffness: impact forces on concrete should be between 6.4 kN and 6.9 kN, while forces of 2.6 kN have been observed on a synthetic turf surface, and 3.9 kN on a polymeric running track (Young and Fleming, 2007). The validity of using fixed energy devices such as these to assess surfaces for athlete-surface interaction has been questioned, as athletes have been shown to maintain peak forces across surfaces of different stiffness in order to compensate for various levels of impact absorption (Ferris et al., 1998; Kerdok et al., 2002; Tillman et al., 2002). In contrast, biomechanical data (peak impact forces) have been shown to rank surfaces in the same order as Artificial Athletes in an integrated study by Meijer et al. (2007), comparing synthetic turf of different stiffness (109, 257, 670 kN m^{-1}).

Regardless of the conflicting evidence, compensatory adjustments are not afforded by the player in accidental collisions with the surface and fixed energy impact devices are therefore appropriate for testing for this purpose (Dixon et al., 1999). Young and Fleming (2007) considered that sports surface impact devices should be developed that are able to vary the force and stress applied to the surface to compensate for the variation in loading that can be applied to non-linear sport surfaces. The forces, stresses, and loading rates applied by athletes is not easily modelled (as considered earlier), as a range of variables contribute to these parameters e.g. biomechanical movement being undertaken, running velocity, player mass, running style, footwear and individual variations (Nigg et al., 1987; Nilsson and Thorstensson, 1989; Smith et al., 2004; Guisasola, 2008). More work is required to characterise specific impact forces and duration of athletes on natural turf in order for specific movements to be replicated.

Despite their wide adoption and implementation on synthetic turf surfaces, the use of Artificial Athlete devices on natural turf has been limited. Thomas and Guerin (1981) used an AAS to assess the deformation of natural turf surfaces of various grass species; Martinez et al. (2004) assessed force reduction and deformation of natural and synthetic turf surfaces, finding the natural turf surface had better force reduction for the same level of deformation. In an early study implementing the PQS framework, Baker and Bell (1986) used the AAS on short pile synthetic turf and natural turf pitches. Mean displacement on both surface types was generally similar, with values reaching up to 7.4 mm. None of these studies evaluated the Artificial Athletes for future use on natural turf, with no reason for their lack of implementation on natural turf found elsewhere in the literature. Presumably the cost of these devices and the large plastic deformations that can occur on these surfaces are limiting issues for the use of the devices. These permanent deformations do not occur on artificial surfaces, and restrict the use of devices with limited measurable deflection range on natural turf, such as the Light Weight Deflectometer (2.2 mm; Young and Fleming, 2007). Severn (2006), during *in-situ* assessment of synthetic hockey pitches, indicated that the AAB was difficult to transport and could not be used in wet weather due to the electrical components of the device.

A comparable device to the Artificial Athletes, which assesses surfaces to athlete-specific impacts, is lacking for use on natural turf sports pitches. This has limited the direct comparison of natural and artificial turf material behaviour and the understanding of the ratio of elastic and plastic deformation occurring on natural turf under athlete-specific loading.

2.4.2.2 Measuring Shoe-Surface Traction

It is clear from the literature that there are greater numbers of testing devices that have been developed to assess traction properties of sports surfaces or movements associated when the foot is fixated on the ground, compared to impact properties. The number of traction devices within this category has grown rapidly in recent years, in response to the correlation between serious injuries such as anterior cruciate ligament (ACL) tears and excessive horizontal surface strength (Lambson et al., 1996), manufacturer-driven research on athletic footwear performance, and the aim to replicate specific athlete movements quantified in biomechanical studies.

The most basic form of device developed within this category are devices similar in principle to the studded disc apparatus, but measuring rotational traction of the surface under a range of boot and stud designs. These devices therefore more closely replicate the boundary conditions of athletes. Devices found in the literature include those used by Torg and Quedenfeld (1974), Bonstingl et al. (1975), Lambson et al. (1996) and Livesay et al. (2006). The latter three devices were used to assess stud and shoe design on the traction of both natural turf and variations of synthetic surfaces. A device outlined by Valiant (1990) was similar in principle to these devices but allowed both rotational and translational traction of surfaces to be quantified. Both of these orientations of surface traction were also measured by the device used by Severn et al. (2010) in the comparison of synthetic turf systems. This type of device has furthered the understanding of the traction characteristics of different stud and boot designs. For example, Lambson et al. (1996) indicated that a higher rotational resistance for a shoe with longer studs found in mechanical tests was related to a significantly higher instance of ACL injuries in American football for athletes wearing these shoes.

A disadvantage of this type of devices is that their portability is low, with the majority of data collection performed in laboratories. PennFOOT, a device developed at Pennsylvania State University, is more portable than these aforementioned devices as the apparatus is transported on wheels (Figure 2-10 left), and has been used to assess *in-situ* surfaces (McNitt et al., 1997; McNitt et al., 2004). The device allows measurement of both translational and rotational traction, a variety of shoes, and variation in the normal force applied. A deficiency of PennFOOT, and the devices outlined above is that the movements applied by the shoes are not based on movements performed by athletes, leaving uncertainty as to surface behaviour under athlete-specific movements.

Figure 2-10. Example ‘Category 2’ testing devices measuring traction properties of *in-situ* surfaces: PennFOOT (left) and the TurfBuster (right).

Increasing in sophistication, other devices have been developed which increase the replication of athlete loading with the surface, either by replicating specific movements or providing more representable loading conditions, biofidelic test feet, or joint movements of athletes. A number of devices have been reported and are summarised in Table 2-2. All devices aim to quantify the level of traction available to athletes on surfaces, whether it is in terms of displacement of a test foot in the surface, forces applied to a test foot, or torque applied to joints

Table 2-2 Details of the range of 'Category 2' traction devices that have been developed for use on sports surfaces.

Device	**Movement replicated**	**Test foot/leg**	**Use on natural turf?**
Strathclyde turf testing rig (Blackburn et al., 2005)	Vertical, horizontal, and rotational loads applied simultaneously	Test foot with pimpled rubber studded tread design	*In-situ* data collected in study
SERG traction rig (Carré et al., 2007)	Forefoot push-off movement	Plate with interchangeable studs	Not found
The TrakTester (Grund et al., 2007)	Every anatomically possible position of the leg and ankle during surface contact can be replicated. Torques and forces applied in tilted position	Biofidelic foot replicating movement of ankle joint; interchangeable shoes	Not found
IBV test device (Rosa et al., 2007)	Lateral movement of shoes replicating displacement and angle during athlete cutting movement	Foot with boots; angle of boots to turf variable	*In-situ* data collected in study
Rotational traction device (Villwock et al., 2009a, b)	Flatfoot rotational movement	Surrogate ankle, with torsional stiffness modelled against cadaver experiments; interchangeable shoes	*In-situ* testing in a further paper (Meyer et al., 2010)
The TurfBuster (Kuhlman et al., 2010)	A range of translational and rotational movements replicated	Biofidelic foot/ankle that allows variation of Flexion, Eversion, and Rotation joints ; interchangeable shoes	Not found

Traction devices such as these offer the opportunity for further understanding of natural turf in relation to athlete-surface interaction. The biofidelity of the test feet and ankles of some of the devices allows replication of a range of joint orientations and human movements that can be examined. The use of cadavers to assess human joint stiffness in the development of the device outlined by Villwock et al. (2009a,b) also represents a means to understand the tolerances of the human body to external forces, and should be explored further in the future. A disadvantage of these devices is that no standardised approach has been used in their development, making cross comparison of results difficult. The quantity of data available in the literature from these devices on *in-situ* natural turf surfaces is also lacking, with data collected so far restricted to synthetic surfaces with a few of the devices (Table 2-2). This has presumably been due to the difficulty in transporting the devices for use *in-situ*, the labour-intensive nature of testing with them (the size of the devices are highlighted in Figure 2-10), and the requirement for trained operators. The costs involved in developing these devices also means they are often built uniquely as ‘one-offs’, further reducing data collection possibilities within a range of physical and climatic conditions. As a result of these limitations, it seems that these types of device will remain as research tools for the foreseeable future.

2.5 SUMMARY OF THE LITERATURE

It is clear from the literature that there are a number of areas that require greater research in order to advance the understanding and testing of surface mechanical behaviour of natural turf pitches. The gaps in current knowledge that are addressed in this research project are summarised in relation to the following research chapters and the research objectives they aim to address:

1 The understanding of mechanical behaviour of natural turf pitches has been limited by deficiencies in current testing devices (Objective 1):
   a. A Category 2 device is lacking that assesses natural turf sports pitches to impacts applicable to those of athletes when impacting the surface, and which is sensitive to the plastic deformation that can occur on these

    surfaces. A testing device, replicating aspects of athlete impacts on natural turf, is presented in Chapter 3 in response to these issues.
   b. Category 1 devices are lacking which are more efficient in their operation than using the CIST and studded disc simultaneously under benchmark testing. This is addressed in Chapter 4 through the adaption of an existing testing device for this application.
2 Recent studies characterising the behaviour of modern natural turf surfaces are lacking. Behaviour of these surfaces is required to be assessed in relation to athlete-specific impacts, to variations in surface construction and soil texture, and to established PQS benchmarks (Objective 3). This gap in current understanding is addressed in Chapter 5 through the undertaking of a season study assessing a range of mechanical properties, and with the implementation of the devices outlined in Chapters 3 and 4. This chapter addresses Objectives 1, 2, 3, and 6.
3 The spatial variation in mechanical behaviour on natural turf pitches has not been fully explored as a result of the small number of test locations typically implemented within *in-situ* surface testing. Spatial variation of surfaces was considered in Chapter 6, using geostatistical techniques (variograms and interpolation), relating to Objectives 4 and 6.
4 The effect of the grass plant in the dynamic behaviour of soils used in natural turf is unclear. This is confounded by the difficulty in separating the effect of the grass leaves and roots when modelling impacts on natural turf:
   a. Chapter 7 assesses the behaviour of grass roots on the stress-strain behaviour of natural turf soils, addressing Objective 5.
   b. Chapter 8 quantifies the effect of grass leaves in the absorption of impacts on natural turf surfaces, addressing Objectives 5 and 6.

2.6 REFERENCES

Adams, W. A. and Jones, R. L. (1979), The effect of particle size composition and root binding on the resistance to shear of sportsturf surfaces, *Rasen, Grunflachen, Begrunungen,* vol. 10, no. 2, pp. 48-53.

Aldous, D. E., Chivers, I. H. and Kerr, R. (2005), Player perceptions of Australian football league grass surfaces, *International Turfgrass Society Research Journal,* vol. 10, pp. 318-326.

Alsop, J. C., Chalmers, D. J., Williams, S. M., Quarrie, K. L., Marshall, S. W. and Sharples, K. J. (2000), Temporal patterns of injury during a rugby season, *Journal of Science and Medicine in Sport,* vol. 3, no. 2, pp. 97-109.

American Society for Testing and Materials (2000a), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test for shock attenuation characteristics of natural playing surface systems using lightweight portable apparatus. F1702-96.* ASTM, West Conshohocken, PA.

American Society for Testing and Materials (2000b), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test method for shock-absorbing properties of playing surface systems and materials. F355-95 Procedure A.* ASTM, West Conshocken, PA.

Angers, D. A. and Larney, F. J. (2008), Soil physical analysis, in: Carter, M. R. and Gregorich, E. G. (eds.) *Soil sample and methods of analysis,* Taylor and Francis, Boca Raton, FL, pp. 713-912.

Baker, S. W. (2004), Construction methods for public sector and professional sports pitches: a review, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass management and science for sports fields,* ISHS, Leuven, pp. 27-38.

Baker, S. W. and Canaway, P. M. (1993), Concepts of playing quality: Criteria and measurement, in: Carrow, R. N., Christians, N. E. and Shearman, R. C. (eds.) *International Turfgrass Research Journal,* Intertec Publishing Corp., Kansas, pp. 172-181.

Baker, S. W. (1991), Temporal variation of selected mechanical properties of natural turf football pitches, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 83-92.

Baker, S. W. (1997), The reinforcement of turfgrass areas using plastic and other synthetic materials: A review, *International Turfgrass Society Research Journal,* vol. 8, pp. 3-13.

Baker, S. W. and Bell, M. J. (1986), The playing characteristics of natural turf and synthetic turf surfaces for association football, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 9-35.

Baker, S. W. and Canaway, P. M. (1991a), The Cost-Effectiveness of Different Construction Methods for Association Football Pitches, II, Ground Cover, Playing Quality and Cost Implications, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 53-65.

Baker, S. W. and Canaway, P. M. (1991b), The cost effectiveness of different construction methods for association football pitches. I. Soil physical properties, *Journal of the Sports Turf Research Institute,* vol. 66, pp. 8-20.

Baker, S. W. and Gibbs, R. J. (1989), Levels of use and the playing quality of winter games pitches of different construction types: Case studies at Nottingham and Warrington, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 9-33.

Baker, S. W., Gibbs, R. J. and Adams, W. A. (1992), Case studies of the performance of different designs of winter games pitches. I. Playing quality and usage, *Journal of the Sports Turf Research Institute,* vol. 68, pp. 20-32.

Baker, S. W. and Isaac, S. P. (1987), The effect of rootzone composition on the performance of winter games pitches II. Playing quality, *Journal of the Sports Turf Research Institute,* vol. 63, pp. 67-81.

Baker, S. W. and Richards, C. W. (1995), The effect of fibre-reinforcement on the quality of sand rootzones used for winter games pitches, *Journal of the Sports Turf Research Institute,* vol. 71, pp. 107-117.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Baroud, G., Nigg, B. M. and Stefanyshyn, D. (1999), Energy storage and return in sport surfaces, *Sport Engineering,* vol. 2, pp. 173-180.

Bartlett, R. (1999), *Sports Biomechanics: Reducing Injury and Increasing Performance,* Spon Press, Oxon.

Bell, F. G. (2000), *Engineering properties of soils and rocks 4th ed.,* Blackwell Science, Oxford.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

Blackburn, S., Nicol, A. and Walker, C. (2005), Development of a biomechanically validated turf testing rig, *Proceedings of the international society of biomechanics 20th congress - ASB 29th Annual Meeting,* July 31 - August 5, Cleveland, Ohio, .

Bonstingl, R. W., Morehouse, C. A. and Niebel, B. W. (1975), Torques developed by different types of shoes on various playing surfaces, *Medicine and science in sports and exercise,* vol. 7, no. 2, pp. 127-131.

Brandon, J. R., Weitzel, T. T., Perumpral, J. V. and Woeste, F. E. (1986), Strength parameters of agricultural soils, *Proceedings of the 1986 Summer meeting American Society of Agricultural Engineers,* June 29 - July 2, San Luis Obispo, CA, .

Bregar, M. J. and Moyer, W. W. (1990), An automated system for field testing and soil impact analysis, in: Schmidt, R. C., Hoerner, E. F., Milner, E. M., et al (eds.) *Natural and artificial playing fields: characteristics and safety features,* American Society for Testing and Materials, Philadelphia, pp. 115-126.

Brown, S. F., Lashine, A. K. F. and Hyde, A. F. L. (1975), Repeated load triaxial testing of a silty clay, *Geotechnique,* vol. 25, no. 1, pp. 95-114.

BS1377-9:1990 (1990), *Soils for civil engineering purposes - in-situ tests,* British Standards Institution, London.

Butler, R. J., Crowell III, H. P. and Davis, I. M. (2003), Lower extremity stiffness: Implications for performance and injury, *Clinical Biomechanics,* vol. 18, no. 6, pp. 511-517.

Canaway, P. M. (1975), Fundamental Techniques in the Study of Turfgrass Wear: An Advanced Report on Research, *Journal of the Sports Turf Research Institute,* vol. 51, pp. 104-115.

Canaway, P. M. (1981), Wear tolerance of turfgrass species, *Journal of the Sports Turf Research Institute.,* vol. 57, pp. 65-83.

Canaway, P. M. (1985), Playing Quality, Construction and Nutrition of Sports Turf, *Proceedings of the Fifth International Turfgrass Research Conference,* , pp. 45-56.

Canaway, P. M. and Bell, M. J. (1986), An apparatus for measuring traction and friction on natural and artificial playing surfaces, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 211-214.

Carré, M. J. and Haake, S. J. (2004), An examination of the Clegg impact hammer test with regard to the playing performance of synthetic sport surfaces, *Sports Engineering,* vol. 7, no. 3, pp. 121-129.

Carré, M. J., Kirk, R. F. and Haake, S. J. (2007), Developing relevant tests for traction of studded footwear on surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Carrow, R. N., Krum, J. M., Flitcroft, I. and van Cline (2010), Precision turfgrass management: Challenges and field applications for mapping turfgrass soil and stress, *Precision Agriculture,* vol. 11, no. 2, pp. 115-134.

Chivers, I. (2008a), Turfgrass sports surfaces and their relationship to player injuries, in: Stier, J. C., Han, L. and Li, D. (eds.), *Proceedings of the second international conference on turfgrass science and management for sports fields,* ISHS, Leuven, .

Chivers, I. H. (2008b), *The development of equipment and techniques for the objective assessment of turf* (unpublished PhD thesis), University of Melbourne, Melbourne.

Chivers, I. H. and Aldous, D. E. (2003), Performance monitoring of grassed playing surfaces for Australian rules football, *Journal of the Sports Turf Research Institute* vol. 79, pp. 73-80.

Clarke, J. D., Nunns, M., Dixon, S. and Carré, M. J. (2010), The effects of soccer boot construction on comfort during playing movements, in *Proceedings of the Second International Conference of the SportSURF Network,* April 2010, Loughborough, .

Clegg, B. (1976), An impact testing device for in situ base course evaluation, in: *Proceedings of the 8th ARRB Conference, vol. 8, no. 8*, Perth, Australia, pp. 1-6.

Clegg, B. (1980), Impact soil test as an alternative to California bearing ratio, *Environmental Conference, Proceedings of the Technical Association of the Pulp and Paper Industry,* vol. 1, pp. 225-230.

Comino, E. and Druetta, A. (2010), The effect of Poaceae roots on the shear strength of soils in the Italian alpine environment, *Soil and Tillage Research,* vol. 106, no. 2, pp. 194-201.

Craig, R. F. (2004), *Craig's soil mechanics,* Seventh ed, Chapman & Hall, London.

Davidson, P. L., Wilson, S. J., Wilson, B. D. and Chalmers, D. J. (2009), An approach to modelling impact energy absorption by surfaces, *Journal of Applied Biomechanics,* vol. 25, pp. 351-359.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J. and Muys, B. (2008), Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength, *Plant and Soil,* vol. 305, no. 1-2, pp. 207-226.

Dixon, S. J., Batt, M. E. and Collop, A. C. (1999), Artificial playing surfaces research: A review of medical, engineering and biomechanical aspects, *International Journal of Sports Medicine,* vol. 20, no. 4, pp. 209-218.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2000), Surface effects on ground reaction forces and lower extremity kinematics in running, *Medicine and science in sports and exercise,* vol. 32, no. 11, pp. 1919-1926.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2005), Compensatory adjustments in lower extremity kinematics in response to a reduced cushioning of the impact interface in heel-toe running, *Sports Engineering,* vol. 8, pp. 47-55.

Dixon, S. J., James, I. T., Blackburn, K., Pettican, N. and Low, D. (2008), Influence of footwear and soil density on loading within the shoe and soil surface during running, *Journal of Sports Engineering and Technology,* vol. 222, pp. 1-10.

Dura, J. V., Hoyos, J. V. and Martinez, A. (1999), The effect of shock absorbing sports surfaces in jumping, *Sports Engineering,* vol. 2, no. 2, pp. 97-102.

Eils, E., Streyl, M., Linnenbecker, S., Thorwesten, L., Völker, K. and Rosenbaum, D. (2004), Characteristic Plantar Pressure Distribution Patterns during Soccer-Specific Movements, *American Journal of Sports Medicine,* vol. 32, no. 1, pp. 140-145.

Ekstrand, J. and Nigg, B. M. (1989), Surface-related injuries in soccer, *Sports Medicine,* vol. 8, no. 1, pp. 56-62.

Ferris, D. P., Louie, M. and Farley, C. T. (1998), Running in the real world: Adjusting leg stiffness for different surfaces, *Proceedings of the Royal Society B: Biological Sciences,* vol. 265, no. 1400, pp. 989-994.

FIFA (2009a), *FIFA quality concept for football turf. Handbook of requirements.* FIFA, Geneva.

FIFA (2009b), *FIFA Quality Concept for Football Turf. Handbook of Test Methods,* FIFA, Geneva.

Fleming, P. and Young, C. (2006), Sports Surfaces Impact Assessment Tools, *The Engineering of Sport,* vol. 6, pp. 319-324.

Fleming, P., Young, C. and Dixon, N. (2004), Performance measurements on synthetic turf hockey pitches, in: Hubbard, M., Mehta, R. and Pallis, J. M. (eds.) *The Engineering of Sport 5 vol. 2,* ISEA, Sheffield, pp. 524-531.

Ford, K. R., Manson, N. A., Evans, B. J., Myer, G. D., Gwin, R. C., Heidt Jr., R. S. and Hewett, T. E. (2006), Comparison of in-shoe foot loading patterns on natural grass and synthetic turf, *Journal of Science and Medicine in Sport,* vol. 9, no. 6, pp. 433-440.

Freeland, R. S., Sorochan, J. C., Goddard, M. J. and McElroy, J. S. (2008), Using ground-penetrating radar to evaluate soil compaction of athletic turfgrass fields, *Applied Engineering in Agriculture,* vol. 24, no. 4, pp. 509-514.

Fritz, M. and Peikenkamp, K. (2003), Simulation of the influence of sports surfaces on the vertical ground reaction forces during landing, *Med. Biol. Eng. Comput.,* vol. 41, pp. 11-17.

Garraway, W. M., Lee, A. J., Hutton, S. J., Russell, E. B. A. W. and Macleod, D. A. D. (2000), Impact of professionalism on injuries in rugby union, *British Journal of Sports Medicine,* vol. 34, no. 5, pp. 348-351.

Gibbs, R. J., Liu, C., Yang, M. H. and Wrigley, M. (2000), Effect of rootzone composition and cultivation/aeration treatment on surface characteristics of golf greens under New Zealand conditions, *Journal of Turfgrass Science,* vol. 76, pp. 37-52.

Girard, O., Racinais, S., Kelly, L., Millet, G. P., and Brocherie, F. (2011), repeated sprinting on natural grass impairs vertical stiffness but does not alter plantar loading in soccer players, *European Journal of Applied Physiology,* vol. 111, no. 10, pp. 2547-2555.

Grimston, S. K., Engsberg, J. R., Kloiber, R. and Hanley, D. A. (1991), Bone mass, external loads, and stress fractures in female runners, *International Journal of Sports Biomechanics,* vol. 7, no. 3, pp. 293-302.

Grossi, N., Liu, C., Yang, M. H. and Wrigley, M. (2004), Tall fescue turf quality and soccer playing characteristics as affected by mowing height, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 319-322.

Grund, T. and Senner, V. (2010), Traction behaviour of soccer shoe stud designs under different game-relevant loading conditions, *Proceedings of the 8th Conference of the International Sports Engineering Association, ISEA,* Vol. 2, 12-16 July 2010, Vienna, pp. 2783-2791.

Grund, T., Senner, V. and Gruber, K. (2007), Development of a test device for testing soccer boots under game-relevant high-risk loading conditions, *Sports Engineering,* vol. 10, no. 1, pp. 55-63.

Guisasola, I. (2008), *Human-natural sports surface interaction* (unpublished PhD Thesis), Cranfield University, Cranfield.

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010a), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010b), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Gulhat, S.K. and Datta, M. (2005) *Geotechnical Engineering*, Tata McGraw-Hill, New Delhi.

Hillel, D. (1998), *Environmental Soil Physics,* Academic Press, San Diego, CA.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

IRB (2011), *IRB Artificial rugby turf performance specification,* IRB, Dublin.

Issoufou, M., Zaman-Allah, M., Ferchichi, A. and Ferjani, E. (2008), Clipping effects on the growth variation, water use efficiency and photosynthetic activity in Buffel grass (Cenchrus ciliaris L.) poaceae, *Asian Journal of Plant Sciences,* vol. 7, no. 1, pp. 95-99.

James, I. T. (2011), Advancing natural turf to meet tomorrow's challenges, *Sports Engineering and Technology,* vol. 225.

James, I. T., Blackburn, D. W. K. and Godwin, R. J. (2007), Mole drainage as an alternative to sand slitting in natural turf sports surfaces on clays, *Soil Use and Management,* vol. 23, no. 1, pp. 28-35.

James, S. L., Bates, B. T. and Osternig, L. R. (1978), Injuries to runners, *American Journal of Sports Medicine,* vol. 6, no. 2, pp. 40-50.

Karmakar S, and Kushwaha R (2005) CFD Simulation of Soil Forces on a Flat Tillage Tool. The society for Engineering in agricultural, food and biological systems, in: *Proceedings for ASAE Annual International Meeting,* 17 - 20 July 2005, Tampa, Florida.

Karg, C. and Haegeman, W. (2009), Elasto-plastic long-term behavior of granular soils: Experimental investigation, *Soil Dynamics and Earthquake Engineering,* vol. 29, no. 1, pp. 155-172.

Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G. and Herr, H. M. (2002), Energetics and mechanics of human running on surfaces of different stiffnesses, *Journal of applied physiology,* vol. 92, no. 2, pp. 469-478.

Kirby, A. and Spells, S. J. (2006), Spatial characterisation of natural and third-generation artificial turf football pitches, *Sports Engineering,* vol. 9, pp. 59-64.

Kirk, R. F. (2007), High-Speed observations of football boot - Surface interactions of players in their natural environment, *Sports Engineering,* vol. 10, no. 3, pp. 129-144.

Kolitzus, H. J. (1984), Functional standards for playing surfaces, in: Frederick, E. C., *Sport Shoes and Playing Surfaces, Biomechanical properties,* Human kinetics publishers Inc, Champaign, IL, pp. 98-118.

Krum, J. M., Carrow, R. N. and Karnok, K. (2010), Spatial mapping of complex turfgrass sites: Site-specific management units and protocols, *Crop Science,* vol. 50, no. 1, pp. 301-315.

Kuhlman, S., Sabick, M., Pfeiffer, R., Cooper, B. and Forhan, J. (2010), Effect of loading condition on the traction coefficient between shoes and artificial turf surfaces, *Journal of Sports Engineering and Technology,* vol. 224, no. 2, pp. 155-165.

Lambson, R. B., Barnhill, B. S. and Higgins, R. W. (1996), Football cleat design and its effect on anterior cruciate ligament injuries: A three-year prospective study, *American Journal of Sports Medicine,* vol. 24, no. 2, pp. 155-159.

Lejeune, T. M., Willems, P. A. and Heglund, N. C. (1998), Mechanics and energetics of human locomotion on sand, *The Journal of Experimental Biology,* vol. 201, pp. 2071-2080.

Li, D., Minner, D. D. and Christians, N. E. (2009), Evaluation of factors contributing to surface stability of sand-based turf, *Agronomy Journal,* vol. 101, no. 5, pp. 1160-1167.

Liu, X. and Huang, B. (2002), Mowing effects on root production, growth, and mortality of creeping bentgrass, *Crop Science,* vol. 42, no. 4, pp. 1241-1250.

Livesay, G. A., Reda, D. R. and Nauman, E. A. (2006), Peak torque and rotational stiffness developed at the shoe-surface interface: The effect of shoe type and playing surface, *American Journal of Sports Medicine,* vol. 34, no. 3, pp. 415-422.

Lüthje, P., Nurmi, I., Kataja, M., Belt, E., Helenius, P., Kaukonen, J. P., Kiviluoto, H., Kokko, E., Lehtipuu, T. P., Lehtonen, A., Liukkonen, T., Myllyniemi, J., Rasilainen, P., Tolvanen, E., Virtanen, H. and Walldén, M. (1996), Epidemiology and traumatology of injuries in elite soccer: A prospective study in Finland, *Scandinavian Journal of Medicine and Science in Sports,* vol. 6, no. 3, pp. 180-185.

Marshall, T. J. and Holmes, J. W. (1988), *Soil Physics,* Second ed, Cambridge University Press, Cambridge.

Martinez, A., Dura, J. V. and Duenas, L. (2004), Artificial and natural turf: Biomechanical differences between surfaces. Communications of the Fifth World Congress on Science and Football, *Journal of Sports Science,* vol. 22, pp. 494-495.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

McMahon, T. A. and Greene, P. R. (1978), Fast running tracks, *Scientific American,* vol. 239, no. 6, pp. 112-121.

McMahon, T. A. and Greene, P. R. (1979), The influence of track compliance on running, *Journal of Biomechanics,* vol. 12, no. 12, pp. 893-904.

McNitt, A. S., Landschoot, P. J. and Waddington, D. V. (2004), Effects of turfgrass, cutting height and soil conditions on traction, *Acta Hort,* vol. 661, pp. 39-49.

McNitt, A. S., Middour, R. O. and Waddington, D. V. (1997), Development and Evaluation of a Method to Measure Traction on Turfgrass Surfaces, *Journal of Testing and Evaluation,* vol. 25, no. 1, pp. 99-107.

Meijer, K., El Kati, R., Savelberg, H. H. C. M., Willems, P. and Wijers, B. (2007), The biomechanics of running on artificial turf, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Meyer, E. G., Villwock, M. R., Powell, J. W., Fouty, A. J. and Haut, R. C. (2010), Rotational injuries of the lower extremity and the use of an in-situ risk assessment tool for rotational traction, in: *Proceedings of the Second International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* April 2010, Loughborough.

Meyers, M. C. (2010), Incidence, mechanisms, and severity of game-related college football injuries on FieldTurf versus natural grass: a 3-year prospective study, *The American Journal of Sports Medicine,* vol. 38, no. 4, pp. 687-697.

Milburn, P. D. and Barry, E. B. (1998), Shoe-surface interaction and the reduction of injury in rugby union, *Sports Medicine,* vol. 25, no. 5, pp. 319-327.

Miller, G. L. (2004), Analysis of Soccer Field Hardness, Nektarios, P. A. (ed.), in: Nektarios, P. A. (ed.), Proceedings of the first international conference on turfgrass science and management for sports fields, ISHS, Leuven, pp. 287-294.

Millet, G., Perrey, S., Divert, C. and Foissac, M. (2006), The role of engineering in fatigue reduction during human locomotion, *Sports Engineering,* vol. 9, pp. 209-220.

Mooney, S. J. and Baker, S. W. (2000), The effects of grass cutting height and pre-match rolling and watering on football pitch ground cover and playing quality, *Journal of Turfgrass Science,* vol. 76, pp. 70-77.

Muir Wood, D. M. (1991), Approaches to modelling the cyclic stress-strain response of soil, in O'Reilly, M. P. and Brown, S. F. (eds.) *Cyclic loading of soils: from theory to design,* Blackie & Sons Ltd, London, pp. 21-69.

Mulqueen, J., Stafford, J. V. and Tanner, D. W. (1977), Evaluation of penetrometers for measuring soil strength, *Journal of Terramechanics,* vol. 14, no. 3, pp. 137-151.

Murphy, J. W., Field, T. R. O. and Thomas, V. J. (1996), Racetrack traction assessment by penetrometer. Part II application of the model, *Journal of Turfgrass Management,* vol. 1, no. 4, pp. 51-62.

Newell, A. J., Hart-Woods, J. C. and Wood, A. D. (1999), The effect of three different levels of shade on the performance of three grass mixtures for use on lawn tennis courts, *Journal of Turfgrass Science,* vol. 75, pp. 82-88.

Nigg, B. M. (1990), The validity and relevance of tests used for the assessment of sports surfaces, *Medicine and science in sports and exercise,* vol. 22, no. 1, pp. 131-139.

Nigg, B. M., Bahlsen, H. A., Luethi, S. M., and Stokes, S. (1987), The influence of running velocity and midsole hardness on external impact forces in heel–toe running, *Journal of Biomechanics*, vol. 20, pp. 951–959.

Nigg, B. M., Bahlsen, H. A., Luethi, S. M. and Stokes, S. (1987), The influence of running velocity and midsole hardness on external impact forces in heel-toe running, *Journal of Biomechanics,* vol. 20, no. 10, pp. 951-959.

Nigg, B. M. and Yeadon, M. R. (1987), Biomechanical aspects of playing surfaces, *Journal of sports sciences,* vol. 5, no. 2, pp. 117-145.

Nilsson, J. and Thorstensson, A. (1989), Ground reaction forces at different speeds of human walking and running, *Acta Physiologica Scandinavica,* vol. 136, no. 2, pp. 217-227.

Norton, K., Schwerdt, S. and Lange, K. (2001), Evidence for the aetiology of injuries in Australian football, *British journal of sports medicine,* vol. 35, no. 6, pp. 418-423.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Orchard, J. (2002), Is there a relationship between ground and climatic conditions and injuries in football?, *Sports Medicine,* vol. 32, no. 7, pp. 419-432.

Orchard, J. W., Chivers, I., Aldous, D., Bennell, K. and Seward, H. (2005), Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass, *British journal of sports medicine,* vol. 39, no. 10, pp. 704-709.

O'Reilly, M. P. and Brown, S. F. (1991), Cyclic loading in geotechnical engineering, in: O'Reilly, M. P. and Brown, S. F. (eds.) *Cyclic loading of soils: from theory to design,* Blackie & Son Ltd., London, pp. 1-18.

Pool, S. T. (1994), Design and construction of winter games pitches, in: Evans, R. D. C. (ed.) *Winter games pitches,* The Sports Turf Research Institute, Bingley, pp. 55-73.

Powrie, W. (2009), *Soil Mechanics - concepts and applications,* 2nd ed, Taylor and Francis, New York.

Reilly, T. and Borrie, A. (1992), Physiology applied to field hockey, *Sports Medicine,* vol. 14, no. 1, pp. 10-26.

Roche, M. B., Loch, D. S., Poulter, R. E. and Zeller, L. C. (2008), Measuring the traction profile on sportsfields: equipment development and testing, in: Stier, J. C., Han, L. and Li, D. (eds.), *Proceedings of the second international conference on turfgrass science and management for sports fields,* ISHS, Leuven, pp. 399-414.

Rogers III, J. N. and Waddington, D. V. (1989), The effect of cutting height and verdure on impact absorption and traction characteristics in tall fescue turf, *Journal of the Sports Turf Research Institute.,* vol. 65, pp. 80-90.

Rogers III, J. N. and Waddington, D. V. (1990a), Effects of management practices on impact absorption and shear resistance in natural turf, in: Schmidt, R. C., Hoerner, E.F., Milner, E. M. and Morehouse, C. A. (eds), *Natural and artificial playing fields: characteristics and safety features,* ASTM, PA., pp. 136-146.

Rogers, J. N. I. and Waddington, D. V. (1990b), Portable apparatus for assessing impact characteristics of athletic field surfaces, in: Schmidt, R. C., Hoerner, E.F., Milner, E. M. and Morehouse, C. A. (eds), *Natural and artificial playing fields: characteristics and safety features,* ASTM, PA., pp. 96-110.

Rosa, D., Sanchis, M., Gamez, J. and Alcántara, E. (2007), Study on the effect of maintenance operations and season on the traction of natural grass pitches, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Severn, K. (2006), *The influence of ageing on the mechanical behaviour of synthetic turf pitches for field hockey* (unpublished PhD thesis), Cranfield University, Cranfield.

Severn, K., Fleming, P. R. and Clarke, J. D. (2010), Science of synthetic turf surfaces: A comparison of traction test methods, in: *Proceedings of the Second International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* April 2010, Loughborough.

Shao, S. and Xie, D. (2002), Dynamic effective shear strength of saturated sand, *ACTA Mechanica Sinica,* vol. 18, no. 4, pp. 387-397.

Sherratt, P. J., Street, J. R. and Gardner, D. S. (2005), Effects of Biomass Accumulation on the Playing Quality of a Kentucky Bluegrass Stabilizer System Used for Sports Fields, *Agronomy Journal,* vol. 97, pp. 1107-1114.

Shipton, P. (2008) *Optimisation of cricket pitch rolling* (unpublished PhD thesis), Cranfield University, Cranfield.

Shorten, M. R. (2007), Sports surfaces and injury: the missing links, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Smith, N., Dyson, R. and Janaway, L. (2004), Ground reaction force measures when running in soccer boots and soccer training shoes on a natural turf surface, *Sports Engineering,* vol. 7, no. 3, pp. 159-167.

Spring, C. A. and Baker, S. W. (2006), Examination of a new form of fibre reinforcement including polypropylene and polyurethane fibres for winter games pitch rootzones, *Journal of Turfgrass and Sports Surface Science,* vol. 82, pp. 30-37.

Stafilidis, S. and Arampatzis, A. (2007), Track compliance does not affect sprinting performance, *Journal of sports sciences,* vol. 25, no. 13, pp. 1479-1490.

Stefanyshyn, D. J. and Nigg, B. M. (2003), Energy and performance aspects in sports surfaces, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. and Dixon, S. (2007), Biomechanical response to systematic changes in impact interface cushioning properties while performing a tennis-specific movement, *Journal of sports sciences,* vol. 25, no. 11, pp. 1229-1239.

Stiles, V. H., Dixon, S. J., Guisasola, I. N. and James, I. T. (2007), Biomechanical response to variations in natural turf surfaces during running and turning, in *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Stiles, V. H., Guisasola, I. N., James, I. T. and Dixon, S. J. (2011), Biomechanical response to changes in natural turf during running and turning, *Journal of Applied Biomechanics,* vol. 27, no. 1, pp. 54-63.

Stiles, V. H., James, I. T., Dixon, S. J. and Guisasola, I. N. (2009), Natural turf surfaces: The case for continued research, *Sports Medicine,* vol. 39, no. 1, pp. 65-84.

Stover, S. M. (2003), The epidemiology of thoroughbred racehorse injuries, *Clinical Techniques in Equine Practice,* vol. 2, no. 4, pp. 312-322.

Stuck, H., Baudzus, W., and Baumann, W. (1984), On frictional characteristics of playing surfaces , in: Frederick, E. C. (ed.) *Sports shoes and playing surfaces*. Human Kinetics, IL., pp. 87-97.

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British Journal of Sports Medicine,* vol. 41, no. 9, pp. 582-587.

Tengbeh, G. T. (1993), The effect of grass roots on shear strength variations with moisture content, *Soil Technology,* vol. 6, no. 3, pp. 287-295.

Tessutti, V., Trombini-Souza, F., Ribeiro, A. P. and Nunes, A. L. S., I.C.N. (2010), In-shoe plantar pressure distribution during running on natural grass and asphalt in recreational runners, *Journal of Science and Medicine in Sport,* vol. 13, pp. 151-155.

Theobald, P., Whitelegg, L., Nokes, L. D. M. and Jones, M. D. (2010), The predicted risk of head injury from fall-related impacts on to third-generation artificial turf and grass soccer surfaces: A comparative biomechanical analysis, *Sports Biomechanics,* vol. 9, no. 1, pp. 29-37.

Thomas, R. and Guerin, J. P. (1981), A method for measuring the quality of sports surfaces, in: Sheard, R. W. (ed.), *Proceedings of the 4th International Turfgrass Research Conference,* July, Guelph, Canada, pp. 151-156.

Tillman, M. D., Fiolkowski, P. and Bauer, J. A. (2002), In-shoe plantar measurements during running on different surfaces: Changes in temporal and kinetic parameters, *Sports Engineering,* vol. 5, pp. 121-128.

Torg, J. S. and Quedenfeld, T. C. (1974), The shoe-surface interface and its relationship to football knee injuries, *Journal of Sports Medicine,* vol. 2, no. 5, pp. 261-269.

Twomey, D. M., Otaga, L. and Saunders, N. (2011a), Challenges in the development of standards for synthetic turf for Australian football and cricket, *Journal of Sports Engineering and Technology,* vol. 225, pp. 93-101.

Twomey, D. M., Otago, L. and Ullah, F. F.,C.F. (2011b), Reliability of equipment for measuring the ground hardness and traction, *Journal of Sports Engineering and Technology,* vol. 225, no. 3, pp. 131-137.

Valiant, G. A. (1990), Traction characteristics of outsoles for use on artificial playing surfaces, in: Schmidt, R. C., Hoerner, E. F., Milner, E. M., et al (eds.) *Natural and artificial playing fields: characteristics and safety features,* ASTM, Philadelphia, pp. 61-68.

Verhelst, R., Malcolm, P., Debuyck, G., Verleysen, P., Degrieck, J. and De Clercq, D. (2009), Force Analysis during 180 degrees turning on two types of artificial turf, in: Alam, F., Smith, L. V., Subic, A., et al (eds.), *The Impact of Technology on Sport III,* 2009, Hawaii, USA .

Villwock, M. R., Meyer, E. G., Powell, J. W., Fouty, A. J. and Haut, R. C. (2009a), The effects of various infills, fibre structures, and shoe designs on generating rotational traction on an artificial surface, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 11-19.

Villwock, M. R., Meyer, E. G., Powell, J. W. and Haut, R. C. (2009b), Development and evaluation of a surrogate ankle for use with a rotational traction measurement apparatus, *Journal of Sports Engineering and Technology,* vol. 223, no. 4, pp. 151-158.

Walker, C. (2007), Computational modelling, the athlete/surface interface and the understanding of surface-related injury, in *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Webster, R. and Oliver, M. A. (2007), *Geostatistics for Environmental Scientists,* Second ed, John Wiley & Sons Ltd, Chichester, England.

Whitlow, R. (2001), *Basic soil mechanics,* Fourth ed, Pearson Education Ltd, Harlow.

Wood, D. M. (1980), *Laboratory investigations of the behaviour of soils under cyclic loading: a review,* CUED/D-Soils/TR 84, Cambridge University, Cambridge.

Wulfsohn, D. and Adams, B. A. (2002), Elastoplastic soil mechanics, in: Upadhyaya, S. K., Chancellor, W. J., Perumpral, J. V., et al (eds.) *Advances in soil dynamics,* American Society of Agricultural Engineers, Michigan, pp. 1-116.

Young, C. and Fleming, P. R. (2007), A review of mechanical impact testing devices for sport surfaces, in *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Zebarth, B. J. and Sheard, R. W. (1985), Impact and shear resistance of turf grass racing surfaces for Thoroughbreds, *American Journal of Veterinary Research,* vol. 46, no. 4, pp. 778-784.

3. DEVELOPMENT OF A SIMPLIFIED DYNAMIC TESTING DEVICE FOR TURFED SPORTS SURFACES

Matt C. J. Caple, Iain T. James, Mark D. Bartlett and David I. Bartlett.

ABSTRACT

The response of natural turf surfaces to loading changes with the force and loading rate applied. Quantification of surface behaviour to athlete loading is complicated by the lack of devices that replicate forces, stresses and loading rates of athletes that can be specifically used on natural turf. To address this issue, a vertical dynamic impact testing device, the DST, was developed. The DST consists of a compressed air driven ram which vertically impacts a studded test foot onto the surface using data from biomechanical studies. The vertical dynamic stress of athlete footstrike during running is replicated, using peak force and mean boot contact area data. The ram pressure is adjustable to allow variation of the stress applied upon impact, potentially replicating a range of athlete-surface interactions. Initial laboratory testing indicated that the device was sensitive to changes in soil condition due to variations in impact data. Total penetration time and distance, and surface energy absorption were all significantly greater in prepared 'soft' soil treatments ($P<0.05$). Loading rate in the first 50 ms after impact was significantly greater in the 'hardest' soil treatment ($P<0.05$). Future research work will determine *in-situ* behaviour of actual playing surfaces, compare device loading rates to those of athletes, and assess surfaces to a range of stresses.

3.1. INTRODUCTION

3.1.1 Dynamic Behaviour of Natural Turf Sport Pitches

Natural turf sports pitches are used extensively for winter sports such as football and rugby. The mechanical behaviour of these surfaces is important for both the prevention of injuries and to aid athlete performance. Dissipation of impacting energy and reduction of loads returned to athletes is regarded as important to prevent injuries (Dixon et al., 1999), while stiffness and energy return from sports surfaces allows athletes to perform athletic movements more efficiently (Stefanyshyn and Nigg, 2003).

Understanding of athlete loading of natural turf surfaces requires further research (Guisasola et al., 2010), to determine how these surfaces provide impact absorption and how they behave during and following unloading in terms of energy return and surface wear. Quantifying the mechanical response of natural turf surfaces to impact is complicated by stress-strain behaviour being dependent upon the magnitude and loading rate of the stress applied (Guisasola et al., 2010). The ability of mechanical devices to replicate the forces, stresses and loading rates of athletes is therefore vital to understand the behaviour of this surface type in the human sport context.

Previous research has identified a lack of sports surface testing devices that replicate loading and boundary conditions of athlete-surface interaction (Nigg, 1990; Dixon et al., 1999; Young and Fleming, 2007), with fewer devices suitable for use on natural turf than synthetic turf sports surfaces. Vertical impact loading of athletes is replicated by the Artificial Athlete Berlin (and similar devices) but testing of natural turf surfaces with these devices has not been reported in the literature reviewed, although the Artificial Athlete Berlin has been used in benchmarking natural turf in the development of synthetic turf. This could be due to the availability of such devices for natural turf research or issues related to large plastic deformations in natural turf (Guisasola et al., 2010) which are not experienced in the testing of elastomeric or synthetic turf surfaces. The Clegg Impact Soil Tester (CIST) is the most commonly used vertical impact device for natural turf sports surfaces, and quantifies peak deceleration of a falling mass onto the surface under performance quality standards (Bartlett et al., 2009). While it is lightweight and portable, the device does not represent contact times, rate of loading or peak forces of athletes (Young and Fleming, 2007). The lack of biomechanically-valid, vertical impact devices specifically for use *in-situ* on natural turf has restricted comparisons between artificial and natural turf sports surfaces. To address these issues, a mechanical vertical testing device was developed to investigate the effects of dynamic impact stresses simulated on natural turf surfaces. The following sections outline the origins and development of the device and the results of a controlled experiment to assess the sensitivity of the device to changes in surface condition.

3.2 THE DST DEVICE

3.2.1 Device Origins and Function

The original Dynamic Surface Tester (DST) device was developed by David Bartlett at ADAS, to provide an objective measure of the 'going' on natural turf racecourses (Bartlett, 2000). It was originally named the Spike Going Meter. The device consists of a compressed-air driven ram (VG040/0100 Numatics Inc., Skelmersdale, UK) of 100 mm stroke length that impacts a test foot vertically into the surface. The device was originally used to calculate surface energy absorption of the turf surface using a spike as the test foot, with data related to a numerical scale of 'Going' (Figure 3-1 left). This parameter relied on measuring the force acting on the test foot by the surface during impact (ground reaction force), as well as measures of the penetration depth and time of the impact. These measures are provided by an Entran ELHS force transducer (Entran, Lexington, KY., USA; 1 kN range, 0.5% combined non-linearity and hysteresis), a linear encoder (rack and pinion single turn 20 kΩ potentiometer; precision ± 0.2 mm; frequency of 533 Hz.), and a crystal-controlled 10 ms timing pulse from the data logger controller. Pressure-controlled testing is created with the pneumatic system of the device, allowing ram pressure to be adjustable between 0.2 - 0.7 MPa and therefore altering the impacting force of the test foot. When the test foot is fired towards the surface, the foot impacts and continues to penetrate into the surface until the ground reaction force is equal to the impacting force of the test foot (assuming Newton's laws of motion), at which point the device stops moving. The foot is defined as not moving when the distance the foot moves between two time points (1.875 ms) is less than 0.32

mm (see Appendix 11.1.1 for program details). Figure 3-1 (right) highlights that the operator of the device is responsible for providing the reaction mass of the impact.

Figure 3-1 Left: The original DST device (with spike test foot), prior to developments made for it to be used on natural turf sports pitches; right: An example of the DST device being used, showing that the operator provides the reaction mass.

3.2.2 Development of the DST

It was decided that for the purpose of this research project, the DST device would be adapted to enable the assessment of turfed sports surfaces to loading conditions more replicable of athletes contacting the surface. This is in comparison to the currently available test devices such as the CIST which can only be regarded as providing a generic indicator of surface mechanical behaviour (an identified gap in the literature highlighted in Chapter 2). A recent biomechanical study of athletes running on natural turf trays in the laboratory (Guisasola, 2008; Stiles et al., 2011) provided loading conditions of athletes to replicate with the use of the device. Within the study, impact variables were recorded using a force plate positioned below the turf surface and pressure insoles within the shoes of the athletes. Mean peak force applied by the athletes during running was 2.12 kN at a contact time of 0.12 s (B, Figure 3-2).

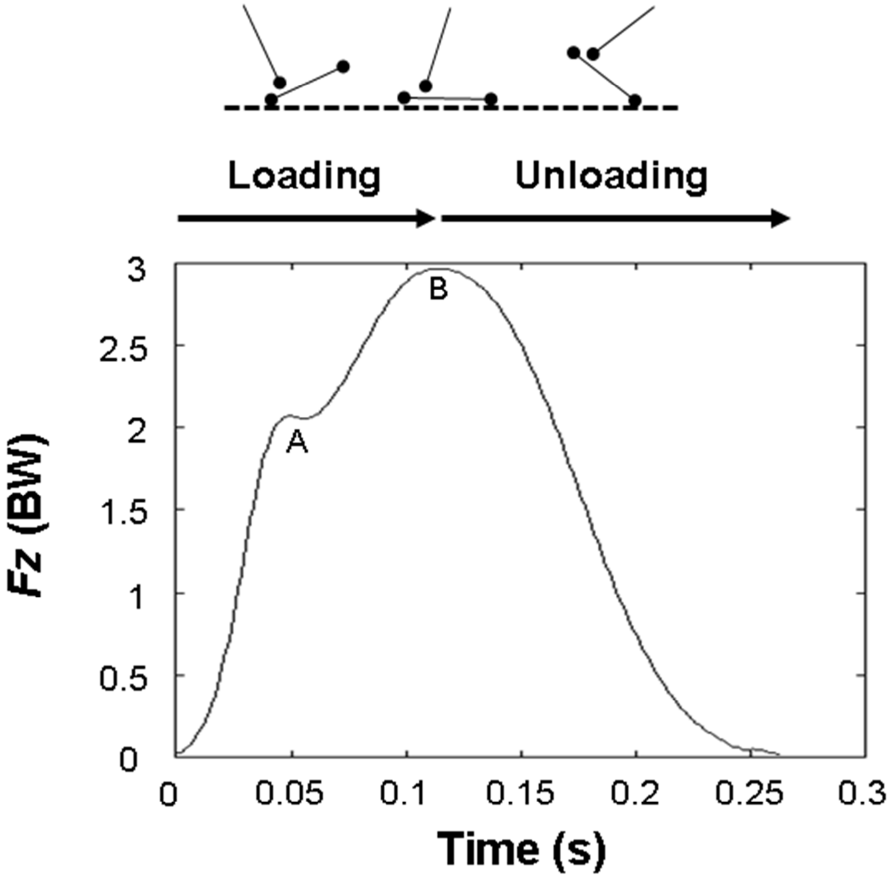

Figure 3-2 A typical vertical force-time history (in terms of body weight, BW) for a heel-toe running footstrike (adapted from Guisasola et al. 2010). Loading and unloading phases and foot contact angles are indicated. A represents peak vertical impact force and B vertical active force.

The rotation of principle stresses applied by athletes during footstrike (rolling motion of the foot; Figure 2-2) was not possible to replicate with the DST. To simplify this movement, a similar approach was taken to that of Guisasola et al. (2010), who used the triaxial apparatus to assess soil samples to stresses comparative to those recorded from the athletes in the biomechanical experiment: the mean external surface area of the boot in contact with the surface during footstrike (3800 mm^2) was calculated, based on mean insole data (2900 mm^2) and a conversion to outside sole area. Based on this area and the 2.12 kN force value, a stress value of 0.56 MPa was derived and applied to the soil samples by the triaxial apparatus, albeit at loading rates almost thirteen times slower than those calculated in the biomechanical study. It was decided that the same level of stress calculated through this method, 0.56 MPa, would be replicated by impacts of the DST.

In the development of the DST, the majority of the hardware of the device was preserved, with small changes made to the device program and the addition of a new test foot and soil impedance probe. To understand the capabilities of the pneumatic system of the DST, initial calibration experiments were undertaken, including performing impacts on a styrene butadiene rubber (SBR) shockpad. These experiments and the physics of the DST impact are discussed in Appendix 11.1.2. For these experiments, the spike test foot was replaced with an aluminium cylinder (41 mm diameter, 38 mm height, 1320 mm^2 surface area), with a single stud positioned in the centre of the foot (Figure 3-3; Figure 11-4, Appendix 11.1.2). The stud is interchangeable, with a British Standard 15 mm length aluminium rugby stud (BS6366:1983) selected for this research. At rest the foot is positioned 35 mm above the surface (Figure 3-3a), and passes through an aperture in a steel base plate during operation, causing a direct impact with the surface. Figure 3-3b illustrates the stage where the test foot is brought to rest by the surface. Maximum surface penetration is limited to 46 mm by ram stroke length, and the foot retracts to its original position (Figure 3-3a) at the end of each test.

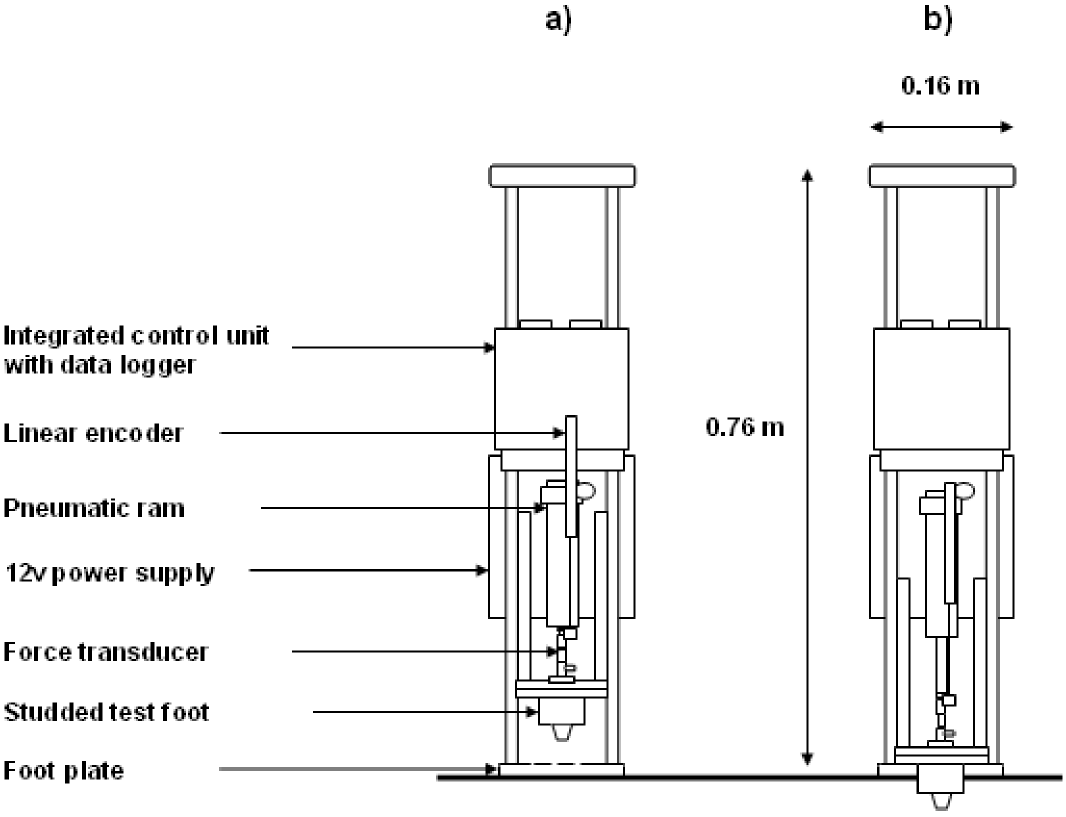

Figure 3-3 A schematic diagram outlining operation of the Dynamic Surface Tester Device: a) device at rest; b) at the end of the penetration phase of measurement. Not drawn to scale.

The calibration experiments indicated that the impact force of the device ranged between 0.26 – 0.82 kN when tested at the range of pressures allowable by the pneumatic system (0.2 – 0.7 MPa), although the device operated more consistently at forces around 0.79 kN provided by an operating pressure of 0.6 MPa (Appendix 11.1.2). This impact force is derived from the final force value measured upon the test foot when the foot is brought to rest by the surface. Using the test foot area of the aluminium cylinder, 1320 mm^2, the stress value that was to be replicated (0.56 MPa) by the device was achievable using an impacting force of 0.74 kN. The aluminium test foot on the device was selected to increase durability during use, and therefore repeatability in surface testing, instead of selection of boot-specific materials. The stud was selected to provide a more realistic boundary condition of athlete interaction with the surface, and to potentially assess stud/test foot penetration ratios. The calibration experiments indicated that the velocity of the test foot upon impact varied between 1.10 and 1.34 m s^{-1} with the variation in ram pressure used (0.2 – 0.7 MPa). Impact speed of the test foot is calculated by the maximum change in distance between two time points (1.875 ms) before impact with the surface. This range of impact velocities is comparable to vertical touchdown velocities (1.10 m s^{-1}) recorded when athletes ran at 4 m s^{-1} (Nigg et al., 1987).

The importance of soil water content to natural turf mechanical behavior was recognised by adding an impedance sensor (ML2x, Delta-T Devices Ltd., Cambridge, UK) to the device as a first stage measurement, to quantify volumetric soil water content. The impact data collected with the DST are stored on the logger and transferred to a PC for processing through a numerical computing script (MatLab 7.1, Mathworks, Natick, MA, USA). The device and air cylinder fit onto a sack-barrow to allow for portability (Figure 11-5, Appendix 11.1.2).

As discussed in the literature (Chapter 2) the energy absorption and loading rate achieved on contact with the surface are considered important in the biomechanical assessment of sports surfaces. Calculation of these two parameters was written into the MatLab script. Total energy absorption of the surface is determined by the DST by calculating the integral of the work done by the test foot during penetration (W) during each timestep (Equation 3.1).

$$W = \int_0^{\mathrm{zmax}} F dz \tag{3.1}$$

Where $z_{\max}$ is the maximum depth of penetration, F is the ground reaction force acting on the test foot, and dz is the vertical displacement interval in each logging cycle. Loading rate in the first 50 milliseconds of impact (dFz_{50}, kN s^{-1}) is calculated by:

$$dFz_{50} = \frac{\Delta F}{50} \tag{3.2}$$

Where ΔF is the difference in force between t = 50 ms and t = 0 ms (i.e. initial impact).

3.3 CONTROLLED EXPERIMENTS WITH THE DST

3.3.1 Soil Characterisation and Experimental Design

Validation experiments were performed with the DST in the Soil Dynamics Laboratory at Cranfield University to assess the sensitivity of the device to changes in soil condition. The soil used was a sandy loam texture (66% sand, 17% silt, 17% clay), as per (BS7755-5.4:1998). Integrated excavation and consolidation machinery which provide uniform soil conditions (Alexandrou and Earl, 1998; Dixon et al., 2008) were used to prepare four different soil only (no grass, no organic matter) treatments. The variation in the soil treatments was created by manipulating soil dry bulk density and water content, and quantified using core sampling for dry density (BS7755-5.6:1999) and a soil water content impedance probe (type ML2x, Delta-T Devices Ltd., Cambridge, UK) respectively. The peak deceleration (multiples of the acceleration due to gravity, g) of a 2.25 kg CIST, (SD Instrumentation Ltd., Bath, UK), dropped three times from 0.45 m vertically onto the test surface, was used to determine soil hardness in each treatment (Table 3-1). Undrained soil shear strength (Cu) was measured with a 19 mm shear vane (Pilcon DR 2149 Pilcon Engineering Ltd, Basingstoke, UK) and reported as per (BS1377-9:1990). The soils were regarded as providing a wide range of mechanical behaviour, as the range in peak deceleration across the treatments (106 g) was greater than the range defined within the ‘acceptable’ category (85 g) for sports pitches under the PQS standards (Baker et al., 2007).

Table 3-1 Mean soil characterisation data for each treatment (n = 18 for each parameter; ± standard error): dry density (ρ_d), water content (θ_v), hardness (2.25 kg Clegg Impact Soil Tester, third drop) and undrained soil shear strength (Cu).

Soil Treatment	ρ_d (g cm^{-3})	ϑ_v (% vol.)	Hardness (g)	Cu (kPa)
1	1.56 ± 0.01	23.1 ± 0.43	105 ± 7.59	83 ± 4.32
2	1.50 ± 0.02	17.2 ± 0.38	165 ± 4.36	96 ± 4.74
3	1.37 ± 0.01	13.1 ± 0.51	59 ± 3.50	20 ± 1.01
4	1.34 ± 0.01	16.7 ± 0.36	65 ± 0.97	27 ± 1.18

Each treatment was split into six plots of size 400 mm x 2200 mm and a randomised block design was used (Figure 3-4). Three replications of soil dry bulk density, volumetric water content and rebound hardness were collected per plot (n = 18), with five replications of DST impacts performed per plot (n = 30). The operating pressure on the DST device was set at 0.6 MPa, resulting in an impact force of 0.79 kN ± 0.03 (impact stress of 0.6 MPa) on the reference 15 mm thick styrene butadiene rubber (SBR) shockpad over concrete.

Figure 3-4 Outline of the experimental plot design used in the soil bin. Note that the nearside three plots were not used in the experiment as a result of inconsistent soil conditions produced by a fault with the soil preparation equipment.

Total penetration distance, total penetration time, total surface energy absorption, and dFz_{50} as measured by the DST were used to assess the variation in the soil treatments. All treatments were analysed for differences with one-way ANOVA and Fisher LSD ($P<0.05$) to determine *post-hoc* differences. Pearson correlation coefficient analysis was performed to assess linear relationships on mean treatment data of the soil characterising variables (Table 3-1) and the DST impact variables. All statistical analysis was performed using Statistica 9 (Statsoft Inc., Tulsa, OK., USA).

3.3. RESULTS AND DISCUSSION

Significant differences ($P<0.05$) were found among the soil treatments for penetration distance, penetration time, surface energy absorption, and loading rate (Figure 3-5). The more loosely packed, lower density soil treatments (Treatments 3 and 4) allowed significantly greater penetration distance (Figure 3-5a), penetration time (Figure 3-5b) and surface energy absorption (Figure 3-5c) than the higher density treatments (1 and 2). This is due to an increase in soil shear strength and resilient modulus with soil dry density (Zhang et al., 2001; Guisasola et al., 2010; Table 3-1), which was confirmed by shear strength (Cu) being linearly correlated with these parameters (r = -0.93 to -0.97; Table 3-2). Soil hardness as measured by the CIST was also linearly correlated with these parameters (r = -0.85 to -0.98; Table 3-2) and with shear strength (Cu, r = 0.93; Table 3-2).

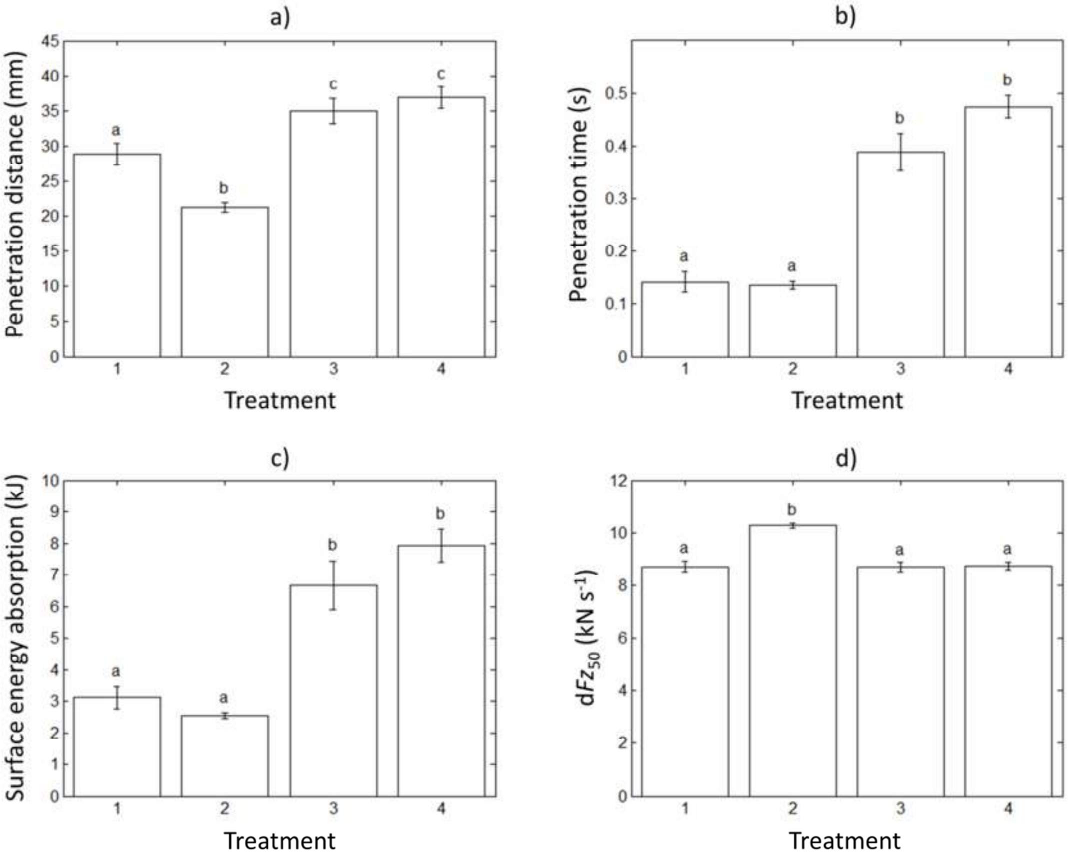

Figure 3-5 The response of soil treatments 1-4 to impact as measured using the DST device: a) mean total penetration distance; b) mean total penetration time; c) mean total surface energy absorption; d) loading rate during the first 50 ms of impact. Letters indicate homogenous groups tested with Fisher LSD (*P*<0.05), whiskers represent standards error (n = 30 for each treatment).

Table 3-2 Pearson correlation (r) of mean treatment data (n = 4) for soil characterisation properties as outlined in Table 3-1 (*P*<0.05), soil hardness determined by the 2.25 kg Clegg Impact Soil Tester, and DST variables penetration distance, penetration time, energy absorption, and loading rate at 50 ms (dFz_{50}).

	Soil hardness	**Penetration distance**	**Penetration time**	**Energy absorption**	**dFz_{50}**
Dry density ρ_d	0.71	-0.77	-0.97	-0.94	0.32
Water content ϑ_v	0.36	-0.36	-0.66	-0.59	-0.09
Cu	0.93	-0.93	-0.97	-0.96	0.65
Soil hardness	>0.99	-0.98	-0.85	-0.88	0.89
Penetration distance			0.9	0.93	-0.85
Penetration time				>0.99	-0.54
Energy absorption					-0.6

Mean force-time histories for the impacts in each treatment are illustrated in Figure 3-6. In these data, zero was defined as the point at which the stud touches the soil, removing the stage where the device moves towards the soil (see Figure 11-3; Appendix 11.1.2). The graph indicates the behaviour of the higher and lower density treatments, but shows that greater force readings were evident on the lower density treatments than the higher density treatments at end of penetration. This behaviour is attributed to both the function of the DST device and the mechanical behaviour of the soil. When movement of the test foot between two time steps is less than 0.32 mm, the device is defined as at rest and the foot is retracted. On the harder treatments, the test foot is brought to rest very quickly (within 0.15 s) by the greater shear strength and resistance to deformation of the soil (Figure 3-6). In contrast, the lower shear strength of Treatments 3 and 4 meant that the device was not fully brought to rest within 0.15 s, but kept penetrating into the soil. Observation of these impacts confirmed that this penetration was at a much slower rate than the initial impact, with soil deformation considered to be more representative of quasi-static failure than dynamic failure at this point in the impact, a result of the strain rate dependency of soil behaviour. This is highlighted in Figure 3-7 for representative impacts from Treatments 2 and 4: Treatment 2 was a stiffer soil, indicated by a smaller penetration distance achieved for a given force; penetration of the test foot continued in Treatment 4 towards the end of the impact with a negligible increase in force applied. The greater force recorded on the lower density treatments (800 N) compared to the higher density treatments (720 N) is as a result of the pneumatic system not being allowed to fully apply the target force due to the rate at which the test foot is brought to rest.

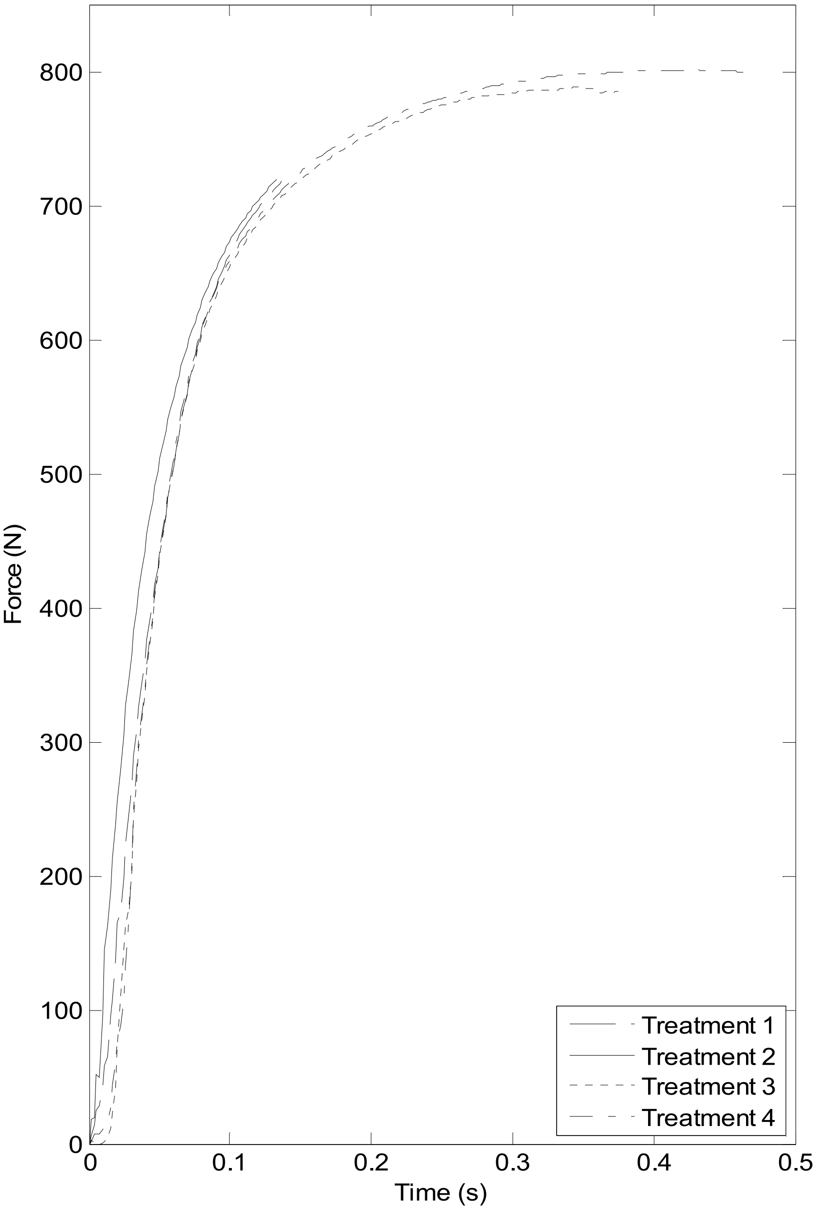

Figure 3-6 Force-time histories depicting mean ground reaction force for each soil treatment as measured with the DST device (n = 30 for each treatment).

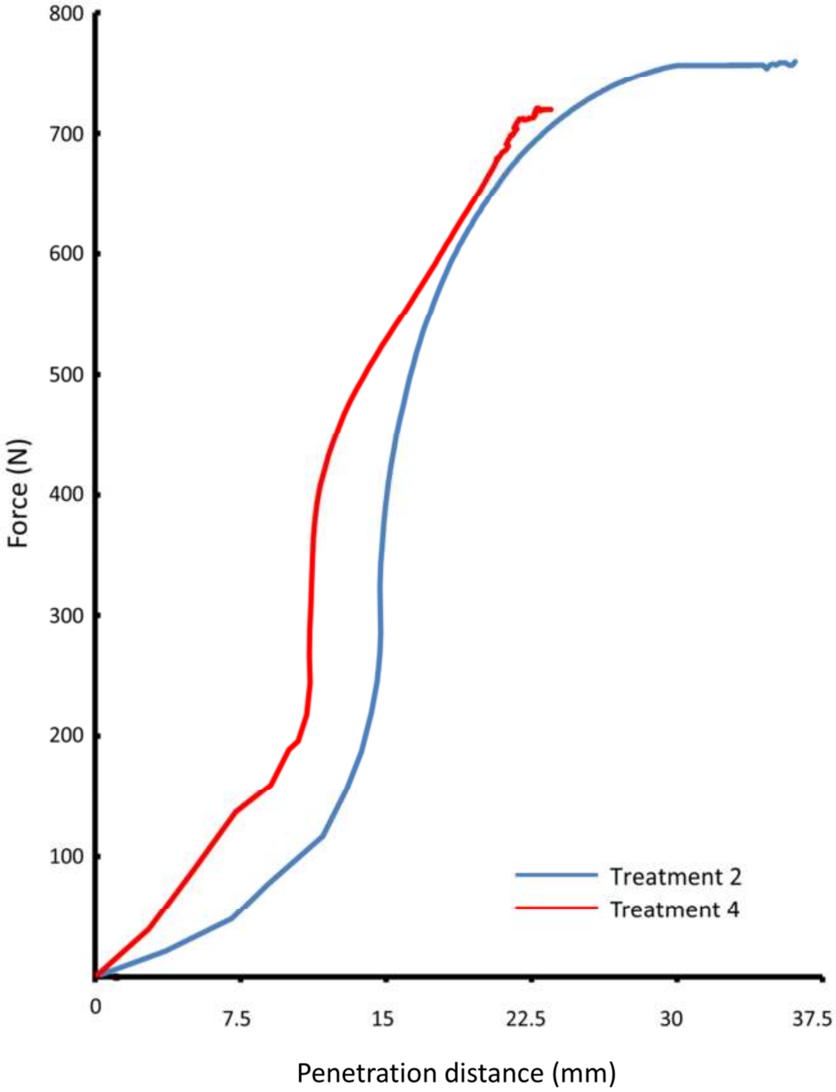

Figure 3-7 Representative force-distance histories of DST impacts from Treatments 2 and 4.

The higher force values and continued penetration of the DST device on the mechanically weaker soils (Treatments 3 and 4) can be argued to be a drawback for the implementation of the device. However, this function of the device aids in differentiating between soil conditions, and the soil behaviour indicated within this experiment (dynamic leading to quasi-static failure) would be expected to occur under the application of loads applied by athletes on these surfaces - longer ground contact times occur on less stiff surfaces and the rate of deformation (strain rate) is not linear throughout the impact. It must also be identified that the soils prepared within this validation experiment are considered to represent the extremities of mechanical behaviour evident within *in-situ* surfaces (Baker et al., 2007).

The strain rates applied by the DST (total and at 0.1 s) for the mean data of the four soil treatments are shown in Table 3-3. Note that the lower density soils (Treatments 3 and 4) allowed greater depth of penetration into the soil within the first 0.1 s of impact and produced a higher strain rate in this period, but the total penetration time in these treatments was much longer than in the higher density soils and resulted in a slower strain rate in total. As a result of this, it is more applicable to indicate the strain rate applied by the device at 0.1 s for future analysis.

Table 3-3 Calculated strain rates of the DST from mean treatment data: total strain rate and strain rates at 0.1 s of impact.

Treatment	Total strain rate (mm s^{-1})	Strain rate at 0.1 s (mm s^{-1})
1	203	230
2	163	180
3	92	280
4	77	300

Rate of loading was only significantly greater ($P<0.05$) in Treatment 2 (Figure 3-5d). Rate of loading is an important variable for assessing sports surfaces for athlete interaction (Dixon et al., 2000), and is not currently performed by other mechanical devices. Although described as dynamic, the data from these initial experiments indicate the DST device loaded the surface 7 times more slowly than subjects in the previous study of Stiles et al. (10.3 kN s^{-1} compared to 75.8 kN s^{-1}), and this aspect will be considered further in future work. Nevertheless, this rate of loading is greater than the maximum rate of loading achieved by the dynamic triaxial apparatus (6.5 kN s^{-1}), used in the Guisasola et al., (2010) study.

The DST can be considered a simplification of athlete-surface interaction by the adoption of mean contact area to produce stress data, and modelling vertical aspects only. However, it provides a further step towards understanding player-surface interaction on natural turf due to the lack of biomechanically-valid vertical impact devices evident for use *in-situ* on this surface type. These initial data support the potential of the device as a tool to assess dynamic strength of natural turf surfaces. Data from *in-situ* surfaces is required for further validation of the device, and will allow assessment of a variety of physical surface conditions, including the effects of turfgrass.

Replicating the dynamic stress an athlete imparts onto a surface, through the development of a mechanical device, allows increased understanding of surface behaviour in response to athlete impacts (e.g. surface deformation), and the extent of the energy absorption an athlete may receive. The stud on the test foot allows stud/test foot penetration ratios to be investigated, and replicates more closely the boundary conditions of athlete-surface impacts (Carré et al., 2007). The function of the DST device measures maximum surface deformation when loaded, important for energy dissipation when athletes impact the surface. The behaviour of the surface during unloading is not determined with the current device configuration but should also be considered, as viscous and elastic properties are important for surface durability and player performance (Guisasola et al., 2010).

The non-linear stress-strain behaviour of sports surfaces requires new testing devices to possess the ability to vary the impacting forces and stresses imparted onto the surface (Young and Fleming, 2007). The DST device possesses this capability in terms of variable ram pressure and interchangeable test feet and studs of different dimensions, and future research will be directed towards assessing surface behaviour to a range of vertical stresses which replicate a range of athlete masses or biomechanical movements.

3.4. IMPLICATIONS

A variable-force dynamic testing device was adapted for use on natural turf sports pitches, which replicates the magnitude of vertical stress of an athlete when running. This device can be used to increase understanding of the behaviour of sports surfaces under athlete loading and the energy dissipation athletes may encounter.

3.5. ACKNOWLEDGMENTS

The authors would like to acknowledge funding from The Engineering and Physical Sciences Research Council (EPSRC) for this research.

3.6. REFERENCES

Alexandrou, A. and Earl, R. (1998), The relationship among the pre-compaction stress, volumetric water content and initial dry bulk density of soil, *Journal of Agricultural Engineering Research,* vol. 71, no. 1, pp. 75-80.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

BS6366:1983 (1983), *Specification for studs for rugby football boots,* British Standards Institute, London.

BS1377-9:1990 (1990), *Soils for civil engineering purposes - in-situ tests,* British Standards Institution, London.

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

BS7755-5.6:1999 (1999), *Soil quality. Physical methods. Determination of dry bulk density.* British Standards Institution, London.

Carré, M. J., Kirk, R. F. and Haake, S. J. (2007), Developing relevant tests for traction of studded footwear on surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Dixon, S. J., Batt, M. E. and Collop, A. C. (1999), Artificial playing surfaces research: A review of medical, engineering and biomechanical aspects, *International Journal of Sports Medicine,* vol. 20, no. 4, pp. 209-218.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2000), Surface effects on ground reaction forces and lower extremity kinematics in running, *Medicine and science in sports and exercise,* vol. 32, no. 11, pp. 1919-1926.

Dixon, S. J., James, I. T., Blackburn, K., Pettican, N. and Low, D. (2008), Influence of footwear and soil density on loading within the shoe and soil surface during running, *Journal of Sports Engineering and Technology,* vol. 222, pp. 1-10.

Guisasola, I. (2008), *Human-natural sports surface interaction* (unpublished PhD thesis), Cranfield University, Cranfield.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Nigg, B. M. (1990), The validity and relevance of tests used for the assessment of sports surface, *Medicine and science in sports and exercise,* vol. 22, no. 1, pp. 131-139.

Nigg, B. M., Bahlsen, H. A., Luethi, S. M. and Stokes, S. (1987), The influence of running velocity and midsole hardness on external impact forces in heel-toe running, *Journal of Biomechanics,* vol. 20, no. 10, pp. 951-959.

Stefanyshyn, D. J. and Nigg, B. M. (2003), Energy and performance aspects in sports surfaces, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. H., Guisasola, I. N., James, I. T. and Dixon, S. J. (2011), Biomechanical response to changes in natural turf during running and turning, *Journal of Applied Biomechanics,* vol. 27, no. 1, pp. 54-63.

Young, C. and Fleming, P. R. (2007), A review of mechanical impact testing devices for sport surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Zhang, B., Zhao, Q. G., Horn, R. and Baumgartl, T. (2001) Shear strength of surface soil as affected by soil bulk density and soil water content, *Soil and Tillage Research,* vol. 59, no. 3-4, pp. 97-106.

4. USING THE GOINGSTICK TO ASSESS PITCH QUALITY

Matt C. J. Caple, Iain T. James, and Mark D. Bartlett.

ABSTRACT:

Mechanical behaviour of natural turf sports pitches is commonly assessed using the Clegg Impact Soil Tester and the studded disc apparatus under benchmark frameworks. Using these devices is time consuming and laborious, which restricts the frequency at which data can be collected on surfaces. To address this, the GoingStick was evaluated for use as a surface assessment tool. The device was originally developed for testing horseracing tracks, and quantifies both the penetration resistance and resistance to shearing of the turf surface. Data were collected on three sports pitches (rugby union and football) of varying sporting level and soil texture over two seasons of sport. A controlled laboratory experiment was also conducted assessing data from the GoingStick and the Clegg Impact Soil Tester for four soil treatments. The first season data highlighted that the maximum measurable value was too low on the device, owing to sports pitches being harder than race tracks. This issue was also found for the harder soil treatments in the laboratory study. Recalibration resolved this issue for the second season, where the entire range of mechanical behaviour was successfully measured. Linear relationships were evident between penetration resistance measured with the GoingStick and impact hardness measured with the third drop of the 2.25 kg Clegg Impact Soil Tester ($r^2 = 0.75$), and between resistance to shearing measured with the GoingStick and peak torque resistance measured by the studded disc ($r^2 = 0.88$). The results of the study indicate the potential for the GoingStick to efficiently quantify the mechanical behaviour of natural turf pitches. Further work should aim to determine benchmark ranges for the measured parameters and incorporate the device within decision support frameworks for surface management.

4.1 INTRODUCTION

A number of motivations exist for quantifying the mechanical behaviour of natural turf sports pitches. These include providing insight into ball-surface interaction, player-surface interaction, and as an indicator for surface maintenance. It is most common to assess mechanical behaviour of pitches using frameworks and devices that benchmark surface behaviour (Bell and Holmes, 1988; American Society for Testing and Materials, 2000). Testing under these frameworks is dominated by drop devices such as the Clegg Impact Soil Tester (CIST; Clegg, 1976) and the studded disc apparatus (Canaway and Bell, 1986). These two devices provide objective measures of vertical (impact hardness) and horizontal (peak torque resistance) mechanical behaviour of the surfaces respectively.

Use of the CIST and studded disc devices simultaneously is time consuming and laborious. While the CIST is lightweight and portable, the studded disc apparatus requires additional ballast of 40 kg for operation. Implementation and transportation of this equipment over a pitch is therefore difficult. Owing to this, data collection with the devices on pitches is often performed at a testing frequency of once a month or less frequent (Baker and Isaac, 1987; Baker et al., 2007). The number of test locations on pitches is also limited: five are commonly used for pitch assessment under the Performance Quality Standard (PQS) framework (Baker et al., 1988; McClements and Baker, 1994; Bartlett et al., 2009). The reliability of data collected with these devices has also been questioned, as Twomey et al., (2011a) showed that data can vary significantly between users, and is also dependent upon the experience of the user. Bartlett et al., (2009) in their review of PQS surface testing on natural turf surfaces, considered it important that new testing methodologies be developed which: allow multiple surface parameters to be quantified from single determinations, are time and resource efficient, easy to use, portable, and can be used in conjunction with decision support systems for surface management.

To address the issues highlighted, the GoingStick was evaluated as a surface assessment tool for natural turf pitches in order to increase the efficiency of surface testing. The device was trialled on *in-situ* pitches over two sporting seasons and within a controlled laboratory environment, with the aim of assessing the capabilities of the device to measure the range of surface behaviour exhibited by natural turf pitches. Data were also compared to that of the CIST and studded disc apparatus to provide reference to standard benchmark equipment.

4.2 METHODOLOGY

4.2.1 The GoingStick

The GoingStick was developed by Cranfield University and is licensed to the TurfTrax Group (Figure 4-1). The device is used to provide an objective measurement of the 'Going' on natural turf racecourse surfaces, a measure of the strength of the surface. As of 2009, it is a requirement under the British Horseracing Authority Rules of Racing that GoingStick readings be made available by racecourses for each fixture staged in the UK (British Horseracing Authority, 2009). The device measures penetration and resistance to shearing of the turf surface, with data integrated when used on racecourses to produce a value of the 'Going'. The device is 870 mm long with a mass of 2.8 kg, and the main components are shown in Figure 4-1i: the 100 mm long, 21 mm wide tine tip and abutment plate (A); the sensor unit (B); and the signal processor (C). Penetration and shear Wheatstone bridges carrying strain gauges are housed within the sensor unit to determine compression and moment forces respectively during operation. Further details of the device components can be found in the literature (Dufour and Mumford, 2008a, b). The reliability of the device was successfully shown in its initial development through repeatability, temperature sensitivity, and comparison trials (Dufour and Mumford, 2008a, b).

Figure 4-1 i) main components of the GoingStick: tine tip and abutment plate (A), the sensor unit (B), and the signal processor (C); ii) measuring penetration resistance of the surface; iii) measuring shear resistance of the surface.

During operation, the tip of the device is pushed vertically into the surface to the full 100 mm depth using the tee-bar (Figure 4-1ii), quantifying peak penetration resistance of the surface at the end of movement. The abutment plate controls the depth of insertion and isolates the sensor from the user's vertical force. The device is then rotated about the abutment plate along the plane of the tip to a minimum angle of 45° to determine the peak translational shear resistance of the surface (Figure 4-1iii). The GoingStick can operate in two modes, engineering and standard user. In the former, 'real-time' penetration and shear values can be viewed during the respective movements. In the standard user mode, peak penetration and shear values are recorded, and three replicates are required to provide mean values, calculated automatically. Within the current setup of the device, data can be viewed in the field in the form of a Going Index (a numerical scale aligned with qualitative descriptors of horseracing 'Going') calculated by an algorithm of penetration and shear data. Actual mean maximum penetration values (in force, N) and shear values (in torque, Nm) are stored on the device and can be viewed when data are downloaded onto a PC using a linear calibration (Figure 11-6 and 11-7, Appendix 11.2). In the penetration resistance measurements, vertical force is transformed into stress (MPa) by dividing data by the cross-sectional area of the tine tip (62.9 mm^2).

4.2.2 *In-situ* Surface Testing

The GoingStick was used to assess the mechanical behaviour of three natural turf pitches in the UK over two sport seasons: 2009/2010 and 2010/2011. The seasons ran from August to May. The pitches (Table 4-1) were selected to cover a broad spectrum of sporting levels, soil textures, and surface constructions (Appendix 11.3). Pitch A was an engineered sand rootzone pitch belonging to a professional football club in the third tier of the English football pyramid. The surface consists of 300 mm of a fibre-reinforced sand soil (Desso Grassmaster System) overlying gravel and drainage layers. Pitch B was a sand ameliorated native soil pitch belonging to a professional rugby team in the second tier of the English rugby pyramid. Pitch C was a native soil rugby pitch belonging to a university and community level rugby team. Soil texture of the pitches was determined using the pipette method (BS7755-5.4:1998), from two soil profile depths (0-100 mm; 200-300 mm). The two soil depths allowed recognition of the sand ameliorated surface (0-100 mm) of Pitch B and the texture of the native underlying soil (200-300 mm). The textures of the soils are placed into a soil classification triangle presented in Appendix 11.3.

Table 4-1 Soil texture of the pitches assessed in the study and number of datasets collected with the GoingStick over the two seasons.

Surfaces		**Soil texture**					**Datasets**	
Pitch	Sport	Rootzone depth (mm)	Sand (%)	Silt (%)	Clay (%)	Textural classification	2009/2010	2010/2011
A	Football	0-100 mm	97 ± 0.4	1 ± 0.2	2 ± 0.2	Sand	20	18
		200-300 mm	96 ± 0.3	2 ± 0.1	2 ± 0.1	Sand		
B	Rugby	0-100 mm	82 ± 1.0	8 ± 1.6	10 ± 1.5	Loamy sand	23	18
		200-300 mm	45 ± 1.6	29 ± 1.5	26 ± 1.3	Clay loam		
C	Rugby/Football	0-100 mm	38 ± 2.8	26 ± 1.0	36 ± 2.3	Clay		
		200-300 mm	33 ± 2.1	29 ± 1.1	38 ± 1.2	Clay	49	33

It was not possible to model the inputs and outputs of water accurately for the pitches, which was beyond the scope of this study; comparison of pitch mechanical behaviour to soil water content is undertaken in detail in Chapter 5. Pitch A had an automated irrigation system; Pitch B applied limited irrigation through stand-up sprinklers; Pitch C applied no supplementary irrigation. Regional weather data (the three pitches were within 27 km of each other), supplied by the UK Met Office defined total rainfall as 438 mm for the first season and 358 mm for the second season (August to May).

Regular visits were paid to the sports facilities across the two sport seasons. The frequency of testing ranged between twice weekly to every three weeks, differed between pitches, and was dependent upon the match and training schedules of the clubs and the maintenance schedules of the grounds managers (Table 4-1). Testing was disrupted in both seasons over the winter due to ground frosts and snow cover on the pitches: 04/01/10 – 17/01/2010 in the first season, 25/11/10 – 12/12/10 in the second season. Peak penetration resistance and peak shear resistance was assessed at 15 locations across the surfaces with the GoingStick (Figure 4-2). These locations were used instead of the five PQS locations as representative data from more areas of the pitch were provided, and was permissible owing to the efficiency of using the GoingStick. Data provided from the 15 locations were used to provide a mean value, a measure of the performance of the pitch for that given test visit. Data were not used to characterise the performance of the different areas of the pitch – this is undertaken in depth in Chapter 6.

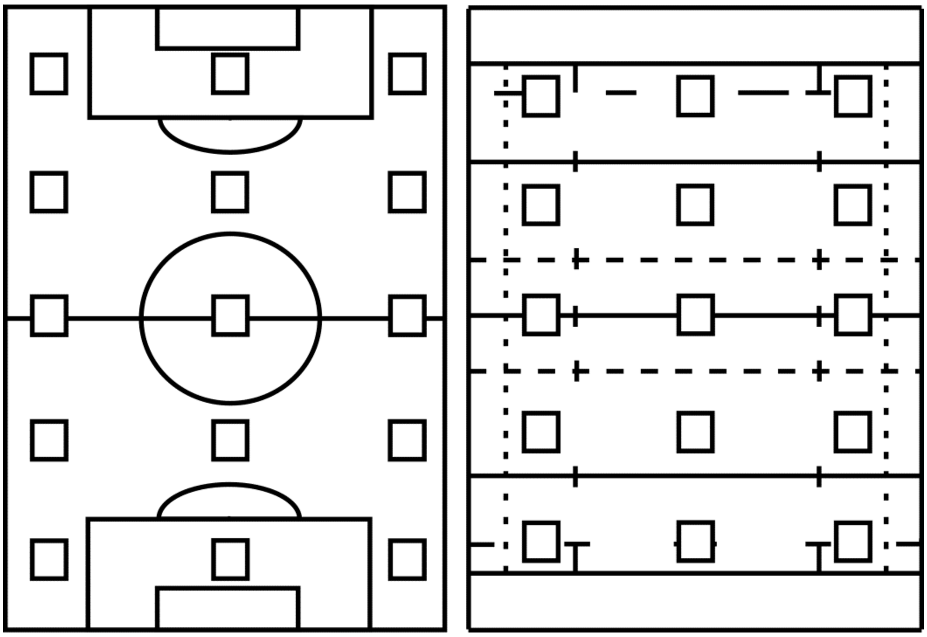

Figure 4-2 Test locations on the sports pitches, Football (left; Pitch A) and rugby (right; Pitches B and C). Not to scale, dimensions of pitches: A = 98 m long, 60 m wide; B = 115.2 m long, 68.6 m wide; C = 105 m long, 68 m wide.

In the second season a 2.25 kg CIST (SDi Instrumentation Ltd., Bath, UK) and a studded disc apparatus were used in conjunction with the GoingStick. The CIST quantifies the peak deceleration (g) of a missile (2.25 kg; 50 mm diameter) after contact with the surface, dropped from a height of 0.45 m. Higher values for peak deceleration equate to a harder surface, with lower peak deceleration values a result of longer ground contact times due to greater plastic deformation (Rogers and Waddington, 1990). The studded disc apparatus measures the peak torque resistance of the turf during the rotation of a loaded (40 kg) disc with 15 mm long studs. The CIST was used in all datasets on all pitches, with the studded disc apparatus used in 17 of the 33 datasets on Pitch C. It was not feasible to incorporate the studded disc apparatus into the testing schedules on Pitches A and B due to time constraints. Three replicates were collected at each test location with the GoingStick and CIST (n = 45); one reading per location was collected with the studded disc (n = 15), limited by the time-consuming and laborious nature of using the apparatus.

4.2.3 Laboratory Testing

A set of controlled laboratory experiments were undertaken within the Soil Dynamic Laboratory at Cranfield University with the GoingStick and the 2.25 kg CIST in October 2009. These experiments allowed soil physical conditions (water content and density) of the tested surfaces to be controlled and provide reference data for the relationship between the GoingStick and the CIST. A sandy loam soil, defined as per the pipette method (BS7755-5.4:1998), was used to prepare four soil-only treatments (free of grass and organic matter) in a soil bin. Differences between treatments were created by manipulating the dry density and water content of the soil (Table 4-2). A randomised block design was used, by splitting each treatment into six plots (400 mm x 2200 mm; Figure 3-4, Chapter 3), with mean plot data produced for penetration resistance and impact hardness from three replicates (n = 18 for each treatment). These experiments were undertaken alongside the DST device experiments (Chapter 3; Caple et al., 2011), and further method detail can be found in Chapter 3.

Table 4-2 Mean soil dry density (ρ_d), and water content (θ_v) for the prepared treatments in the laboratory experiment (n = 18 for each parameter; ± standard error).

Soil treatment	ρ_d **(g cm^{-3})**	ϑ_v **(% vol.)**
1	1.56 ± 0.01	23.1 ± 0.43
2	1.50 ± 0.02	17.2 ± 0.38
3	1.37 ± 0.01	13.1 ± 0.51
4	1.34 ± 0.01	16.7 ± 0.36

4.2.4 Statistical Analysis

In the *in-situ* study, mean values were produced for peak penetration resistance, peak shear resistance, peak deceleration, and peak torque resistance for each test visit, derived from the data collected at the 15 test locations. These mean data were then analysed with descriptive statistics (mean, minimum, maximum, interquartile range) to assess the central tendency and range of the data across the seasons. Linear regression analysis was used to assess the relationships between the vertical (penetration resistance and impact hardness) and horizontal (shear resistance and peak torque resistance) surface properties measured with the testing devices from the second season. Linear regression analysis was used to assess the relationship between mean penetration resistance and impact hardness for each plot in the laboratory experiment. All data analysis was performed with Statistica 9 software (Statsoft Inc., Tulsa, OK., USA).

4.3 RESULTS AND DISCUSSION

A functional requirement for the future implementation of the GoingStick is for the device to quantify a large range of surface mechanical behaviour, which can be exhibited temporally on natural turf pitches (Holmes and Bell, 1986; Baker, 1991). Large data ranges were evident in the *in-situ* data (Figures 4-3 and 4-4; Table 4-3), and were shown to be generally greater for Pitches B and C. This was expected due to the greater variation in strength that clay-dominated pitches receiving limited irrigation exhibit in comparison to intensively managed sand rootzones (Bell and Holmes, 1988). The laboratory experiment and the first season data highlighted that an issue was encountered with the measurement range of the GoingStick: the maximum measurable values of the original horseracing calibration (H1) was not sufficient to quantify the greater values of strength on natural turf pitches (Figure 4-3). This is explained by the requirement for more deformable surfaces providing higher impact absorption on horseracing surfaces (Peterson et al. 2008). This issue was also prevalent for the laboratory data, which was collected using the H1 calibration: data from Treatments 1 and 2 (higher density) were affected by the maximum measurable range in three and four treatment plots respectively. These two plots were shown to exhibit the highest values for peak deceleration and vane shear resistance in Chapter 3, and penetration resistance of soil is known to increase with an increase in density (Ayers and Perumpral, 1982). This issue prompted a second calibration (H2) to be developed and used from November 2009 onwards in the *in-situ* study. Further analysis within the first season of data revealed this new calibration was also not suitable to measure the range of strength on these surfaces (Figure 4-3). This issue was resolved between seasons with the development of a sports pitch calibration (SP1), which was shown to be successful in capturing the whole range of strength values across the second season on all pitches (Figure 4-4). Further details of the calibrations of the GoingStick are presented in Appendix 11.2.

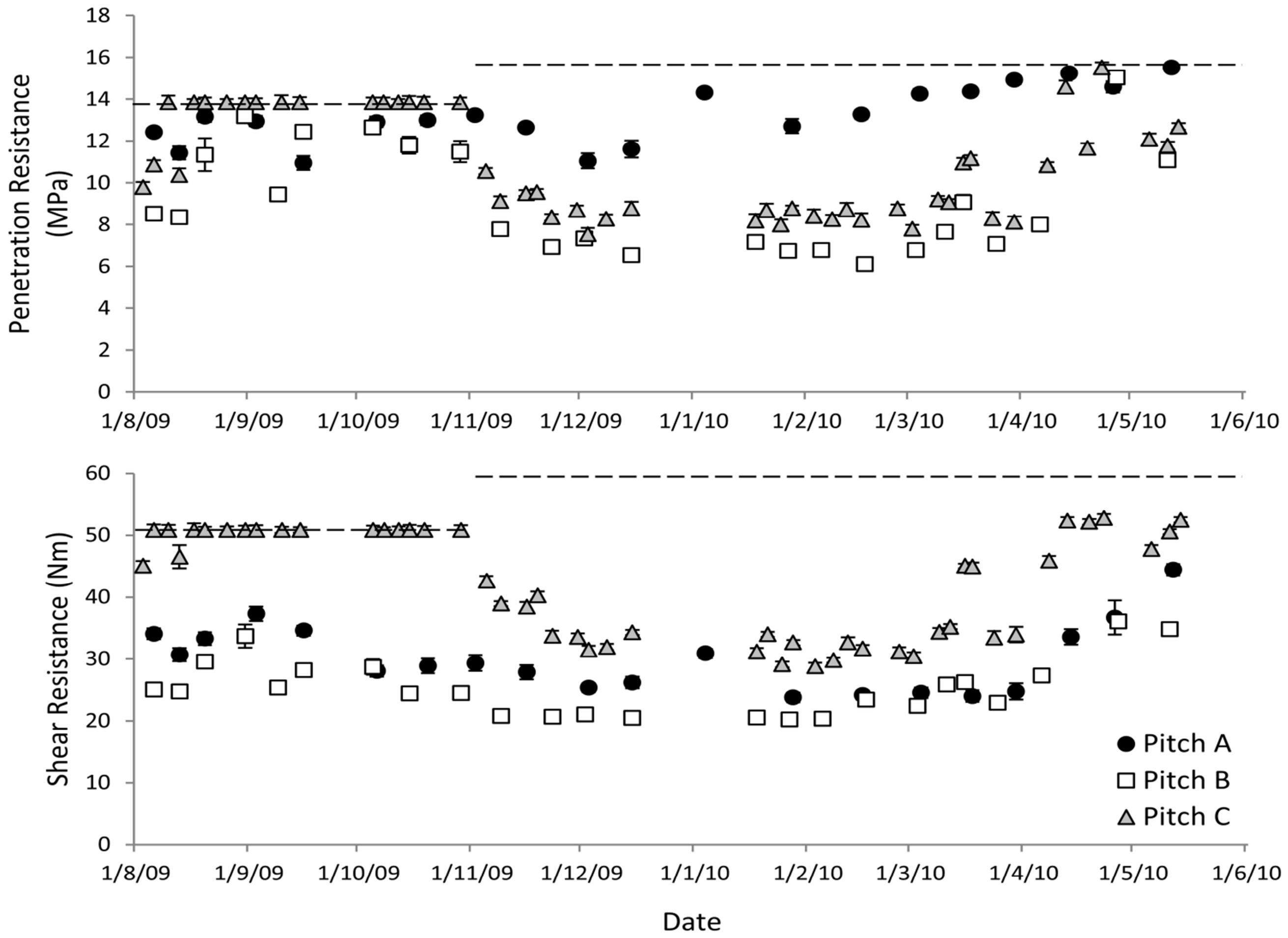

Figure 4-3 Mean penetration resistance (top) and resistance to shearing (bottom) measured with the GoingStick on the three sports pitches (A, B, C) across the 2009/2010 season. Whiskers represent standard error of the mean. Dashed lines represent the maximum measurable values of the GoingStick horseracing calibrations: H1 (1st August – 31st October); H2 (1st November – 31st May).

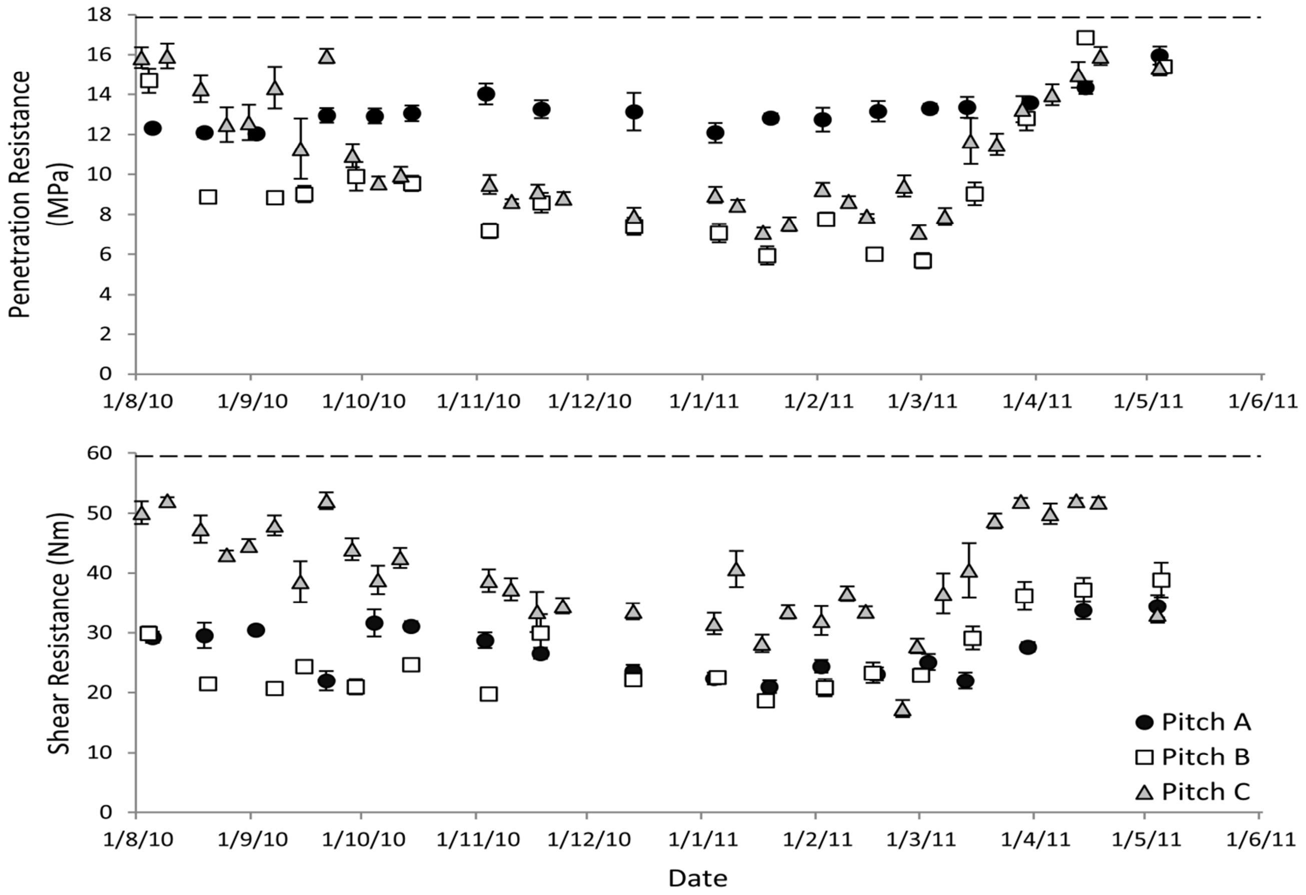

Figure 4-4 Mean penetration resistance (top) and resistance to shearing (bottom) measured with the GoingStick of the three sports pitches (A, B, C) across the 2010/2011 season. Whiskers represent standard error of the mean. Dashed lines represent the maximum measurable values of the sports pitch calibration (SP1)

Table 4-3 Descriptive statistics of mean (± standard error) penetration resistance and shear resistance data measured by the GoingStick on the three pitches (A, B and C) in the 2009/2010 and 2010/2011 seasons. *denotes data was affected by the maximum measurable value of the horseracing calibrations (H1 and H2).

	2009/2010				**2010/2011**			
	Mean	**Min.**	**Max.**	**Int. range**	**Mean**	**Min.**	**Max.**	**Int. range**
Pitch A								
Penetration resistance (MPa)	13.2 ± 0.3*	11.0	15.5*	1.8	13.1 ± 0.2	12.1	15.9	0.6
Shear resistance (Nm)	30.1 ± 1.2	23.8	44.6	8.8	24.0 ± 1.0	21.0	34.4	7.3
Pitch B								
Penetration resistance (MPa)	9.1 ± 0.5	6.1	15.0	4.4	9.5 ± 0.8	5.7	16.9	2.7
Shear resistance (Nm)	25.3 ± 0.4	20.2	36.1	6.8	25.8 ± 1.5	18.7	38.8	8.9
Pitch C								
Penetration resistance (MPa)	10.9 ± 0.4*	7.6	15.5*	5.1	11.1 ± 0.5	7.1	15.9	5.3
Shear resistance (Nm)	42.3 ± 1.3*	28.8	52.8*	17.3	40.1 ± 1.5	17.3	52.1	14.4

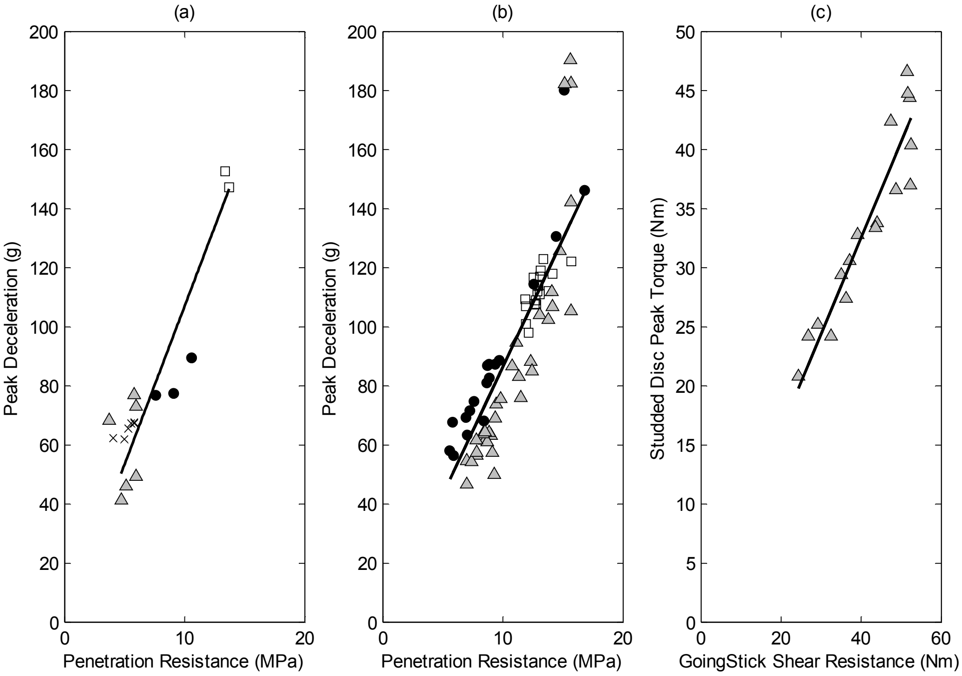

Figure 4-5 Linear regression analysis between the GoingStick and the CIST and studded disc apparatus: a) mean peak deceleration (CIST, third drop) against mean penetration resistance (GoingStick) in the laboratory experiment for each plot (Treatment 1 = circles, Treatment 2 = squares, Treatment 3 = triangles, Treatment 4 = crosses; $r^2 = 0.78$). Data that was affected by the measurable range of the GoingStick H1 calibration was removed; b) mean peak deceleration against mean penetration resistance from Pitches A, B, and C in the *in-situ* study (2010-2011 season; Pitch A = circles, Pitch B = squares, Pitch C = triangles; $r^2 = 0.75$); c) mean peak torque resistance measured with the studded disc apparatus against mean resistance to shearing measured with the GoingStick on Pitch C in the *in-situ* study (2010-2011 season; n = 17; $r^2 = 0.88$).

Mean data from the soil bin plots affected by the measurable range of the GoingStick were removed from linear regression analysis for the soil bin data (Figure 4-5a). A linear relationship ($r^2 = 0.75$) was evident between impact hardness (peak deceleration) of the third drop of the 2.25 kg CIST and peak penetration resistance measured by the GoingStick from the *in-situ* data (Equation 4.1; Figure 4-5b):

$$y = 8.6605x \qquad (4.1)$$

Although both penetration resistance and impact hardness quantify the resistance of the soil-turf surface to failure, they are different surface properties related to the function of the testing devices - shape/surface area of the devices, soil failure mechanisms, and strain rate application. Strain rates of the GoingStick and studded disc apparatus devices were calculated and presented in Appendix 11.4, and a rate of 140 mm s^{-1} was derived for the penetration function of the GoingStick. Strain rates of up to 1257 mm s^{-1} were calculated for the 2.25 kg CIST based on data presented by Rogers and Waddington (1990). Soil behaviour under constant-speed quasi-static penetration stress of a probe (GoingStick) is dominated by plastic failure, a function of soil particle shear resistance, plastic flow, and compression, as well as metal-soil friction forces. In contrast, under dynamic impact from the flat-faced CIST missile, soil particle movement can be restricted and data are reliant upon both plastic deformation and the stiffness of the soil and is characterised by the missile rebounding from the surface. The correlation between data produced from the devices suggests that the surface properties are related on a range of different natural turf pitches. This relationship was only evident for the third drop of the CIST, with lower r^2 values evident for drops one (0.31) and two (0.14). This indicates that the impact hardness of natural turf is more closely related to penetration hardness data when the soil has been compacted (made harder) under two prior drops.

A linear relationship (r^2 = 0.88) was also evident for peak shear resistance measured with the GoingStick and with peak torque resistance measured with the studded disc from the *in-situ* data (Equation 4.2; Figure 4-5c):

$$y = 0.8133x \qquad (4.2)$$

Both of these surface properties are a product of the turf resisting horizontal shearing failure, and this behaviour is dependent upon the complex interactions of the components within the natural turf system: soil (shear strength), grass roots, and thatch. A correlation was evident despite the different functions of the devices - the shearing depth of the GoingStick (100mm) is deeper than the studded disc (15 mm), and the orientation of applied stresses are different (torsional and translational). This correlation is most likely explained by the similar strain rate of rotation applied by the devices: 48 degrees per second for the GoingStick shear function and 49 degrees per second for the studded disc apparatus (see Appendix 11.4). Further work is required to gauge the relationship between these two devices on a larger range of turf pitches, particularly on a sand rootzone surface.

The initial correlation between the GoingStick and the CIST and studded disc shown in this study allows comparison of data collected with the GoingStick to the established PQS benchmark ranges. 'Acceptable' benchmark ranges for CIST and studded disc data under the PQS framework are 35 - 120 g for impact hardness and a minimum of 20 Nm for shear resistance on a football pitch (Bell and Holmes, 1988; Baker et al., 2007). Additionally, FIFA recommend that peak torque resistance using the studded disc on synthetic turf surfaces should not exceed 50 Nm (FIFA, 2009). The range of data recorded for impact hardness and peak torque on the pitches was between 47 - 146 g and 20.8 - 46.6 Nm respectively, covering the majority of these benchmark ranges. The ability of the GoingStick to measure the range of data outlined by PQS benchmarks aids in validating the implementation of the device as a means to quantify natural turf pitches, although caution is required when using benchmark frameworks not to apply them to a situation they were not designed for: the upper limit of surface hardness is currently used to gauge whether surfaces are safe for play in Australian football (Twomey et al., 2011b). The PQS framework was originally developed to provide minimum values for maintenance and to improve the quality of pitches, not to provide insight into the safety of a sports pitch as they were based on player perceptions of playing quality rather than injury data. The PQS ranges also require evaluating for modern natural turf pitches, as comprehensive studies assessing sports pitches have not been undertaken since the development of the framework in the 1980s and 1990s.

Further evaluation of the GoingStick within this two-season study showed that the efficiency and portability of the device allowed mechanical behaviour of the pitches to be quantified from 15 pitch locations in 15 minutes. Provision of comparative data from both the CIST and studded disc is more time consuming (~1 hour), and supports the use of the GoingStick as a more efficient testing device. Additionally, the damage the device causes to the turf surface (a divot that can be replaced) is also less severe than an indentation and a circular ‘trench’ provided by the CIST and studded disc apparatus respectively. The efficiency of using the GoingStick, the usefulness of the data produced (going index), the ease of downloading data, and ease of use by non-specialists, were key components in the acceptance of the device and subsequent widespread implementation in the horseracing industry. For use on natural turf pitches, the device offers the opportunity for more precise surface management, providing objective surface condition data to grounds managers on a regular basis (e.g. daily), which can be used as a decision support tool for maintenance operations (Mumford, 2006). The device also provides the opportunity to quantify surface condition of pitches within integrated studies, such as matching surface condition to injury data, which has only been undertaken in a limited number of studies (Orchard, 2001; Takemura et al., 2007). It is recognised that further data are required to continue the development of the device from a larger number of pitches and seasons of sport, representing a wider range of sporting levels, surface constructions, soil textures, and climatic conditions. Future work should also develop benchmarks for surface behaviour, in order for data to be useful for researchers and grounds managers.

4.4 CONCLUSIONS

The GoingStick was trialled as a means to assess the mechanical behaviour of natural turf pitches. With the use of a new sports pitch calibration, the device successfully measured the range of mechanical behaviour exhibited on three pitches of varying soil texture across a sport season. The two parameters measured by the device, peak penetration resistance and peak shear resistance, were shown to be linearly correlated to data provided by the CIST (impact hardness) and studded disc apparatus (peak torque resistance) respectively. The portability of the device also provides a means to assess surfaces more efficiently than current methodologies. The device should be implemented within decision-support frameworks for surface management and as a research tool to increase understanding of surface behaviour in the future.

4.5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of the ground managers at the sports clubs for allowing access to the pitches, and Mike Maher at TurfTrax for technical assistance with GoingStick calibration. This work was supported by the UK Engineering and Physical Sciences Research Council.

4.6 REFERENCES

American Society for Testing and Materials (2000), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test for shock attenuation characteristics of natural playing surface systems using lightweight portable apparatus. F1702-96.* ASTM, West Conshohocken, PA.

Ayers, P. D. and Perumpral, J.V. (1982) Moisture content and density effects on cone index. *Transactions of the ASABE*, vol. 25, pp. 1169-1172.

Baker, S. W. (1991), Temporal variation of selected mechanical properties of natural turf football pitches, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 83-92.

Baker, S. W., Cole, A. R. and Thornton, S. L. (1988), Performance standards and the interpretation of playing quality for soccer in relation to rootzone composition, *Journal of the Sports Turf Research Institute,* vol. 64, pp. 120-132.

Baker, S. W. and Isaac, S. P. (1987), The effect of rootzone composition on the performance of winter games pitches II. Playing quality, *Journal of the Sports Turf Research Institute,* vol. 63, pp. 67-81.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

British Horseracing Authority (2009), *The Rules of Racing*, available at: http://rules.britishhorseracing.com (accessed 14th October 2011).

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

Canaway, P. M. and Bell, M. J. (1986), An apparatus for measuring traction and friction on natural and artificial playing surfaces, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 211-214.

Caple, M. C. J., James, I. T., Bartlett, M. D. and Bartlett, D. I. (2011a), Development of a simplified dynamic testing device for turfed sports surfaces, *Journal of Sports Engineering and Technology,* vol. 225, pp. 103-109.

Clegg, B. (1976), An impact testing device for in situ base course evaluation, in: *Proceedings of the 8th ARRB Conference, vol. 8, no. 8*, Perth, Australia, pp. 1-6.

Dufour, M. J. D. and Mumford, C. (2008a), The development and environmental applications of the Goingstick®, in: Fuss, F. K. Subic, A. and Ujihashi, S. (eds) *Impact of Technology on Sport II*; London: Taylor & Francis, pp. 149-154.

Dufour, M. J. D. and Mumford, C. (2008b), GoingStick technology and electromagnetic induction scanning for naturally-turfed sports surfaces, *Sports Technology,* vol. 1, no. 2-3, pp. 125-131.

FIFA (2009), *FIFA quality concept for football turf. Handbook of requirements.* FIFA, Geneva.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

Mumford, C. (2006), *The optimisation of Going management on UK racecourses using controlled water applications,* (unpublished EngD thesis), Cranfield University, Cranfield.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Peterson, M. L., Wayne McIlwraith, C. and Reiser II, R. F. (2008), Development of a system for the in-situ characterisation of thoroughbred horse racing track surfaces, *Biosystems Engineering,* vol. 101, no. 2, pp. 260-269.

Rogers, J. N., and Waddington, D. V. (1990) Effects of management practices on impact absorption and shear resistance in natural turf, in: Schmidt RC, Hoerner EF, Milner E M, and Morehouse CA. *Natural and artificial playing fields: characteristics and safety features*; Philadelphia: ASTM, pp. 136-146

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British journal of sports medicine,* vol. 41, no. 9, pp. 582-587.

Twomey, D. M., Otago, L. and Ullah, F. F. (2011a), Reliability of equipment for measuring the ground hardness and traction, *Journal of Sports Engineering and Technology,* vol. 225, no. 3, pp. 131-137.

Twomey, D. M., Otaga, L. and Saunders, N. (2011b), Challenges in the development of standards for synthetic turf for Australian football and cricket, *Journal of Sports Engineering and Technology,* vol. 225, pp. 93-101.

5. MECHANICAL BEHAVIOUR OF NATURAL TURF SPORTS PITCHES ACROSS A SEASON

Matt C. J. Caple, Iain T. James, and Mark D. Bartlett

ABSTRACT

A study assessing the mechanical behaviour of six natural turf pitches of varying sporting level and surface construction was undertaken over a period of 10 months, spanning a sporting season (August 2010 – May 2011). Penetration resistance and shear resistance was measured with the GoingStick, impact hardness and surface energy absorption was measured with the 2.25 kg Clegg Impact Soil Tester and the Dynamic Surface Tester device respectively. The two sand rootzone pitches were more resistant to deformation and more consistent in their impact behaviour (impact hardness and energy absorption) through the season than the native soil pitches containing greater proportions of silt and clay. Greater consistency was shown for penetration resistance and shear resistance on one of the sand rootzone pitches, with the other behaving comparatively to the native soil pitches for these parameters. The sand rootzone surfaces exhibited greater ($P<0.05$) impact hardness than the native soil pitches in the winter period of the season (November to mid-March) compared to the beginning or end periods of the season, where data were statistically similar ($P>0.05$). The greater consistency of sand rootzone surfaces should be considered for the effect it may have on player and team performance, and injury potential. Analysis of data against Performance Quality Standard benchmarks indicated that all data on the sand rootzones exceeded preferred values for impact hardness, indicating these ranges may be obsolete for the modern elite natural turf surface. Implementation of benchmark frameworks in their current form should only be used as a maintenance tool, and not to assess if surfaces are safe for use, as test devices do not replicate the interactions of players and sports surfaces.

5.1 INTRODUCTION

Natural turf pitches are used for sports such as football and rugby and consist of turfgrass growing within a soil rootzone. The mechanical behaviour of these pitches is quantified because of the relationship this component has with aspects of surface performance: ball-surface interaction, the performance and safety of players, and the durability of the pitch. The mechanical behaviour of surfaces is most commonly assessed in terms of behaviour under impact, and horizontal behaviour relating to player traction. The energy returned and absorbed by sports surfaces during impact affects the rebound heights of balls, the absorption of impacting force from players, and contributes to the efficiency at which athletes perform sporting movements (McMahon and Greene, 1979; Bell and Holmes, 1988; Dura et al., 1999) Additionally, shear strength of natural turf is important in providing traction to players wearing studded footwear, although excessive traction causing foot fixation is regarded as a cause of injury (Torg and Quedenfeld, 1974).

5.1.1 Quantifying Mechanical Behaviour

Quantifying the mechanical behaviour of turf pitches has been historically dominated by assessing behaviour in relation to benchmark ranges of quality. This approach became popular in the mid-1980s in the UK, in order to increase the quality of pitches and to provide minimum quality indicators to aid surface management. Impact hardness and shear resistance are the most common mechanical properties quantified, and alongside tests for ball bounce and roll, surface evenness, grass cover and length, form part of the Performance Quality Standard (PQS) framework for natural turf (Bell and Holmes, 1988). Since its inception, this framework has been implemented primarily to compare between pitches, quantify pitch performance over time, across sporting levels, provide decision support for maintenance, and aid research into surface design (Baker and Isaac, 1987; Baker and Gibbs, 1989; Bartlett et al., 2009)

Impact hardness of turf pitches is quantified with drop devices, the most popular being the Clegg Impact Soil Tester (CIST; Clegg, 1976). The device consists of a weighted cylindrical missile (0.5 kg or 2.25 kg; 50 mm diameter) containing an accelerometer that is dropped from a set height (0.55 m or 0.45 m respectively) onto the surface. Hardness is quantified by the peak deceleration (g) of the missile after impact with the surface, with larger values indicating a harder surface. The 0.5 kg missile was used in early studies assessing sports pitches in the UK, but the 2.25 kg missile has now been adopted as the preferred mass because of a perceived lower ratio of energy absorbed by the grass foliage (Baker et al., 2007). Shear resistance of surfaces is measured with the studded disc apparatus (Canaway and Bell, 1986) under the PQS framework. The device consists of a studded circular disc that is loaded with 40 kg of weight on a central shaft. The peak torque (Nm) required in initiating rotation of the studs (15 mm length) in the turf is measured with a torque wrench. Although the device measures the resistance of the turf to shear forces, the device is commonly described as providing a measure of traction, owing to the relation of turf shear resistance to the traction players receive on turf (Guisasola et al., 2010a). Both the studded disc and CIST have been used worldwide to assess natural turf pitches (Chivers and Aldous, 2003; Magni et al., 2004), with the CIST most notably implemented in the ASTM standards for natural turf sports fields (American Society for Testing and Materials, 2000), and a variant of the studded disc used under the FIFA standards for synthetic turf (FIFA, 2009a). Other objective testing devices that have been used to assess the mechanical surface behaviour on natural turf pitches include soil penetrometers and shear vanes (Holmes and Bell, 1986; Orchard, 2001; Takemura et al., 2007), although their use has not been widely adopted in the UK.

5.1.2 Temporal Variations

The sports of football and rugby are played over the winter in the UK. A number of studies assessing the temporal variation in playing quality of turf pitches using the PQS framework have been performed (Holmes and Bell, 1986; Baker and Isaac, 1987; Bell and Holmes, 1988; Baker and Gibbs, 1989; Baker, 1991; Baker and Canaway, 1991a; Baker and Richards, 1995). The studies represented a range of sporting levels and surface constructions (soil texture and drainage designs), and the findings contributed to understanding of the mechanical behaviour of pitches over time, with soil texture, soil water content, and with sporting wear from play. Temporal variations in mechanical behaviour were shown to be smaller on sand rootzone pitches and those with drainage systems, in comparison to soils containing greater proportions of clay. The latter exhibited low strength in the winter months and became very hard in drier months, caused by fluctuations in soil water content owing to variable rainfall and ET rates, and the greater water retention of the soil (Baker, 1991; Hillel, 1998; Guisasola et al., 2010a). In comparison, the smaller variations in mechanical behaviour on sand soils was caused by the greater infiltration and hydraulic conductivity rates of these soils, and strength characteristics that are less sensitive to water content (Baker and Canaway, 1991b; Guisasola et al., 2010a). The greater surface consistency provided by sand rootzone pitches over the season led to the adoption of this surface type as the preferred construction at the elite level of football and rugby, where resources permitted (James, 2011).

The majority of temporal studies on natural turf pitches were performed over 20 years ago. Advances in the construction of sand rootzones surfaces i.e. the increased use of soil-reinforcing materials (Baker, 1997), coupled with improvements in maintenance techniques and machinery, have resulted in an evolution of the modern turf pitch (James, 2011). It is identified that the mechanical behaviour of these modern pitches requires quantifying, including how they perform in comparison to the PQS benchmarks devised in the mid-1980s. This paper details a season-long study assessing a range of pitches varying in soil texture and surface construction, and aims to provide important reference data for surface performance in the modern era. Mechanical behaviour of surfaces was assessed with the 2.25 kg CIST, the GoingStick, and the Dynamic Surface Tester (DST) device (Caple et al., 2011a). Based on previous research, the hypothesis was proposed that the magnitude of variation would be smaller on pitches with sand rootzone soils in comparison to 'native' soils containing greater proportions of silt and clay. This was proposed in response to lower hydraulic conductivity and strength characteristics that are more sensitive to changes in soil water content on clay soils.

5.2 METHODS

5.2.1 Sports Pitches

Six pitches were selected for the study at four sports clubs (A-D). The sports clubs and pitches were carefully selected to represent a range of sporting level (elite to amateur) and to represent a range of surface constructions and soil textures that are typical of those evident in the UK (Table 5-1; Appendix 11.5). Sports clubs have been anonymised to protect commercial interests. Club A is a professional football club in the third tier of the English football pyramid; Club B is a professional football club in the second tier of the English football pyramid; Club C is a professional rugby club in the second tier of the English rugby pyramid; Club D is a university/community level rugby team. Match pitches (MP) and training pitches (TP) were assessed at clubs A and C, with just the match pitches assessed at clubs B and D. Soil texture of the pitches was determined using the pipette method (BS7755-5.4:1998), from two soil profile depths (0-50 mm; 200-300 mm) at 15 locations across the surface (Figure 5-1).

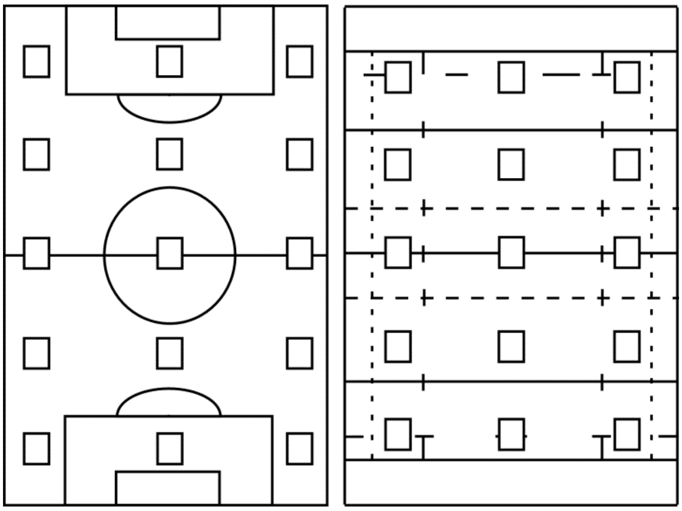

Figure 5-1 Layout of test locations on the sports pitches (not to scale): Football (left); Rugby (right).

Table 5-1 Details of surface construction and soil textures of the six sports pitches assessed within the study; number of datasets collected on each pitch within the 2010/2011 season.

Surfaces		**Soil texture**								**Datasets**
Club	**Pitch**	**Rootzone depth (mm)**	**Sand (%)**				**Silt (%)**	**Clay (%)**	**Textural classification**	
Engineered sand rootzones			**Total**	**0.6-2.0 mm**	**0.212-0.6 mm**	**0.063-0.212 mm**				
A	MP - Desso 'GrassMaster'	0-50	97 ± 0.4	6.0 ± 0.6	80.7 ± 0.5	10.3 ± 0.6	1 ± 0.2	2 ± 0.2	Sand	18
		200-300	96 ± 0.3				2 ± 0.1	2 ± 0.1	Sand	
B	MP - Fibresand	0-50	95 ± 0.4	6.6 ± 0.5	77.9 ± 0.4	10.4 ± 0.8	3 ± 0.4	2 ± 0.2	Sand	13
		200-300	95 ± 0.4				2 ± 0.1	3 ± 0.3	Sand	
Native soil										
A	TP	0-50	64 ± 1.6				18 ± 0.8	18 ± 1.1	Sandy loam	18
		200-300	57 ± 1.2				21 ± 0.7	22 ± 0.9	Sandy clay loam	
C	MP	0-50	82 ± 1.0				8 ± 1.6	10 ± 1.5	Loamy sand	18
		200-300	45 ± 1.6				29 ± 1.5	26 ± 1.3	Clay loam	
C	TP	0-50	83 ± 1.4				6 ± 0.6	11 ± 0.9	Loamy sand	
		200-300	44 ± 1.5				32 ± 0.9	23 ± 1.5	Clay loam	17
D	MP	0-50	38 ± 2.8				26 ± 1.0	36 ± 2.3	Clay	
		200-300	33 ± 2.1				29 ± 1.1	38 ± 1.2	Clay	33

The pitches were placed into two construction categories – engineered sand rootzone and ‘native soil’. The former type of pitch consists of 300 mm of sand soil overlying gravel and piped drainage layers; the latter consists of a pitch managed on the existing soil evident at the location. The two sand rootzone pitches consisted of different reinforcement materials: the Desso ‘Grassmaster’ System consists of synthetic grass fibres stitched vertically into the turf to a depth of 200 mm; the Fibresand pitch consists of polypropylene fibres (106 μm diameter, 25 mm length) incorporated into the sand before the rootzone is installed (Baker and Richards, 1995). A greater proportion of sand was evident in the surface layer (0-50 mm) than the deeper soil layer (200-300 mm) at three of the four native soil pitches (Table 5-1). This is a result of the annual application of sand to the surface on these pitches as part of maintenance procedures to maintain surface levels and increase water infiltration. This sand amelioration alters the textural classification of the surface layer, with the deeper soil layer that was quantified (200-300 mm) considered to represent the native soil evident at the site. D-MP did not show this sand layering effect, owing to the minimal maintenance that is performed on the pitch, common of community level facilities. The grass species evident on the sports pitches was not objectively quantified, but visual inspections and discussions with grounds managers revealed that Pitches A-MP and B-MP possessed a monoculture of dwarf perennial ryegrass (*Lolium perenne*; cultivar unknown) that are selected for elite level surfaces owing to their high tolerance to the effects of wear and shaded conditions; Pitches A-TP, C-MP, C-TP, and D-MP were dominated by a mix of perennial ryegrass and annual meadow grass (*Poa annua*), with the latter a less desirable but invasive grass specie in the UK that can dominate less intensively managed pitches. Maintenance of the pitches was representative of the sporting level of the sports clubs, ranging from intensive management (Pitches A-MP, B-MP, A-TP), moderate management (Pitches C-MP and C-TP), to minimal management (D-MP).

The study was conducted over the 2010/2011 sporting season. Football and rugby seasons run from August to May in the UK. The frequency of testing of the pitches ranged between 1-3 weeks, kept at regular intervals for each pitch where possible. This frequency was dependent upon the match and training schedules of the clubs, the management schedules of the grounds managers, and the proximity of the clubs (see

Table 5-1). It was not possible to model the inputs and outputs of water accurately for the pitches: A-MP and B-MP had automated irrigation systems; A-TP, C-MP, and C-TP had limited irrigation applied through basic stand-up sprinklers when required; D-MP had no supplementary irrigation applied. Regional weather data supplied by the UK Met Office defined total rainfall (August to May inclusive) in the region applicable for Clubs A, C, and D as 358 mm, and 290 mm for the region applicable to Club B.

5.2.2 Surface Testing

The mechanical behaviour and the soil water content of the pitches were quantified during each visit. Quasi-static measures of surface mechanical behaviour were measured with the GoingStick, and dynamic impact behaviour of the pitches was measured with the CIST and DST devices. All devices provide measures of the surface resisting deformation when stressed, but the strain rate applied by the devices varies (as considered in Chapters 3 and 4): 140 mm s^{-1} for the GoingStick penetration function, 48 degrees of rotation per second for the GoingStick shear function; up to 1257 mm s^{-1} for the 2.25 kg CIST; up to 300 mm s^{-1} for the DST device. The GoingStick was developed as a tool to quantify the mechanical behaviour of natural turf horse racing surfaces (Dufour and Mumford, 2008), and has since been trialled on natural turf sports pitches (Caple et al., 2011b; Chapter 4). The device quantifies both penetration resistance and shear resistance of the turf surface. A flat steel tine (100 mm long, 21 mm wide) is pushed into the ground to determine peak penetration resistance of the surface, then rotated about the abutment plate along the plane of the tine to a minimum angle of 45° to determine the translational shear resistance of the surface. It was not feasible to use the studded disc apparatus within the study: the labour-intensive nature of testing with the device, namely transporting in excess of 40 kg across the pitch, means that testing regularly and efficiently with the apparatus is difficult. However, shear resistance data of the GoingStick and the studded disc apparatus were shown to be linearly correlated ($r^2 = 0.88$) in the previous study, with a conversion factor of 0.8133 (Caple et al., 2011b; Chapter 4).

A 2.25 kg Clegg Impact Soil Tester (SDi Instrumentation Ltd., Bath, UK) was used to quantify impact hardness of the surface. The device was dropped from a standard height of 0.45 m onto the surface, with the third drop of three consecutive drops used for data analysis. The DST device (Caple et al., 2011a) was used to assess the behaviour of the surface to athlete-specific impact stresses. The device was developed based on biomechanical data of athletes running on natural turf (Stiles et al., 2011), with the vertical impact stress of the athletes replicated by the device. During a test, a compressed-air driven ram impacts a single-studded cylindrical (41 mm diameter, 38 mm height) test foot into the surface. The test foot stops moving when the soil resistance brings the foot to rest. Surface energy absorption as measured with the device was selected to quantify the surfaces, and a greater value for this parameter equates to a softer surface. Impacts were made on a reference styrene butadiene rubber shockpad (15mm thick) over concrete prior to each dataset, which ensured consistency in device performance over time. The regulator pressure of the device was set at 0.58 MPa, producing an impacting force of 696 N ± 12 on the shockpad. This equates to an impact stress value of 0.53 MPa, which is 94% of the mean stress value calculated for player impacts when running at 3.83 m s^{-1} (Guisasola, 2008).

Volumetric soil water content (0-60 mm depth) of the sports pitches was quantified using a soil water impedance probe (type ML2x, Delta-T Devices Ltd., Cambridge, UK). Data for each parameter was collected at 15 locations across the pitches (Figure 5-1), with three replicates collected per test location, producing 45 readings per dataset. Data collection was affected by adverse weather conditions between 25/11/10 – 12/12/10, and 20/12/2010 – 27/12/2010, owing to severe ground frosts and snow cover. Use of the pitches was disrupted in these periods with a number of matches and training sessions postponed.

5.2.3 Statistical Analysis

Mean data were produced for the parameters in each dataset. These data were then assessed for their central tendency and variability across the season using descriptive summary statistics (mean, minimum, maximum, interquartile range, and coefficient of variation). The relationship between parameters was assessed using Pearson correlation coefficients, and analysed for significance ($P<0.05$). Data analysis was performed with Statistica 9 (Statsoft Inc., Tulsa, OK., USA).

5.3 RESULTS

5.3.1 Variation across the Season

The mechanical behaviour and soil water content of A-MP was the most consistent across the season, exhibited by the smallest coefficients of variation (CoV) for all measured parameters (Table 5-2). Using this statistical parameter as a measure of dataset variability, the other sand rootzone pitch (B-MP) was also less variable than the native soil pitches for peak deceleration and soil water content. The variability in surface energy absorption of B-MP (16.1) was lower than all of the native soil pitches, but similar to C-MP (23.4) and C-TP (20.4). Variability for penetration resistance on B-MP was similar to the native soil pitches across the season, while shear resistance variability was greater (Table 5-2; Figures 5-2 – 5-6). The mechanical behaviour of the training pitch (A-TP) had a greater range and variation in the dataset across the season than the match pitch (A-MP) at Club A. In comparison, the training (C-TP) and match pitches (C-MP) behaved more similarly at Club C (Table 2; Figures 5-2 – 5-6).

Table 5-2 Descriptive statistics of the mechanical parameters and soil water content on the pitches outlined in Table 5-1 across the 2010/2011 season.

Parameter	Mean	Min.	Max.	Int. range	CoV.
Penetration resistance (MPa)					
A-MP	13.2 ± 0.2	12.1	15.9	0.6	7.1
A-TP	10.6 ± 0.8	6.2	16.3	6.0	31.8
B-MP	10.6 ± 0.6	7.8	16.6	2.5	21.6
C-MP	9.5 ± 0.8	5.7	16.9	2.7	35.0
C-TP	10.7 ± 0.7	7.1	16.8	2.2	28.9
D-MP	11.1 ± 0.5	7.1	15.9	5.3	26.9
Shear resistance (Nm)					
A-MP	24.0 ± 1.0	21	34.4	7.3	15.8
A-TP	40.1 ± 1.9	29.5	52.1	15.4	20.4
B-MP	16.2 ± 1.7	9.6	30.9	4.4	36.9
C-MP	25.8 ± 1.5	18.7	38.8	8.9	24.4
C-TP	31 ± 2.0	22.5	50.9	6.9	26.0
D-MP	40 ± 1.5	17.3	52.1	14.4	21.5
Peak deceleration (g)					
A-MP	112 ± 2	98	123	9	6.0
A-TP	86 ± 7	51	158	21	33.5
B-MP	126 ± 5.5	96	158	24	15.8
C-MP	90 ± 8	56	180	21	36.8
C-TP	102 ± 10	63	214	30	41.4
D-MP	88 ± 7	47	190	42	44.0
Energy absorption (kJ)					
A-MP	0.91 ± 0.02	0.81	1.01	0.15	8.0
A-TP	1.35 ± 0.14	0.69	2.76	0.65	42.4
B-MP	0.79 ± 0.04	0.49	0.98	0.13	16.1
C-MP	1.13 ± 0.06	0.60	1.47	0.25	23.4
C-TP	1.12 ± 0.06	0.61	1.52	0.15	20.4
D-MP	1.44 ± 0.11	0.59	2.67	0.85	42.2
Volumetric soil water content (%)					
A-MP	17.4 ± 0.3	14.5	20.9	1.1	8.1
A-TP	33.9 ± 2.9	13.7	50.1	21.8	26.0
B-MP	26.9 ± 1.4	18.3	34.8	2.6	18.8
C-MP	28.8 ± 2.0	12.3	40.2	8.6	28.9
C-TP	28.1 ± 2.3	7.6	43.0	8.9	34.4
D-MP	38.2 ± 2.0	15.4	53.0	17.8	29.7

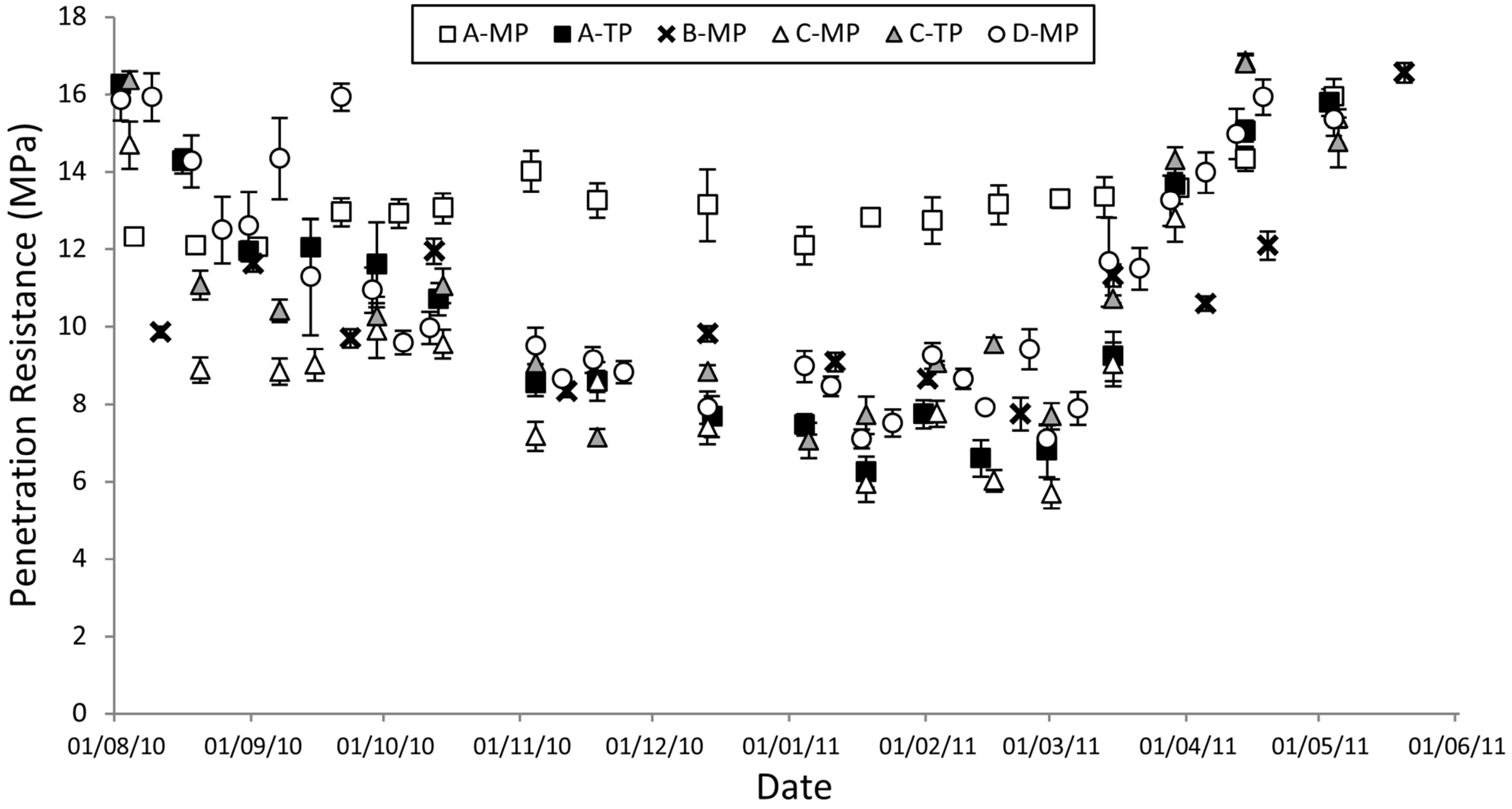

Figure 5-2 Mean peak penetration resistance of the six football pitches across the 2010/2011 sporting season measured with the GoingStick. Abbreviations outlined in Table 5-1. Whiskers represent standard error of the mean.

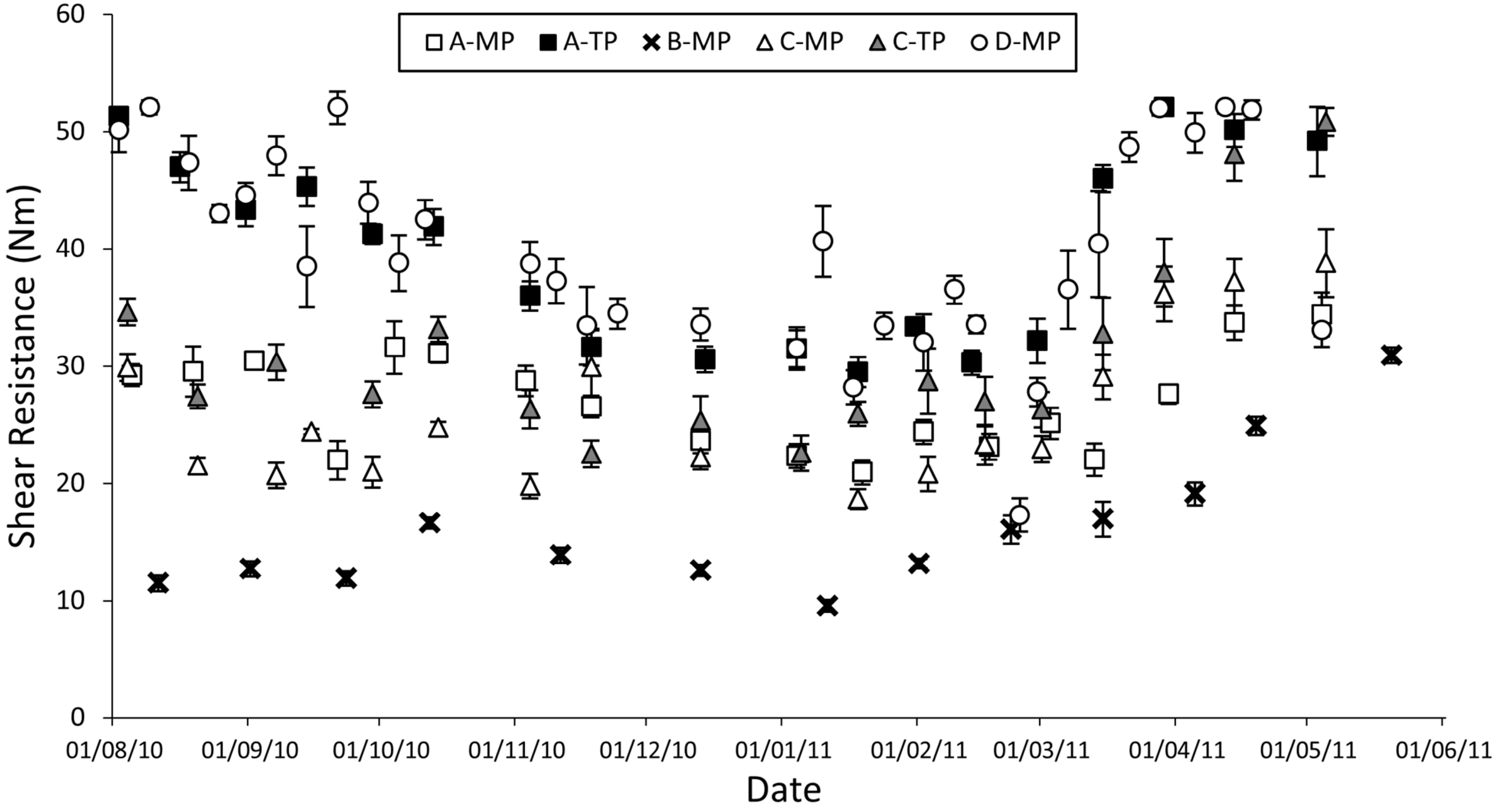

Figure 5-3 Mean peak shear resistance of the six football pitches across the 2010/2011 sporting season measured with the GoingStick. Abbreviations outlined in Table 5-1. Whiskers represent standard error of the mean.

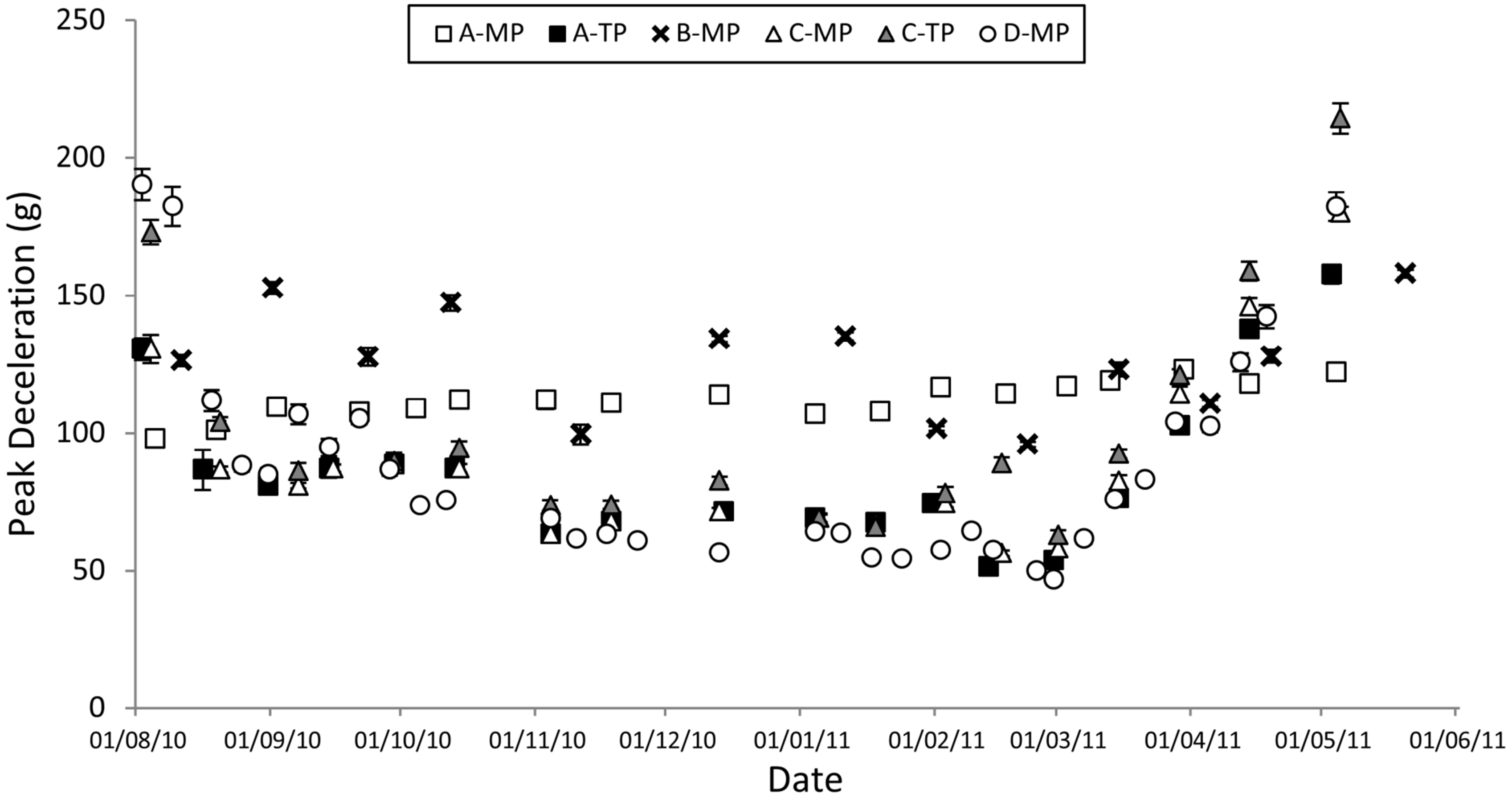

Figure 5-4 Mean peak deceleration of the six football pitches across the 2010/2011 sporting season measured with the CIST. Abbreviations outlined in Table 5-1. Whiskers represent standard error of the mean.

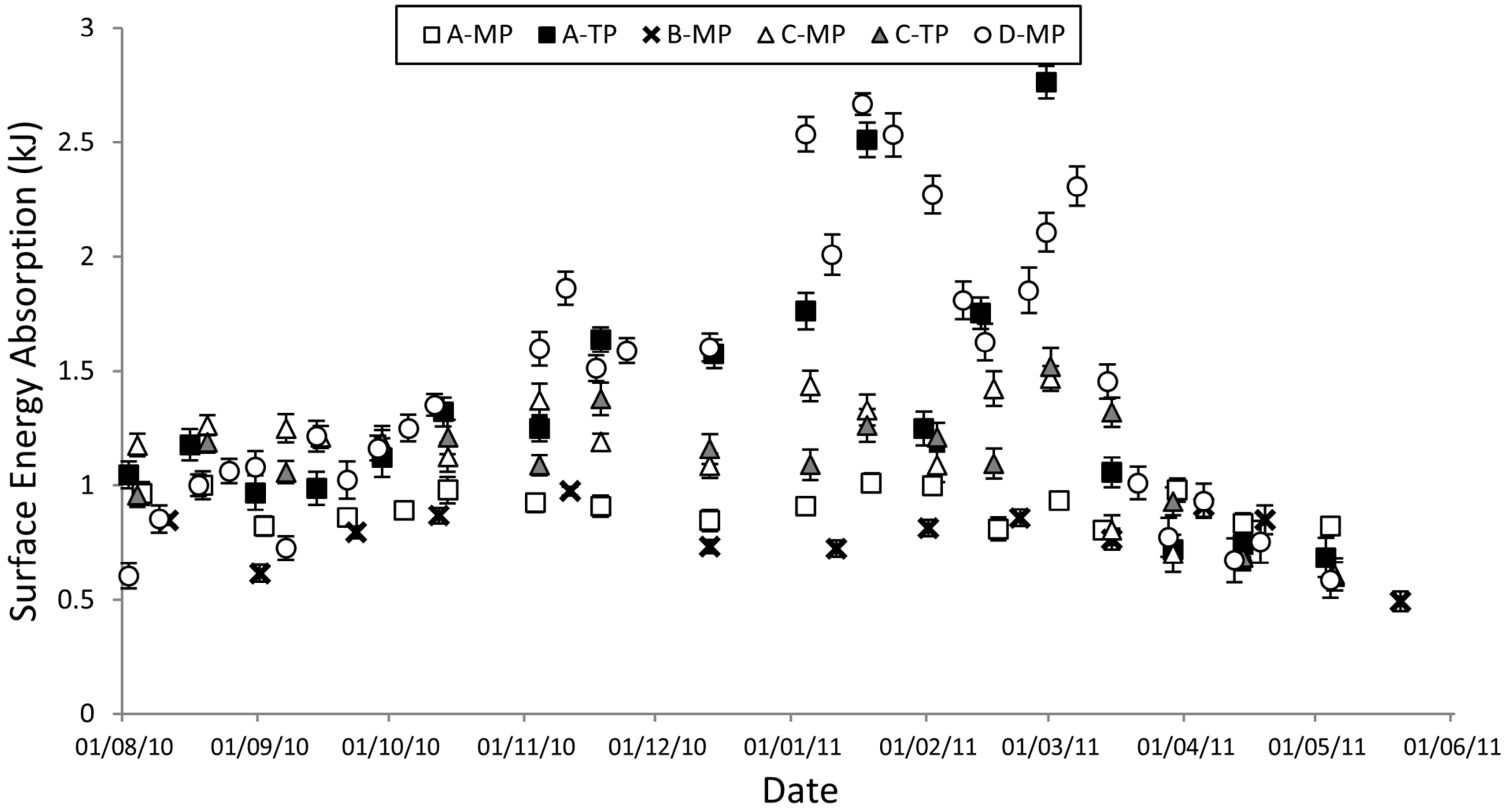

Figure 5-5 Mean surface energy absorption of the six football pitches across the 2010/2011 sporting season measured with the DST device. Abbreviations outlined in Table 5-1. Whiskers represent standard error of the mean.

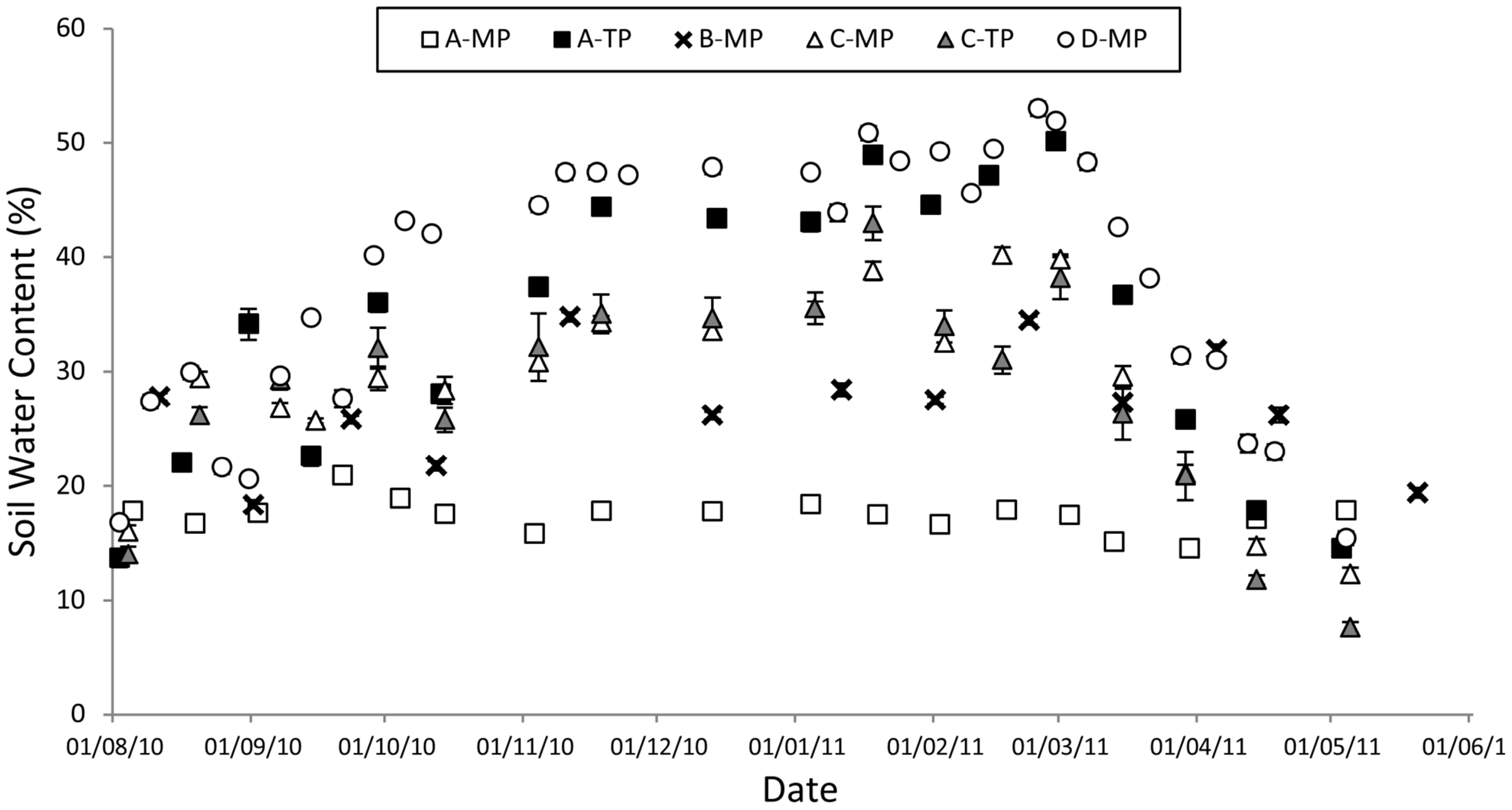

Figure 5-6 Mean volumetric soil water content of the six football pitches across the 2010/2011 sporting season measured with a soil water impedance probe. Abbreviations outlined in Table 5-1. Whiskers represent standard error of the mean.

In Figures 5-2 – 5-5, it was shown that the native soil pitches typically exhibited high strength and resistance to deformation during impact in the early part of the season (August to November), which reduced during the winter period (beginning of November to mid-March) and finally increased again in the spring (mid-March onwards). Grouping data by these three periods in the season (beginning, mid, and end), data were analysed for differences among pitches using one-way ANOVA and Unequal N HSD analysis. Analysis most notably showed: A-MP exhibited greater penetration resistance in the mid-season than all other pitches; A-MP and B-MP showed greater peak deceleration in the mid-season compared to all the native soil pitches; A-MP and B-MP exhibited smaller energy absorption during the mid-season compared to the two pitches with the highest ratio of clay in the surface layer, A-TP and D-MP; B-MP had smaller values for resistance to shear than all other pitches in all three periods of the season ($P<0.05$ in all instances). Within-pitch data analysed for differences among periods in the season most notably showed: penetration resistance, shear resistance, and peak deceleration was smaller; energy absorption was greater in the mid-season period compared to the beginning and end of season periods on A-TP and D-MP ($P<0.05$).

A-MP had the greatest mean value for penetration resistance, with C-MP the lowest. The two sand rootzone pitches exhibited the lowest mean values of shear resistance across the season, and this was attributed to the lower maximum values recorded on these pitches (34.4 Nm and 30.9 Nm). The A-MP data exhibited the smallest CoV for this parameter, with this value greatest on the other sand pitch, B-MP. In contrast, the smallest interquartile range was evident for the B-MP, indicating the dataset contained outliers (Figure 5-3). The greatest mean values for shear resistance were recorded on the two surfaces with greatest proportions of clay in the surface layer (A-TP and D-MP), although the interquartile ranges were greatest for these two pitches (Table 5-2).

The sand rootzone pitches exhibited the greatest mean values for peak deceleration. Greater maximum values were generally found on the native soil pitches, although values for A-TP and B-MP were the same (158). Minimum values were greater on the sand pitches (Table 5-2; Figure 5-4). Mean energy absorption measured with the DST was smallest on the sand rootzone surfaces, indicating surfaces were less deformable during impact. These surfaces were also less variable across the season (Table 5-2; Figure 5-5).

5.3.2 Relationship with Soil Water Content

Correlation coefficients among all parameters are presented in Table 5-3. Values were low and non-significant ($P>0.05$) between the mechanical surface parameters and soil water content on A-MP. In comparison, penetration resistance, peak deceleration (negative) and surface energy absorption (positive) had significant ($P<0.05$) linear relationships with soil water content on B-MP. This behaviour is explained by B-MP experiencing a greater range in soil water content than A-MP (Figures 5-6 and 5-7). This is despite the two soil materials having a very similar particle size distribution (Table 5-1). On the four native soil pitches, with the exception of energy absorption and shear resistance at C-MP, all parameters were shown to have significant ($P<0.05$) linear relationships with soil water content (Table 5-3; Figure 5-7).

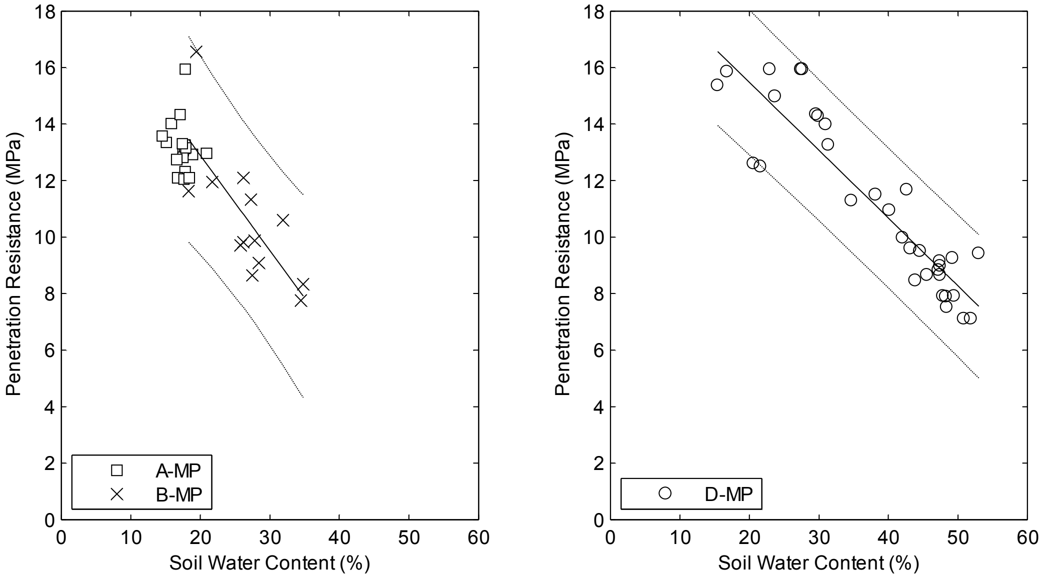

Figure 5-7 Scatter graphs of mean peak penetration resistance measured by the GoingStick against soil water content, left: A-MP and B-MP, linear regression model fitted for B-MP ($r^2 = 0.56$); right: at D-MP, with linear regression model fitted ($r^2 = 0.84$). Dashed lines represent 95% confidence interval.

Table 5-3 Pearson correlation coefficients for the mechanical parameters and soil water content of the pitches outlined in Table 5-1. * indicates significant at $P<0.05$ level; all values presented to two decimal places.

	Penetration resistance	**Shear resistance**	**Peak deceleration**	**Energy absorption**	**Soil water content**
A-MP					
Penetration resistance		-0.07	0.58*	-0.12	-0.15
Shear resistance			-0.24	0.11	-0.3
Peak deceleration				-0.31	-0.16
Energy absorption					-0.44
Soil water content					
A-TP					
Penetration resistance		0.98*	0.88*	-0.74*	-0.95*
Shear resistance			0.85*	-0.77*	-0.96*
Peak deceleration				-0.55	-0.85*
Energy absorption					0.71*
Soil water content					
B-MP					
Penetration resistance		0.8*	0.77*	-0.67*	-0.75*
Shear resistance			0.28	-0.33	-0.28
Peak deceleration				-0.75*	-0.91*
Energy absorption					0.76*
Soil water content					
C-MP					
Penetration resistance		0.63*	0.96*	-0.46	-0.92*
Shear resistance			0.49	-0.27	-0.44
Peak deceleration				-0.44	-0.92*
Energy absorption					0.44
Soil water content					
C-TP					
Penetration resistance		0.86*	0.96*	-0.6*	-0.94*
Shear resistance			0.73*	-0.42	-0.77*
Peak deceleration				-0.59*	-0.93*
Energy absorption					0.61*
Soil water content					
D-MP					
Penetration resistance		0.95*	0.82*	-0.87*	-0.82*
Shear resistance			0.77*	-0.81*	-0.7*
Peak deceleration				-0.77*	-0.66*
Energy absorption					0.82*
Soil water content					

5.3.3 Relationship between Parameters

Low correlation coefficients were evident between data on A-MP. This is attributed to the small ranges of data evident for the mechanical parameters (Table 5-3). The quasi-static mechanical parameters measured by the GoingStick (penetration resistance and shear resistance), were shown to be linearly correlated on all pitches (r = 0.63 - 0.98; $P<0.05$) except A-MP. Significant ($P<0.05$) relationships were also evident between peak deceleration and penetration resistance on all pitches (r = 0.58 - 0.96). Data from the impact devices (CIST and DST) were significantly correlated on three of the six pitches ($P<0.05$ in all instances).

5.3.4 Comparison to Surface Benchmarks

The PQS benchmark ranges for impact hardness and peak torque measured with the CIST and studded disc devices are outlined in Table 5-4. These are based on the original limits proposed by Bell and Holmes (1988) and McClements and Baker (1994), and the updated limits for the 2.25 kg CIST (Baker et al., 2007). The conversion factor of 0.8133 found in previous work was used to compare between GoingStick and studded disc shear data (Caple et al., 2011b; Chapter 4). Comparing these data to the PQS values, minimum values at all the pitches with the exception of A-TP fell below the minimum benchmark limits for peak torque resistance. Mean values at A-MP (19.5) and B-MP (13.2) fell below these limits. Maximum values are not evident for peak torque resistance measured with the studded disc on natural turf, although a limit of 50 Nm is recommended for rotational resistance under the FIFA one star standards on synthetic turf using the same equipment (FIFA, 2009b). Using this value, no datasets exceeded the recommended limits for peak torque resistance. None of the datasets fell below either the preferred or acceptable minimum values for surface hardness. However, 24% of the datasets exceeded the maximum acceptable limits, and 68% of the datasets exceeded the preferred limits, including all datasets at the two sand rootzone pitches (Figure 5-4).

Table 5-4 Performance Quality Standard benchmark ranges for use of the 2.25 kg CIST (peak deceleration) and studded disc apparatus (peak torque) on natural turf sports pitches (Bell and Holmes, 1988; McClements and Baker, 1994; Baker et al., 2007).

	Peak deceleration (g)	Peak torque (Nm)
Football		
Acceptable	35-120	≥20
Preferred	45-90	≥30
Rugby		
Acceptable	30-110	≥25
Preferred	40-70	≥35

5.4 DISCUSSION

Previous temporal studies assessing the variation of surface behaviour over a season have tested at a resolution of monthly intervals or less frequent (Baker and Isaac, 1987; Baker and Gibbs, 1989; Baker, 1991; Baker et al., 1992; Baker et al., 2007). This study assessed surfaces at a higher resolution. Testing at this resolution was aided by the more efficient assessment of shear resistance provided by the GoingStick in comparison to peak torque resistance quantified by the studded disc apparatus (Caple et al., 2011b). A number of internal (soil texture, grass roots, soil water content, soil density, reinforcement materials) and external (climatic conditions, sporting wear, management) variables can contribute to the mechanical behaviour of sports pitches. It was not possible to control or measure a number of these parameters during this study, owing to the quantity of collected data and testing resolution, the intensive schedules of use on the pitches, and the intrusive nature of some of the test procedures. Despite this, the study provides important reference data of the mechanical behaviour of a range of modern surfaces, to allow further studies to expand on the findings shown here.

The two sand rootzone pitches exhibited more consistent impact behaviour (energy absorption and peak deceleration) over the season than the native soil pitches. Pitch A-MP was also more consistent in its quasi-static mechanical behaviour measured with the GoingStick. Based on the data, the hypothesis that the magnitude of temporal variation would be smaller for sand rootzone surfaces was accepted. However, it was shown in the GoingStick data on B-MP that sand rootzone surfaces can exhibit temporal variations in a similar magnitude to native soil pitches containing higher proportions of clay. The strength of the B-MP pitch was considered to be lower in the studied season in comparison to other seasons by the grounds manager. This behaviour was explained by extreme weather conditions that were encountered during the winter, with heavy snow and severe ground frosts contributing to a noted significant loss of grass cover with little recovery growth. Additionally, extensive maintenance work was undertaken during the summer previous to the 2010-2011 season, involving removing the turf on the pitch, levelling the surface, and establishing new grass from seed. The pitch was used by the team for pre-season preparation too soon, without adequate compaction of the rootzone and the establishment of an extensive root system. The presence of grass roots and increased soil density are recognised to increase the strength of sand rootzone surfaces (Baker and Gibbs, 1989; Guisasola et al., 2010a). The loss of strength of B-MP is clearly highlighted in Figures 5-2 and 5-3, where the strength does not increase until the end of season period (mid-March onwards), when grass growth increased and the surface was compacted.

The modern sand rootzone surface is reinforced to increase surface strength. The study included two common types of reinforcement systems, the Desso Grassmaster System and Fibresand. The Desso surface was shown to be more consistent in quasi-static mechanical behaviour measured with the GoingStick, although the Fibresand surface was considered to be subjected to greater external factors that reduced grass cover and surface strength, making comparisons between surface constructions difficult. Despite the variation between the two sand pitches for quasi-static strength over the season, similar (P>0.05) mean data was evident between the pitches from the CIST and DST impact devices: minimum CIST values were 98 g and 96 g and maximum surface energy absorption values were 1.01 kJ and 0.98 kJ for the A-MP and B-MP pitches respectively. This indicated the sand surfaces maintained resistance to deformation during impact, even when quasi-static shear strength was lost. This behaviour is attributed to both the type of loading encountered and the mineralogy of the soil. In the dynamic tests, the strain rates applied by the CIST and DST (1257 mm s^{-1} and 300 mm s^{-1} respectively) means soil particles do not have time to reorganise to produce plastic strain when loaded quickly (Guisasola et al., 2010b). In the case of horizontal shear resistance measured with the GoingStick, this behaviour is also explained by the soil being confined when stressed vertically by the impact devices in compression, whereas the soil can move upwards and outwards (unconfined) when sheared horizontally by the GoingStick. In addition, the lack of cohesion in sand soils (as opposed to clay soils) contributes to the reduction in shear resistance on sand rootzones, particularly when grass cover and roots are lost (Baker and Isaac, 1987). This was a driving force behind the addition of synthetic fibres for surface reinforcement.

Sand rootzone pitches require sophisticated irrigation systems to prevent the soil drying out. If this occurs, sand soils can become weak (James, 2011). Application of water from irrigation is therefore carefully scheduled to maintain soil water content within a narrow range, increasing the tension forces between water and soil particles and increased shear strength of the soil. Maintaining soil water content within a narrow range is also contributed to by the large infiltration rates and hydraulic conductivity of these soils. Soil water content was maintained within a narrow range on A-MP over the season (14.5% - 20.9% soil water content; Figure 5-7). Careful management of soil water content on these surfaces contributes to consistent mechanical behaviour, which was shown on the A-MP. The larger range of soil water content recorded on the B-MP may be explained by the Fibresand fibres increasing water retention, differences in pitch maturity influencing hydraulic conductivity, or irrigation management. This is despite the similar soil textures and sand fractions of the two pitches (Table 5-1). Sports facilities which contain clay-dominated pitches lose strength when soil water content increases in the winter months as the soil is closer to the plastic state and plasticity dominates when the soil is stressed. Facilities with native soils often lack irrigation systems due to more restrictive maintenance resources, meaning not only do these soils lose strength with an increase in soil water, but the soil can dry out and become very hard in drier months (Baker, 1991). This behaviour was exhibited on the native soil pitches, through large data ranges and high CIST values (e.g. up to 214 g on the C-TP).

The DST was developed to replicate the applied stress of athletes when running. Although a simplification of athlete-surface interaction, the device more closely replicates the impacts provided by players than the CIST device (Caple et al., 2011c).

The portability of the device also allowed for its implementation in all datasets in the study. Mean data showed that the energy absorption of the sand pitches was lower than the native soil surfaces. This has been shown in biomechanical and laboratory experiments, and is attributed to the increased stiffness and frictional properties of sand rootzone soils (Guisasola et al., 2010b; Stiles et al., 2011). It is identified that research is required to assess the contribution that playing on these stiffer surfaces may have to athlete injury and performance (Stiles et al., 2009).

The mechanical behaviour of a sports surface has been cited as one of many potential causal mechanisms for athlete injury (Orchard, 2001; Orchard, 2002; Gabbett et al., 2007; Alentorn-Geli et al., 2009). Loss of player performance (e.g. loss of traction) and injury is considered to occur when surface behaviour falls outside desirable limits (Torg and Quedenfeld, 1974; Valiant, 1990; Shorten, 2003). Considering this, the increased temporal consistency of sand rootzone surfaces may be of benefit to players in comparison to playing on variable clay-dominated pitches. Similarly, training and playing matches on surfaces varying in their mechanical behaviour (evident at Club A) may be detrimental to players, in terms of predicting different ball bounce behaviour and the requirement to biomechanically adapt to the behaviour of a different surface (Dixon et al., 2005). An ‘early season bias’ of injury occurrences has been recognised in pitch-based sports, with mechanically harder surfaces at this stage of the season cited as a prominent causal mechanism in injury (Orchard, 2001; Orchard, 2002; Takemura et al., 2007). Some of the clay-dominated native soil pitches (A-TP and D-TP) exhibited higher resistance to deformation in the beginning of the season compared to the winter period, and coaches and physiotherapists should consider this aspect when conditioning players on these surfaces.

5.5 SURFACE TESTING AND STANDARDS

The hardness of the sand rootzone surfaces exceeded the preferred benchmark values of the PQS framework on all test visits. The principal aim of surface maintenance in the 1980s when the PQS benchmark limits were devised was to provide sufficient surface hardness and traction, as surfaces were often weak and unplayable in winter months. Stiles et al. (2009) considered that the evolution in maintenance and the construction of turf pitches since the production of PQS benchmarks has provided harder surfaces with higher traction, which is demanded by players and mirrors developments in player technique and fitness over the same period. Confirmation of this is provided by the hardness data in this study, and suggests that the PQS benchmarks for impact hardness may be obsolete for the modern elite sand rootzone surface. When GoingStick shear data was converted to studded disc data using the conversion factor from a previous study (Caple et al., 2011b), mean shear resistance values on both sand rootzone surfaces fell below minimum PQS benchmark values (20 Nm). Data from these devices were considered to correlate in Chapter 4 as a result of their similar strain rates (48 and 49 degrees of rotation per second). However, caution must be used when using these values as this original relationship was established on a clay loam surface, and it may be that the relationship between the two devices is different for a reinforced sand rootzone surface that lacks cohesive soil properties. Additionally, on the latter type of surface, the different orientation of applied stresses (torsional compared to translational shear) and depth of shear planes (15 mm compared to 100 mm) of the studded disc and GoingStick devices may have a more profound effect on the surface behaviour and produce data that does not correlate. This should be investigated further.

The use of PQS benchmarks for natural turf has evolved since their introduction, from providing benchmarks of quality for grounds maintenance, to being used as a safety tool. For instance, surfaces exhibiting CIST values of over 120 g are deemed unsuitable for use and result in ground closures in Australian Football (Twomey et al., 2011). While the original PQS limits were based on player perceptions of comfort and quality (Bell and Holmes, 1988), they are not based on injury data or any established injury tolerances to the human body. Two different categories of testing devices are identified for quantifying mechanical behaviour of natural turf pitches: 1) those providing information on general surface condition, and 2) those replicating aspects of player-surface interaction in order to further understanding in this discipline. Devices such as the CIST, studded disc, and GoingStick fall into the former category as they do not replicate the loading by athletes onto the surface in terms of rate, direction, or magnitude (Nigg, 1990; Young and Fleming, 2007) but instead provide a generic indicator of surface behaviour.

The implementation of Category 1 devices should be restricted to use as maintenance tools – assessing between pitches or over time, or providing decision-support. Any standards that are used with this type of device should not be misinterpreted as limits for player safety unless the limits are based on robust epidemiological evidence related to the use of that device. New updated benchmark ranges are required for the CIST device, and for the GoingStick in order for it to be widely adopted as a surface assessment tool. Benchmarks of surface quality cannot be proposed from the data presented here alone, but rather these results provide a foundation for future comparison of data. It is suggested that separate ranges are required for categorising the behaviour of sand rootzone surfaces and native soil pitches (containing higher proportions of clay). This is required because a clay pitch behaving comparatively to a sand pitch in regards to surface hardness would possess different traction characteristics. It is also recognised that future use of any standards has to be flexible, and more importantly should be sensitive to the particular climate and maintenance resources evident at each facility. It is important that standards are only used as guidelines, as regulating surface behaviour on natural turf in a similar manner to synthetic turf is not realistic owing to the potential exclusion from participation that this may produce for facilities poor in resources (McAuliffe, 2008). Despite this, frequent testing of turf pitches with suitable devices is required to increase understanding of surface behaviour.

Category 2 testing devices aim to replicate components of athlete-surface interactions such as loading and boundary conditions of athletes e.g. the replication of vertical stress provided by the DST device (McNitt et al., 1997; Carré et al., 2007; Grund et al., 2007; Rosa et al., 2007; Kuhlman et al., 2010; Caple et al., 2011a). The number of test devices that fall into this latter category has increased in recent years, as more research is being devoted to understanding the mechanisms involved in player biomechanics and injuries. Research has aimed to define injury thresholds of athletes in head impacts and for traction movements, with test devices for natural turf being recently developed to replicate high-risk injury situations (Grund et al., 2007; Theobald et al., 2010). These types of devices provide the opportunity to establish ‘safe’ limits of surface behaviour. However, collection of data with Category 2 devices is difficult as they are often built as ‘one-offs’ or prototypes, sometimes designed for laboratory use only, lack portability, and are labour-intensive in their function. The sophistication and expense involved in these devices also means their widespread use is not feasible. This has restricted the quantity and resolution of *in-situ* data collected, and highlights that a compromise is often required between data quantity and quality in assessing the mechanical behaviour of natural turf (Bartlett et al., 2009).

5.6 CONCLUSIONS

A study assessing the mechanical behaviour of a range of sports pitches over a season was undertaken. The study signifies a contribution to the understanding of the mechanical behaviour of modern sports pitches at a higher testing resolution than has previously been considered in the literature. The sand rootzone pitches evident at the elite level of football exhibited lower variation in impact behaviour across the season in comparison to native pitches containing greater proportions of clay. This is a result of lower hydraulic conductivity and strength characteristics that are more sensitive to changes in soil water content on clay and silt dominated soils. However, the strength of these pitches can potentially vary in similar magnitude to native soil pitches depending on a number of factors such as soil water content, the ratio of grass cover, maintenance of surfaces, surface construction, and climatic conditions. The lower, yet more consistent energy absorbing properties of sand rootzone surfaces should be considered for their effect on player performance and injury potential. Coaches and physiotherapists at elite sports clubs should be wary of the variation that can occur on clay-dominated soils when conditioning players, in addition to training and playing on surfaces of varying mechanical behaviour. Benchmark ranges for surface hardness under the PQS framework should be re-evaluated for application on the modern elite sand rootzone surface, as data in the study consistently exceeded the maximum values in the framework. The implementation of PQS surface benchmarks, in their current form, should be used as guidelines for surface management purposes and not to gauge whether surfaces are safe for play. This latter aspect is more likely to be achieved through defining tolerances to the human body and using sophisticated devices that replicate specific interactions between players and the surface.

5.7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of the ground managers at the sports clubs for allowing access to the pitches, David Bartlett for supplying and providing technical support for the DST, and Mike Maher at TurfTrax for technical assistance with the GoingStick. This work was supported by the UK Engineering and Physical Sciences Research Council.

5.8 REFERENCES

Alentorn-Geli, E., Myer, G. D., Silvers, H., Samitier, G., Romero, D., Lazaro-Haro, C. and Cugat, R. (2009), Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors, *Journal of knee surgery sports traumatology arthroscopy,* vol. 17, pp. 705-729.

American Society for Testing and Materials (2000), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test for shock attenuation characteristics of natural playing surface systems using lightweight portable apparatus. F1702-96.* ASTM, West Conshohocken, PA.

Baker, S. W. (1991), Temporal variation of selected mechanical properties of natural turf football pitches, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 83-92.

Baker, S. W. (1997), The reinforcement of turfgrass areas using plastic and other synthetic materials: A review, *International Turfgrass Society Research Journal,* vol. 8, pp. 3-13.

Baker, S. W. and Canaway, P. M. (1991a), The Cost-Effectiveness of Different Construction Methods for Association Football Pitches II Ground Cover, Playing Quality and Cost Implications, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 53-65.

Baker, S. W. and Canaway, P. M. (1991b), The cost effectiveness of different construction methods for association football pitches. I. Soil physical properties, *Journal of the Sports Turf Research Institute,* vol. 66, pp. 8-20.

Baker, S. W. and Gibbs, R. J. (1989), Levels of use and the playing quality of winter games pitches of different construction types: Case studies at Nottingham and Warrington, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 9-33.

Baker, S. W., Gibbs, R. J. and Adams, W. A. (1992), Case studies of the performance of different designs of winter games pitches. I. Playing quality and usage, *Journal of the Sports Turf Research Institute,* vol. 68, pp. 20-32.

Baker, S. W. and Isaac, S. P. (1987), The effect of rootzone composition on the performance of winter games pitches II. Playing quality, *Journal of the Sports Turf Research Institute,* vol. 63, pp. 67-81.

Baker, S. W. and Richards, C. W. (1995), The effect of fibre-reinforcement on the quality of sand rootzones used for winter games pitches, *Journal of the Sports Turf Research Institute,* vol. 71, pp. 107-117.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

Canaway, P. M. and Bell, M. J. (1986), An apparatus for measuring traction and friction on natural and artificial playing surfaces, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 211-214.

Caple, M. C. J., James, I. T., Bartlett, M. D. and Bartlett, D. I. (2011a), Development of a simplified dynamic testing device for turfed sports surfaces, *Journal of Sports Engineering and Technology,* vol. 225, pp. 103-109.

Caple, M. C. J., James, I. T., Bartlett, M. D. (2011b), Using the GoingStick to assess pitch quality. Submitted to *Journal of Sports Engineering and Technology.*

Caple, M. C. J., James, I. T., and Bartlett, M. D. (2011c), The effect of grass leaf height on the impact behaviour of natural turf sports field surfaces, *Sports Technology,* (Accepted)

Carré, M. J., Kirk, R. F. and Haake, S. J. (2007), Developing relevant tests for traction of studded footwear on surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Chivers, I. H. and Aldous, D. E. (2003), Performance monitoring of grassed playing surfaces for Australian rules football, *Journal of Turfgrass and Sports Surface Science,* vol. 79, pp. 73-80.

Clegg, B. (1976), An impact testing device for in situ base course evaluation, in: *Proceedings of the 8th ARRB Conference, vol. 8, no. 8*, Perth, Australia, pp. 1-6.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2005), Compensatory adjustments in lower extremity kinematics in response to a reduced cushioning of the impact interface in heel-toe running, *Sports Engineering,* vol. 8, pp. 47-55.

Dufour, M. J. D. and Mumford, C. (2008a), The development and environmental applications of the Goingstick®, in: Fuss, F. K. Subic, A. and Ujihashi, S. (eds) *Impact of Technology on Sport II*; London: Taylor & Francis, pp. 149-154.

Dura, J. V., Hoyos, J. V. and Martinez, A. (1999), The effect of shock absorbing sports surfaces in jumping, *Sports Engineering,* vol. 2, no. 2, pp. 97-102.

FIFA (2009a), *FIFA Quality Concept for Football Turf. Handbook of Test Methods,* FIFA, Geneva.

FIFA (2009b), *FIFA quality concept for football turf. Handbook of requirements.* FIFA, Geneva.

Gabbett, T., Minbashian, A. and Finch, C. (2007), Influence of environmental and ground conditions on injury risk in rugby league, *Journal of Science and Medicine in Sport,* vol. 10, pp. 211-218.

Grund, T., Senner, V. and Gruber, K. (2007), Development of a test device for testing soccer boots under game-relevant high-risk loading conditions, *Sports Engineering,* vol. 10, no. 1, pp. 55-63.

Guisasola, I. (2008), *Human-natural sports surface interaction* (unpublished PhD thesis), Cranfield University, .

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010a), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010b), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Hillel, D. (1998), *Environmental Soil Physics,* Academic Press, San Diego, CA.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

James, I. T. (2011), Advancing natural turf to meet tomorrow's challenges, *Sports Engineering and Technology,* vol. 225, pp. 115-129.

Kuhlman, S., Sabick, M., Pfeiffer, R., Cooper, B. and Forhan, J. (2010), Effect of loading condition on the traction coefficient between shoes and artificial turf surfaces, *Journal of Sports Engineering and Technology,* vol. 224, no. 2, pp. 155-165.

Magni, S., Volterrani, M. and Miele, S. (2004), Soccer pitches performances as affected by construction method, sand type and turfgrass mixture, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 281-285.

McAuliffe, K. W. (2008), The role of performance testing and standards in the sports turf industry: a case study approach, in: Stiel, J. C., Han, L. and Li, D. (eds.), *Proceedings of the Second International Conference on Turfgrass Management for Sports Fields,* 24-29 June, 2007, ISHS, Leuven, pp. 391-398.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

McMahon, T. A. and Greene, P. R. (1979), The influence of track compliance on running, *Journal of Biomechanics,* vol. 12, no. 12, pp. 893-904.

McNitt, A. S., Middour, R. O. and Waddington, D. V. (1997), Development and Evaluation of a Method to Measure Traction on Turfgrass Surfaces, *Journal of Testing and Evaluation,* vol. 25, no. 1, pp. 99-107.

Nigg, B. M. (1990). The validity and relevance of tests used for the assessment of sports surfaces. *Medicine and Science in Sports and Exercise, 22*(1), 131-139.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Orchard, J. (2002), Is there a relationship between ground and climatic conditions and injuries in football? *Sports Medicine,* vol. 32, no. 7, pp. 419-432.

Rosa, D., Sanchis, M., Gamez, J. and Alcántara, E. (2007), Study on the effect of maintenance operations and season on the traction of natural grass pitches, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. H., Guisasola, I. N., James, I. T. and Dixon, S. J. (2011), Biomechanical response to changes in natural turf during running and turning, *Journal of Applied Biomechanics,* vol. 27, no. 1, pp. 54-63.

Stiles, V. H., James, I. T., Dixon, S. J. and Guisasola, I. N. (2009), Natural turf surfaces: The case for continued research, *Sports Medicine,* vol. 39, no. 1, pp. 65-84.

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British Journal of Sports Medicine,* vol. 41, no. 9, pp. 582-587.

Theobald, P., Whitelegg, L., Nokes, L. D. M. and Jones, M. D. (2010), The predicted risk of head injury from fall-related impacts on to third-generation artificial turf and grass soccer surfaces: A comparative biomechanical analysis, *Sports Biomechanics,* vol. 9, no. 1, pp. 29-37.

Torg, J. S. and Quedenfeld, T. C. (1974), The shoe-surface interface and its relationship to football knee injuries, *Journal of Sports Medicine,* vol. 2, no. 5, pp. 261-269.

Twomey, D. M., Otaga, L. and Saunders, N. (2011), Challenges in the development of standards for synthetic turf for Australian football and cricket, *Journal of Sports Engineering and Technology,* vol. 225, pp. 93-101.

Valiant, G. A. (1990), Traction characteristics of outsoles for use on artificial playing surfaces, in: Schmidt, R. C., Hoerner, E. F., Milner, E. M., et al (eds.), *Natural and artificial playing fields: characteristics and safety features,* ASTM, Philadelphia, pp. 61-68.

Young, C. and Fleming, P. R. (2007), A review of mechanical impact testing devices for sport surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

6. SPATIAL ANALYSIS OF THE MECHANICAL BEHAVIOUR OF NATURAL TURF SPORTS PITCHES

Matt C. J. Caple, Iain T. James, and Mark D. Bartlett

ABSTRACT

The mechanical behaviour of three sports pitches was spatially analysed using geostatistical techniques (variograms and interpolation) at three times across the sporting season. Pure nugget variograms were evident for penetration and shear resistance measured with the GoingStick, surface energy absorption measured with the Dynamic Surface Tester (DST) device, and soil water content. Descriptive statistics and interpolated surface maps of the data confirmed the surfaces exhibited random variation in their mechanical properties, and temporal variation was similar in magnitude to detected spatial variation. Impact hardness quantified with the Clegg Impact Soil Tester (CIST) was the only property that was spatially dependent, and this was attributed to the stress-history applied by the first two drops of the device. Temporal and spatial variation of properties was generally smaller on a sand rootzone pitch, in comparison to two native soil pitches. Consideration should be given to the effect that spatial variability of sports pitches may have on player performance or injury risks throughout the sporting season: DST data suggest that the impact attenuation athletes would receive when running on the surface would vary on a small spatial scale. The methodology was considered robust for use in future spatial analysis.

6.1 INTRODUCTION

The mechanical behaviour of a sports surface is a key component in ball-surface and athlete-surface interaction. Surface mechanical properties have been shown to influence ball bounce and ball roll, the ability of athletes to perform particular movements quickly and efficiently, and are considered to be an important factor in the occurrence or prevention of injuries (McMahon and Greene, 1979; Bell and Holmes, 1988; Lambson et al., 1996; Kerdok et al., 2002). Consistent spatial behaviour of sports surfaces is important in the performance of the surface. Unpredictable ball behaviour after contact with the surface is detrimental to the quality and enjoyment of the game, while surface inconsistency has been suggested as a causal mechanism in injury occurrence on sports surfaces (Meyers, 2010).

Natural turf sports pitches are used for a variety of team sports such as football (soccer), rugby codes, Gaelic sports, lacrosse, and American football. The mechanical behaviour of natural turf has previously been described in terms of impact hardness, shear strength, penetration resistance, soil stress-strain behaviour, and surface energy absorption (Orchard, 2001; Baker et al., 2007; Li et al., 2009; Guisasola et al., 2010a, b; Caple et al., 2011a). Mechanical behaviour of surfaces are known to be dependent upon a number of intrinsic (soil texture, soil water content, soil bulk density, grass density) and extrinsic (climatic conditions, management operations, wear from play, the magnitude and rate of applied stress) factors, which have been shown to cause temporal variation in surfaces (Rogers III and Waddington, 1990; Baker, 1991; Tengbeh, 1993; Vanini et al., 2007; Guisasola et al., 2010a, b). The two most common mechanical properties quantified on sports pitches *in-situ* are impact hardness and shear resistance (traction). These two components are typically quantified using the Clegg Impact Soil Tester (CIST; Clegg, 1976) and the studded disc apparatus respectively (Canaway and Bell, 1986), with benchmark ranges for these devices in Performance Quality Standards (PQS) frameworks for natural turf sports pitches (Bell and Holmes, 1988).

Surface management of natural turf sports pitches aims to produce homogenous surfaces with consistent mechanical behaviour. However, factors that produce temporal variation in mechanical behaviour can potentially contribute to spatial variation on these surfaces. Spatial variation has been identified previously on sports pitches through the assessment of impact hardness, shear resistance, and ball rebound (Baker and Bell, 1986; Holmes and Bell, 1986; Bell and Holmes, 1988; McClements and Baker, 1994). These studies collected data at 3-12 locations across sports pitches, comparing areas such as ‘goalmouths’, ‘centre,’ and ‘wings’. The studies found that mechanical behaviour differed in central areas of the pitch that were subjected to perceived higher concentrations of wear from play. These areas were typically harder and had lower resistance to shear, which was often attributed to rootzone compaction and lower grass cover. Wear on football pitches is perceived to be typically concentrated in a diamond pattern, extending out from one goalmouth to the halfway line and tapering towards the opposite goal (Holmes and Bell, 1986). Sand rootzone surfaces were found to have less variation in mechanical behaviour across the pitch in comparison to native soil rootzones (those containing higher ratios of silt and clay), while rugby pitches have been shown to exhibit less concentration of wear than football pitches (Holmes and Bell, 1986; McClements and Baker, 1994).

The low number of pitch test locations used in the aforementioned spatial studies restricts analysis of the whole pitch surface. Geostatistics are a branch of statistics used to analyse spatial data which is applied in environmental science fields such as mineral resource mapping in mining and precision farming in agriculture (James and Godwin, 2003; Taylor et al., 2003; Emery and González, 2007). The structure and nature of sampled data are determined with variograms, while interpolation techniques allow estimation of unsampled regions with surface maps (Chilés and Delfiner, 1999). Use of variograms and interpolation techniques offer the opportunity to spatially analyse the whole surface of sports pitches, yet to date implementation remains rare for this purpose. Carrow et al. (2010) used a mobile sensor to measure and map volumetric water content of two sports pitches. Discrepancies in the uniformity of applied irrigation were identified, and this technique was presented as part of a ‘precision turfgrass management’ (PTM) concept, which has been undertaken more intensively on golf courses (Carrow et al., 2010; Krum et al., 2010). In terms of measuring mechanical behaviour, Miller (2004) used variograms and interpolation to assess impact hardness of two sports pitches (sand; native soil) with data collected from 80 locations across the surface. Seven and nine datasets were collected respectively on the sand and native soil pitches over a two year period, and spatial variation was determined as 50% greater in the native soil surface than the sand surface. Freeland et al. (2008) mapped surface compaction of an American football sports field by using ground-penetrating radar and interpolated impact hardness data from 77 test locations. Overlapped, concentrated areas of surface variation were identified with the two techniques in the study. Analysis of the identified spatial variation and evaluation of methodologies was brief in these studies, indicating further research is required in these areas.

This study used variograms and interpolation techniques to assess the spatial variation in mechanical properties for three sports pitches of different soil texture. Three datasets were collected on each pitch across the sporting season. Mechanical properties were assessed with the 2.25 kg CIST, the GoingStick and the Dynamic Surface Tester (DST) device. The study also aimed to evaluate the viability of these geostatistical techniques for use on sports pitches, and outline future recommendations for spatial assessment.

6.2 METHODOLOGY

6.2.1 Sports Surfaces

Three sports pitches were selected for the study, representing a range of ability levels and soil textures (Table 6-1). Pitch A is used by University and community level football teams (and corresponds to pitch D-MP in Chapter 5); Pitch B is used by a professional rugby union team in the second tier of the English rugby union pyramid (and corresponds to Pitch C-MP in Chapter 5); Pitch C is used by a professional football team in the second tier of the English football pyramid (and corresponds to Pitch B-MP in Chapter 5). All pitches were used for the home matches of each sports club. Pitch A is managed on a native clay-dominated soil, Pitch B is a sand ameliorated surface overlying a native clay loam soil, Pitch C is an engineered sand rootzone overlying a drainage system. Soil particle size distribution was determined using the pipette method (BS7755-5.4:1998) at 15 locations across the pitches (Figure 6-1). Samples were analysed at two depths: 0-50 mm, where players interact with the surface (Dixon et al., 2008), and 200-300 mm to determine whether soil properties below the player-surface interaction profile could influence surface hydrology. For Pitches A and C, particle size distribution was similar at both depths but on Pitch B, regular dressings of sand have been applied over a number of years, providing a soil texture in the top 50 mm that is greater in sand content than that of the native soil at 200-300 mm depth (Table 6-1). This layering was not present on Pitch A due to the minimal maintenance that is performed, and on Pitch C due to the surface being an engineered rootzone layered uniformly with a high ratio of sand. As previously considered in Appendix 11.5, the pitches were considered to provide a good representation of the soil texture/surface construction, maintenance intensities, and sporting levels that are evident at natural turf sports facilities in the UK.

Table 6-1 Mean soil textures of the three pitches assessed in the study at 0-50 mm and 200-300 mm rootzone depths (n = 15); dimensions of the three pitches.

	Sand (%)	**Silt (%)**	**Clay (%)**	**Classification**	**Pitch Length (m)**	**Pitch Width (m)**
Pitch A						
0-50 mm depth	37	29	34	Clay Loam	91.1	57.5
200-300 mm depth	36	28	36	Clay		
Pitch B						
0-50 mm depth	82	8	10	Loamy Sand	115.2	68.6
200-300 mm depth	45	29	26	Clay Loam		
Pitch C						
0-50 mm depth	95	3	2	Sand	100	67.7
200-300 mm depth	95	2	3	Sand		

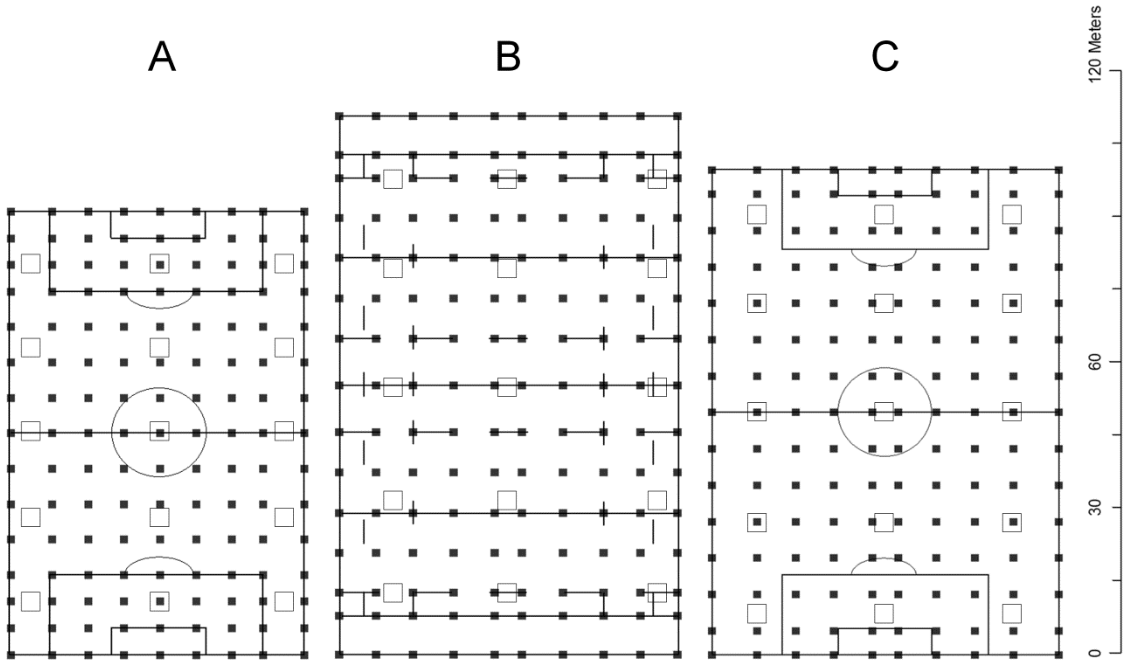

Figure 6-1 Scale drawings indicating the layout of test locations at pitches A, B, and C (dimensions presented in Table 6-1): soil texture (hollow markers); mechanical parameters and volumetric soil water content (solid markers).

6.2.2 Surface Testing

The surfaces of the sports pitches were tested three times across the sporting season (Table 6-2). Dates were chosen to represent the beginning (1), mid (2), and end of the sporting seasons (3), which run from August to May. A range of mechanical surface parameters and soil volumetric water content were assessed using a high resolution 135 (Pitch A) or 150 (Pitches B and C) node grid strategy across the pitches (Figure 6-1). The difference in grid node number reflects the difference in size between the pitches (Table 6-1).

Table 6-2 Dates of data collection on the three sports pitches, 1 = beginning of season; 2 = mid-season; 3 = end of season.

	Test Date		
Pitch	**1**	**2**	**3**
A	09/09/2010	06/01/2011	21/04/2011
B	15/09/2010	05/01/2011	12/05/2011
C	01/09/2010	11/01/2011	20/05/2011

Impact hardness of the surfaces was quantified with the 2.25 kg Clegg Impact Soil Tester (SDi Instrumentation Ltd., Bath, UK). The device consists of a 2.25 kg cylindrical missile (50 mm diameter, 295 mm length) containing an accelerometer. The missile is dropped from a height of 0.45 m onto the surface and impact hardness is quantified by the peak deceleration (g) of the missile after impact with the surface. Deceleration is dependent upon the stress-strain behaviour of the soil; larger values for peak deceleration indicate a harder surface (Clegg, 1980). The device is used within testing frameworks for natural turf, and data is often related to the potential impact attenuation athletes may receive on the surface (Bell and Holmes, 1988; American Society for Testing and Materials, 2000). The device was dropped three times onto the surface with the third drop used for data analysis, as per the manufacturer's guidelines.

The GoingStick (Dufour and Mumford, 2008) was used to determine surface penetration resistance and shear resistance. The device comprises a 100 mm long, flat steel tip that is pushed fully into the ground to determine peak surface penetration resistance, then pulled back along the plane of the tip to an angle of 45° to determine translational shear resistance of the surface. Shear resistance of sports pitches are typically quantified in terms of peak torque using the studded disc apparatus (Canaway and Bell, 1986). This apparatus was not used in this study, due to the magnitude of weight that is required to operate the device (40 kg), which was not practical to transport over the pitches to test at 150 locations. However, shear resistance data of the GoingStick have been shown to be linearly correlated ($r^2 = 0.88$) with peak torque resistance of the studded disc on a clay loam sports pitch (Caple et al., 2011b; Chapter 4).

The Dynamic Surface Tester (DST; Caple et al., 2011a) device was used to quantify the energy absorption of the surfaces. The device is a compressed-air driven vertical impact device, which has been developed to simulate the dynamic stress applied to the surface by athletes when running. During a test, a 100 mm stroke ram attached to a single-studded cylindrical (41 mm diameter, 38 mm height) test foot impacts and penetrates the surface. Testing terminates when the soil resistance brings the foot to rest. It follows that a greater value for energy absorption equates to a softer surface due to work done on the soil. For the study, the regulator pressure of the DST was set at 0.58 MPa, producing an impacting force of 677 N ± 13 on a reference styrene butadiene rubber shockpad (15mm thick) over concrete. This resulted in an actual vertical impact stress of 0.51 MPa, 91% of the mean stress value calculated for players running at 3.83 m s^{-1} (Guisasola, 2008). Impacts were made on the reference shockpad surface prior to each dataset to ensure impact force was consistent across test dates. Soil volumetric water content of the sports pitches was quantified using a soil water impedance probe (type ML2x, Delta-T Devices Ltd., Cambridge, UK). One reading for impact hardness, penetration resistance, shear resistance, surface energy absorption, and volumetric water content were collected per test location.

6.2.3 Statistical Analysis

Analysis of the pitch data was performed in three ways. Firstly, descriptive statistics were produced for each parameter to assess central tendency and variability. Frequency histograms were produced to determine the shape of the distribution, with transformation of data undertaken if skewness values exceeded -1 or 1 as recommended prior to spatial analysis (Webster and Oliver, 2007). Pearson correlation coefficients were determined across the mechanical behaviour and soil water content data. Within-pitch data were analysed for differences over time using one-way ANOVA and Fisher LSD ($P<0.05$). Data analysis was performed using Statistica 9 (Statsoft Inc., Tulsa, OK., USA).

Secondly, the spatial structure of data was assessed with variograms, which represent the relationship between lag distance (h) and half the variance of the difference between all pairs of measurements separated by h (Clark, 1979). 'Semi-variance' ($\gamma(h)$) is conventionally used to define this parameter, and the variogram for a set of data can be formulated using Equation 6.1 (Webster and Oliver, 2007). The lag distance is the spatial range over which pairs of locations are grouped to reduce the large number of possible combinations among data points. If a grid survey is used then it is common to use grid spacing as lag distance (Isaaks and Srivastava, 1989).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \tag{6.1}$$

where $N(h)$ is the number of pairs of data separated by lag h, and z is the value of a given property at location x_i. A generalised variogram model is shown in Figure 6-2, illustrating the important components which describe the characteristics of spatial variation. The nugget (C_o) describes the value at which the model intercepts the y axis and theoretically represents variation that occurs over distances less than the shortest sampling interval, and/or potential error in sampling. The sill ($C + C_o$) represents the total variance of the dataset, and the range (A_o) the finite lag distance where spatial dependency occurs.

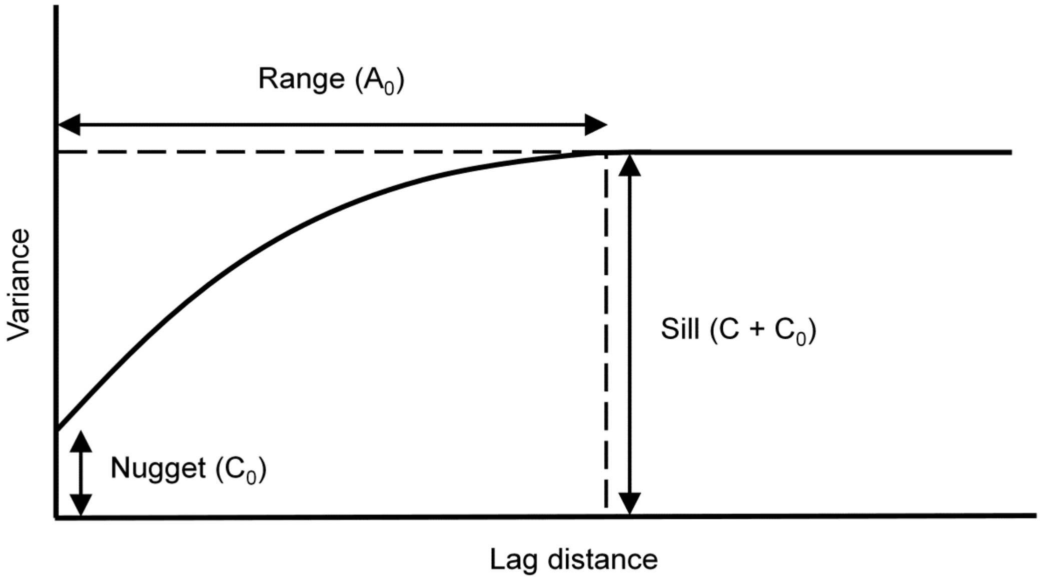

Figure 6-2 A generalised variogram (spherical model) showing important model parameters: nugget (C_o), sill ($C + C_o$), and range (A_o).

Variograms for the measured parameters were plotted in VESPER (v1.6; Australian Centre for Precision Agriculture). The shape of the plotted variogram determines whether data is spatially dependent, i.e. semi-variance is a function of distance (Figure 6-2). In this study, if data fitted this criterion, models were fitted using the weighted least squares approach (Jian et al., 1996). The VESPER software selects an appropriate model of the best fit of ɣ to h data, based on the smallest sum of square error. Root mean square error values (RMSE) for the models are produced by the software to quantify the fit of the model. Several models can be fitted to describe variograms; the model that fitted the experimental variograms in this study was the spherical model (Figure 6-2), considered the most commonly used model for describing spatial data (Isaaks and Srivastava, 1989). This model exhibits linear behaviour at small distances near the origin and converges to the sill, with the variogram calculated by:

$$\gamma(h) = \left\{ \begin{array}{ll} 0, & h = 0 \\ C_o + (C - C_o)\left\{\frac{3h}{2A_o} - \frac{1}{2}\left(\frac{h}{A_o}\right)^3\right\}, & 0 \leq h \leq r \\ C_o + (C - C_o), & h \geq r \end{array} \right\} \tag{6.2}$$

where C_o is the nugget ($C_o \geq 0$), C is the sill ($C \geq C_o$), A_o is the range ($A_o \geq 0$), and h is the lag as in Equation 6.1 (Clark, 1979; Webster and Oliver, 2007). Physical parameters conforming to these bounded models typically exhibit transition features that have a common extent, appearing as patches, with the mean diameter of these patches representing the range of the model (Webster and Oliver, 2007). Variograms typically decompose when the maximum lag interval is approached, where the number of pairs of data and reliability in the data decreases (Clark, 1979). Lag distances of the variograms were therefore limited to 70 m, 90 m and 80 m for Pitches A, B and C. These distances accounted for 77% 78% and 80% of the maximum pitch length distance respectively (Table 6-1).

The third stage of analysis was plotting of surface maps of the data, allowing for visual assessment of the measured parameters. For data exhibiting spatial dependency, semi-variogram model parameters (nugget, partial sill, range) were used to produce surface maps using the ordinary kriging interpolation method. This method generates unbiased predictions of unsampled locations using the spatial variability obtained from the variogram model (Isaaks and Srivastava, 1989). For data not exhibiting spatial dependency, surface maps were produced using the inverse distance weighting (IDW) interpolation. This technique calculates weighted averages of known sampled data values to predict unsampled locations, with sampled data that is closer to the unsampled location having more influence on values than those further away (Webster and Oliver, 2007). Surface maps were produced using ArcMap 10 software (ESRI, Redlands, CA, USA).

6.3 RESULTS

6.3.1 Descriptive Statistics

A comparison of mean data across the season (Table 6-3) showed that the pitches exhibited temporal variations in their mechanical properties. The test devices all quantify the resistance of the surface to deformation, albeit in different forms. It has been shown that natural turf surfaces are more resistant to deformation when values of penetration resistance, shear resistance, and impact hardness are higher; energy absorption is lower (Caple et al., 2011a,b,c). The pitches generally exhibited an inverse relationship between resistance to deformation and water content – lowest in the mid-season dataset coupled with the highest soil water content for all pitches ($P<0.05$). In a number of instances for Pitches A and B, resistance to deformation was highest in the end of the season dataset coupled with the lowest soil water content ($P<0.05$). Comparison among the pitches showed that the impact behaviour (quantified by peak deceleration and surface energy absorption) of Pitch C varied less in magnitude over time than on Pitches A and B, although mean values were statistically different ($P<0.05$) between test dates. This trend was not evident for quasi-static parameters measured with the GoingStick, as mean values of penetration resistance and shear resistance of Pitch C were shown to vary in similar magnitude to Pitches A and B across the season (Table 6-3). This indicates a strain rate sensitivity of soil behaviour, which has previously been considered in Chapters 3, 4, and 5.

Table 6-3 Descriptive statistics of soil water content and mechanical properties from the three pitches (A, B, C) at three times across the season (1 = beginning of season; 2 = mid-season; 3 = end of season; test dates outlined in Table 6-1). SE = standard error; min. = minimum value; max. = maximum value; int. range = interquartile range; CoV = coefficient of variation. Letters indicate homogenous groups within-pitches tested with one-way ANOVA and Fisher LSD ($P<0.05$).

	Pitch A					**Pitch B**					**Pitch C**				
	Mean (± SE Mean)	**Min.**	**Max.**	**Int. Range**	**CoV**	**Mean (± SE Mean)**	**Min.**	**Max.**	**Int. Range**	**CoV**	**Mean (± SE Mean)**	**Min.**	**Max.**	**Int. Range**	**CoV**
Vol. Soil Water Content (%)															
1	36.3 ± 0.2a	27.8	42.2	2.3	0.06	25.7 ± 0.3a	10.3	40.9	5.7	0.16	18.3 ± 0.2a	12.8	26.3	3.3	0.13
2	45.9 ± 0.2b	39.9	52.1	3.6	0.06	35.5 ± 0.3b	25.7	48.5	4.9	0.11	28.4 ± 0.2b	21.1	34.4	3.5	0.09
3	18.1 ± 0.3c	10.6	24.8	6.3	0.21	12.7 ± 0.3c	7.7	23.5	5.3	0.26	19.4 ± 0.4c	10.1	30.1	6.4	0.22
Penetration Resistance (MPa)															
1	10.2 ± 0.1a	5.5	14.6	2.1	0.16	9.2 ± 0.1a	7.0	11.8	1.2	0.10	11.6 ± 0.1a	8.9	15.7	1.4	0.09
2	8.0 ± 0.1b	5.0	11.9	2.1	0.17	7.1 ± 0.1b	4.4	9.2	1.1	0.14	9.1 ± 0.1b	6.8	12.4	1.5	0.13
3	15.6 ± 0.1c	10.8	17.4	1.7	0.09	15.5 ± 0.1c	9.9	17.5	2.2	0.10	16.5 ± 0.1c	13.1	17.5	1.1	0.06
Shear Resistance (Nm)															
1	41.1 ± 0.6a	25.4	52.3	9.3	0.16	23.1 ± 0.3a	9.5	33.2	4.1	0.16	12.7 ± 0.2a	8	19.3	4.1	0.20
2	30.4 ± 0.3b	18.8	40.4	5.1	0.13	22.6 ± 0.3a	14.9	33.2	4.1	0.15	12.7 ± 0.2a	5.7	17.2	3.8	0.19
3	48.7 ± 0.4c	27	52.7	5.7	0.10	36.5 ± 0.6b	17.2	52.8	11.3	0.20	30.9 ± 0.3b	16.7	41.4	5.1	0.13
Peak Deceleration (g)															
1	80 ± 1.0a	63	105	12	0.11	87 ± 1.0a	68	116	11	0.09	153 ± 1.0a	115	199	23	0.10
2	57 ± 0.6b	36	78	10	0.13	69 ± 1.0b	51	87	9	0.10	135 ± 1.0b	108	172	15	0.08
3	160 ± 2.0c	101	237	42	0.18	152 ± 2.0c	88	198	26	0.14	158 ± 2.0c	88	198	26	0.14
Surface Energy Absorption (kJ)															
1	1.32 ± 0.02a	0.75	2.20	0.35	0.21	1.21 ± 0.03a	0.74	4.75	0.36	0.35	0.62 ± 0.01a	0.44	1.37	0.14	0.19
2	2.76 ± 0.12b	1.15	9.17	1.21	0.50	1.26 ± 0.07a	0.69	9.34	0.27	0.66	0.72 ± 0.01b	0.49	1.34	0.13	0.18
3	0.77 ± 0.02c	0.12	2.05	0.25	0.33	0.79 ± 0.02b	0.17	1.89	0.23	0.27	0.59 ± 0.02c	0.41	1.29	0.10	0.20

The descriptive statistics indicated that variation in the datasets was high. Large ranges and interquartile ranges of the mechanical properties and soil water content were evident on a number of occasions in the datasets. These instances were more prevalent in Pitches A and B, in particular: surface energy absorption in the mid-season datasets on both pitches, shear resistance in the beginning of season dataset on Pitch A and end of season dataset on Pitch B, and peak deceleration on Pitch A in the end of season dataset (Table 6-3). The coefficient of variation (CoV) was typically higher for surface energy absorption measured with the DST than for penetration resistance, shear resistance, and peak deceleration (Table 6-3).

6.3.2 Analysis of Spatial Dependence

Two distinct variogram shapes were produced from the pitch data (Figure 6-3). Peak deceleration measured with the CIST (drop three) was the only surface parameter that portrayed spatial dependence on the three pitches over the three datasets, and typically took the shape of the variogram on the left in Figure 6-3. The other mechanical properties measured (penetration resistance, shear resistance, and energy absorption) and volumetric soil water content were not spatially dependent across all three test dates. Variograms of these data exhibited constant variance with distance (‘pure nugget’ variation), indicated in the variogram on the right of Figure 6-3. All of the variograms produced from the analysis (54) can be viewed in Appendix 11.6.

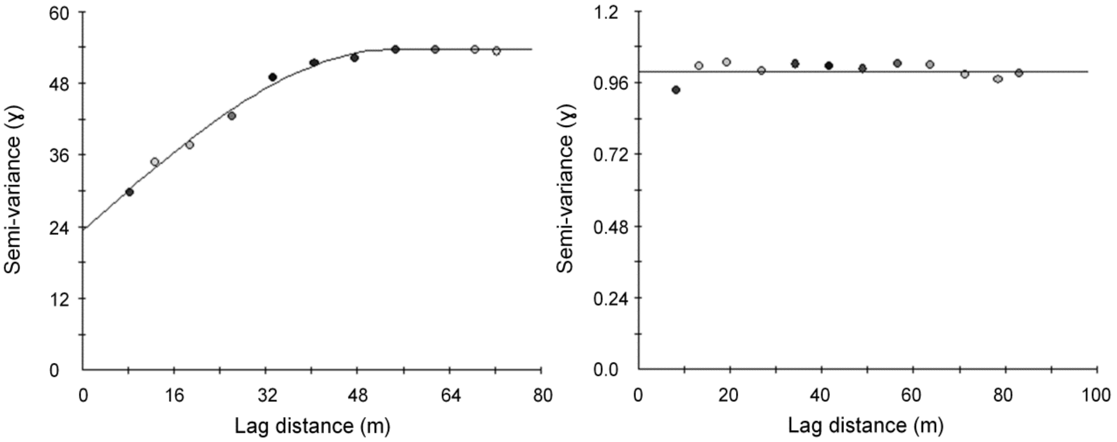

Figure 6-3 Examples of the two variograms shapes produced from the spatial data. Left: A variogram fitted with the spherical model on the CIST data (Pitch B, dataset 2); Right: A variogram exhibiting pure nugget variation, typical of data collected for penetration resistance, shear resistance, surface energy absorption, and soil volumetric moisture content (penetration resistance; Pitch B, dataset 2). Lag distances limited to 90 m (from a maximum of 130 m), due to the typical decomposition that occurs on variograms when the maximum lag interval is approached.

The nature of the spatial dependency detected with the CIST is indicated by the geostatistical parameters in Table 6-4. The nugget and sill values differ in magnitude over time and across pitches, and due to this it is common to use the nugget/sill ratio of the datasets to assess the strength of the spatial dependence. Using the Cambardella et al., (1994) ratios (<25% indicates strong spatial dependence, 25% to 75% indicates moderate spatial dependence, and >75% indicates weak spatial dependence), peak deceleration was strongly spatially dependent for the beginning and end of season datasets on Pitch A, and for the end of season datasets on Pitches B and C. Inspection of the range/lag distance ratio indicated that the range of spatial dependence did not bridge the entire lag distance in all datasets on Pitches A and B and for the end of season dataset on Pitch C, indicating localised spatial dependency of impact hardness within the pitches. For the beginning and mid-season datasets on Pitch C, the high ratio indicated long range spatial dependency across the whole surface of the pitch. The range of spatial dependence was consistently greater on Pitch C throughout the season (Table 6-4).

Table 6-4 Geostatistical model details and parameters, produced for the CIST data collected on the three pitches (A, B, and C) at three times over the season 1 = beginning; 2 = mid; 3 = end.

	Model	Nugget	Sill	Range (m)	Range/Lag Distance (%)	Nugget/Sill (%)	RMSE
Pitch A							
1	Spherical	11	101	50	71	11	2.6
2	Spherical	27	57	31	44	47	1.1
3	Spherical	127	930	42	60	14	19.2
Pitch B							
1	Spherical	32	83	40	44	39	4.3
2	Spherical	23	54	54	60	43	0.7
3	Spherical	81	405	26	29	20	21.4
Pitch C							
1	Spherical	110	298	77	96	37	5.5
2	Spherical	85	188	79	99	45	7.9
3	Spherical	57	245	45	50	23	7.3

6.3.3 Surface Maps

Kriged surface maps of CIST data are shown in Figure 6-4; IDW interpolated maps of the remaining parameters are shown in Figures 6-5 – 6-8. Map intervals for the parameters were selected to be of equal quantity and to allow incorporation of the whole range of data collected on the surfaces for each particular unit. A maximum of eight intervals was selected to comply with peer-reviewed journal guidelines. IDW does not have a smoothing function or estimation of error like kriging interpolation, causing maps to exhibit ‘spots’ of data that are evident in the maps. Some concentrated areas of spatially correlated data were evident in central areas of the pitches on some of the kriged surface maps (e.g. Figure 6-4 A3, B1, B2, C3). The IDW maps indicated that the distribution of variation in surface behaviour was predominantly random (Figures 6-5 – 6-8). Inspection of the surface maps indicated that the extent of the spatial variation occurring within the pitches for the mechanical properties and soil water content was shown to be similar to the variation that occurred on these surfaces temporally (Figures 6-4 – 6-8).

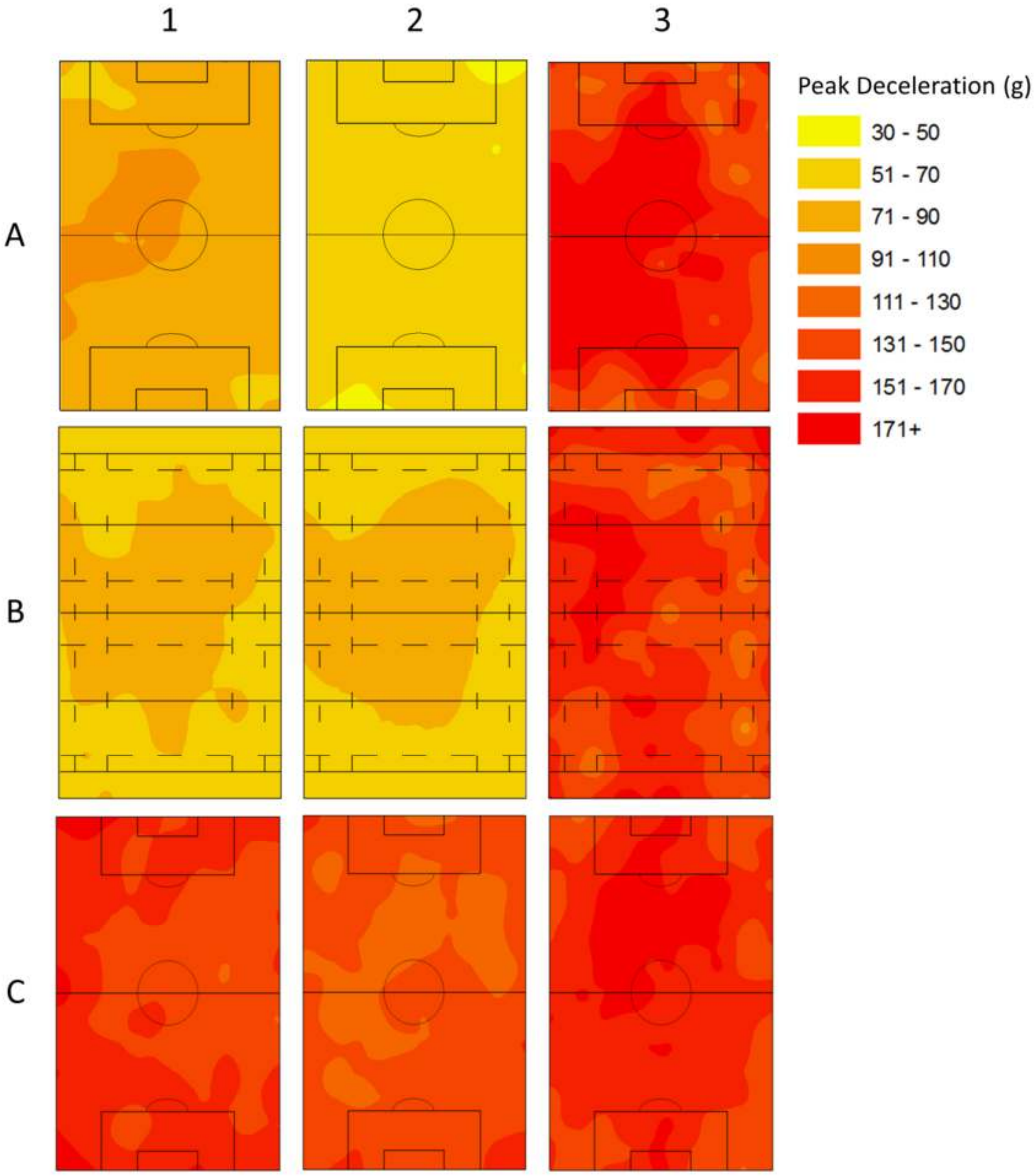

Figure 6-4 Kriging interpolation surface maps of peak deceleration measured with the CIST from the three pitches (A, B, and C) at three times across the season (1 = beginning of season, 2 = mid-season, 3 = end of season). See Table 6-2 for pitch dimensions.

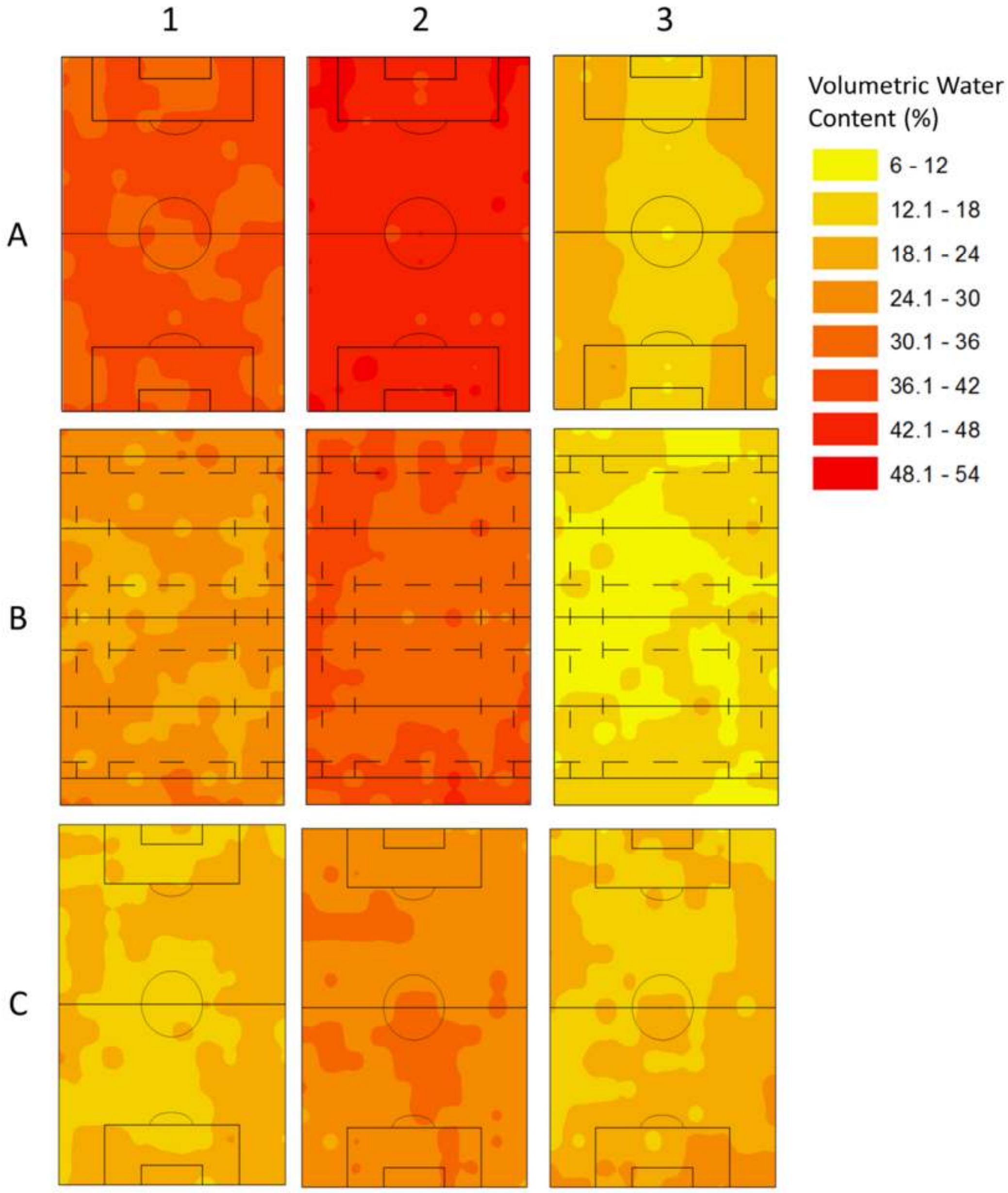

Figure 6-5 Inverse Distance Weighting (IDW) interpolation surface maps of soil volumetric water content measured with a soil water impedance probe from the three pitches (A, B, and C) at three times across the season (1 = beginning of season, 2 = mid-season, 3 = end of season). See Table 6-2 for pitch dimensions.

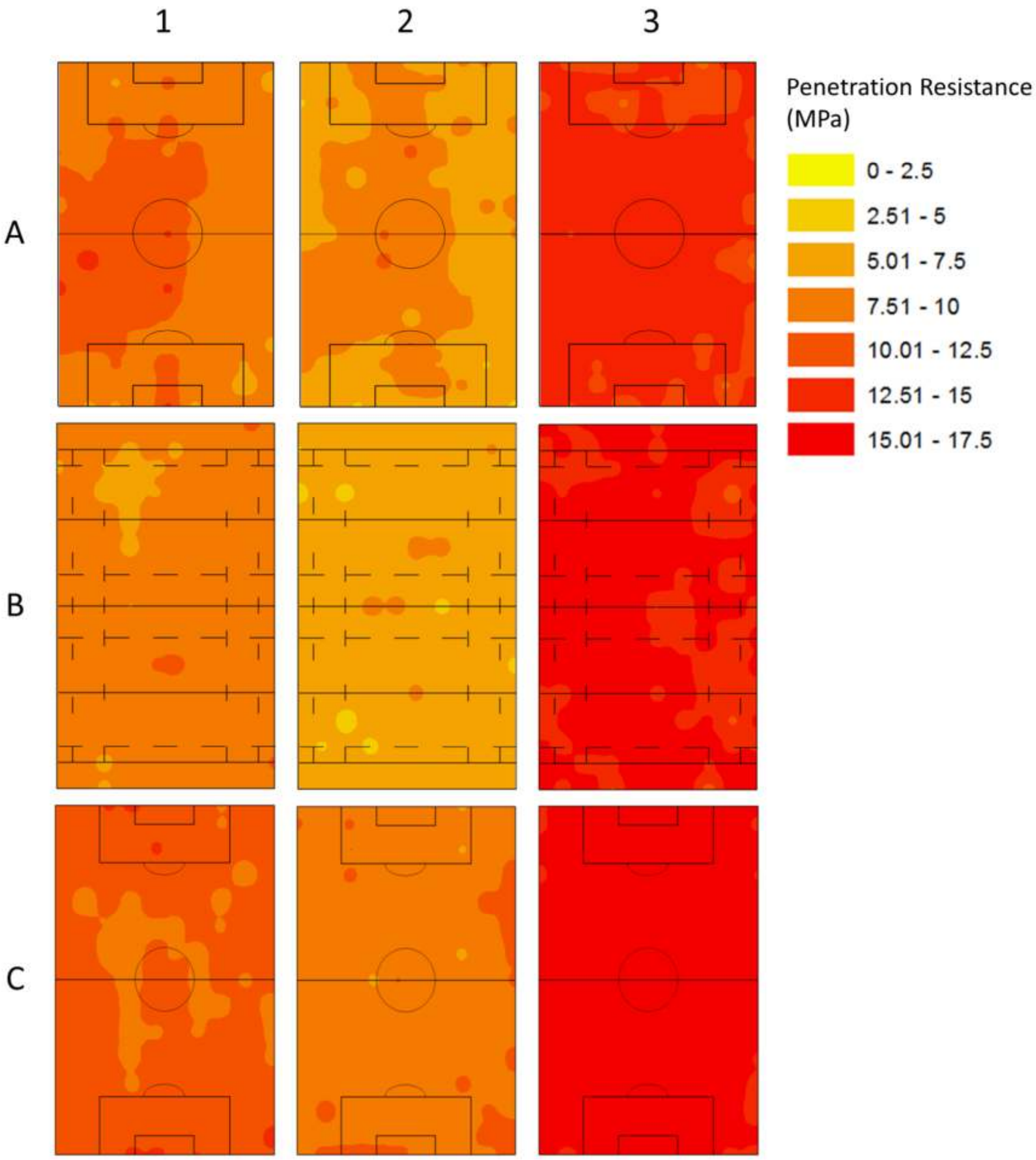

Figure 6-6 Inverse Distance Weighting (IDW) interpolation surface maps of penetration resistance measured with the GoingStick from the three pitches (A, B, and C) at three times across the season (1 = beginning of season, 2 = mid-season, 3 = end of season). See Table 6-2 for pitch dimensions.

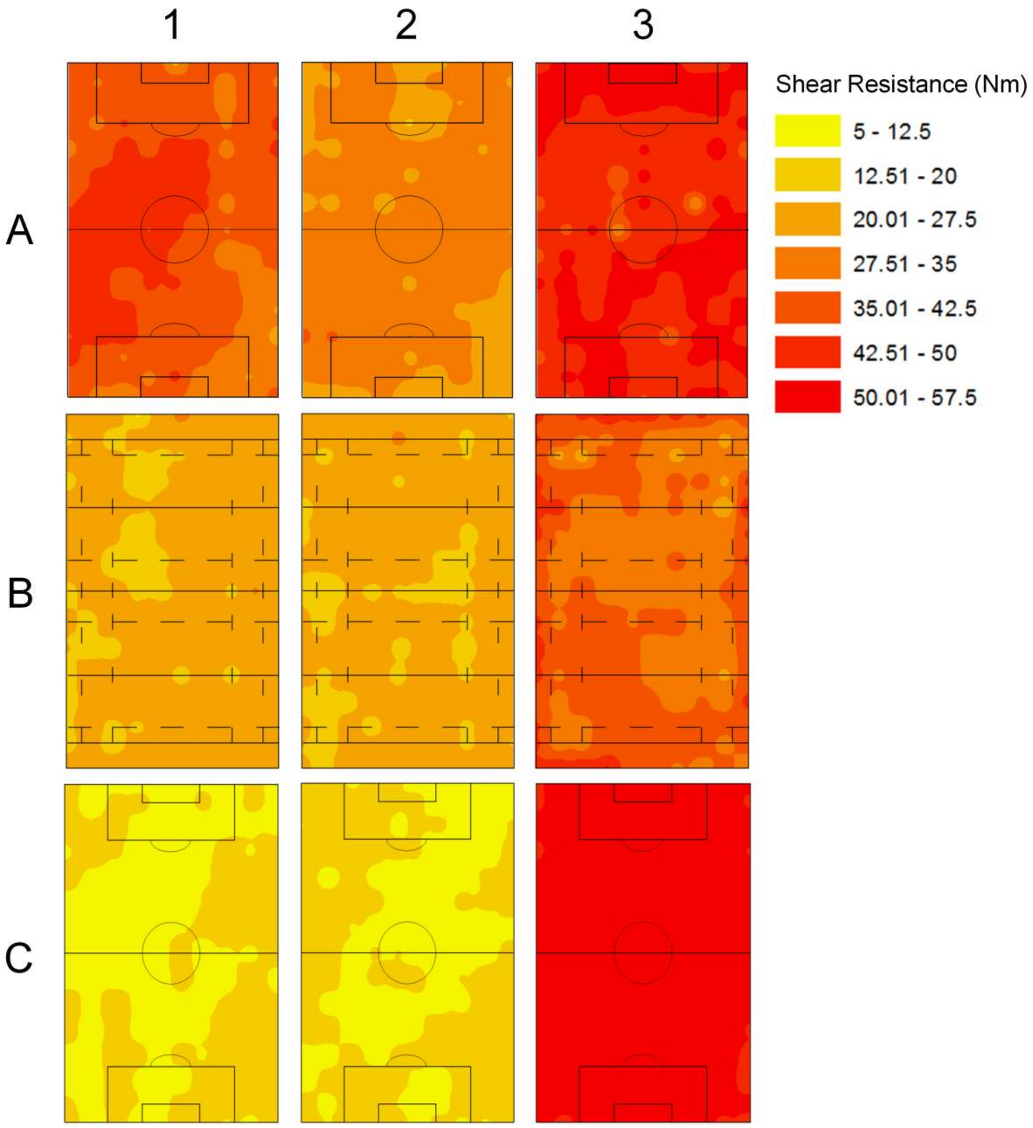

Figure 6-7 Inverse Distance Weighting (IDW) interpolation surface maps of shear resistance measured with the GoingStick from the three pitches (A, B, and C) at three times across the season (1 = beginning of season, 2 = mid-season, 3 = end of season). See Table 6-2 for pitch dimensions.

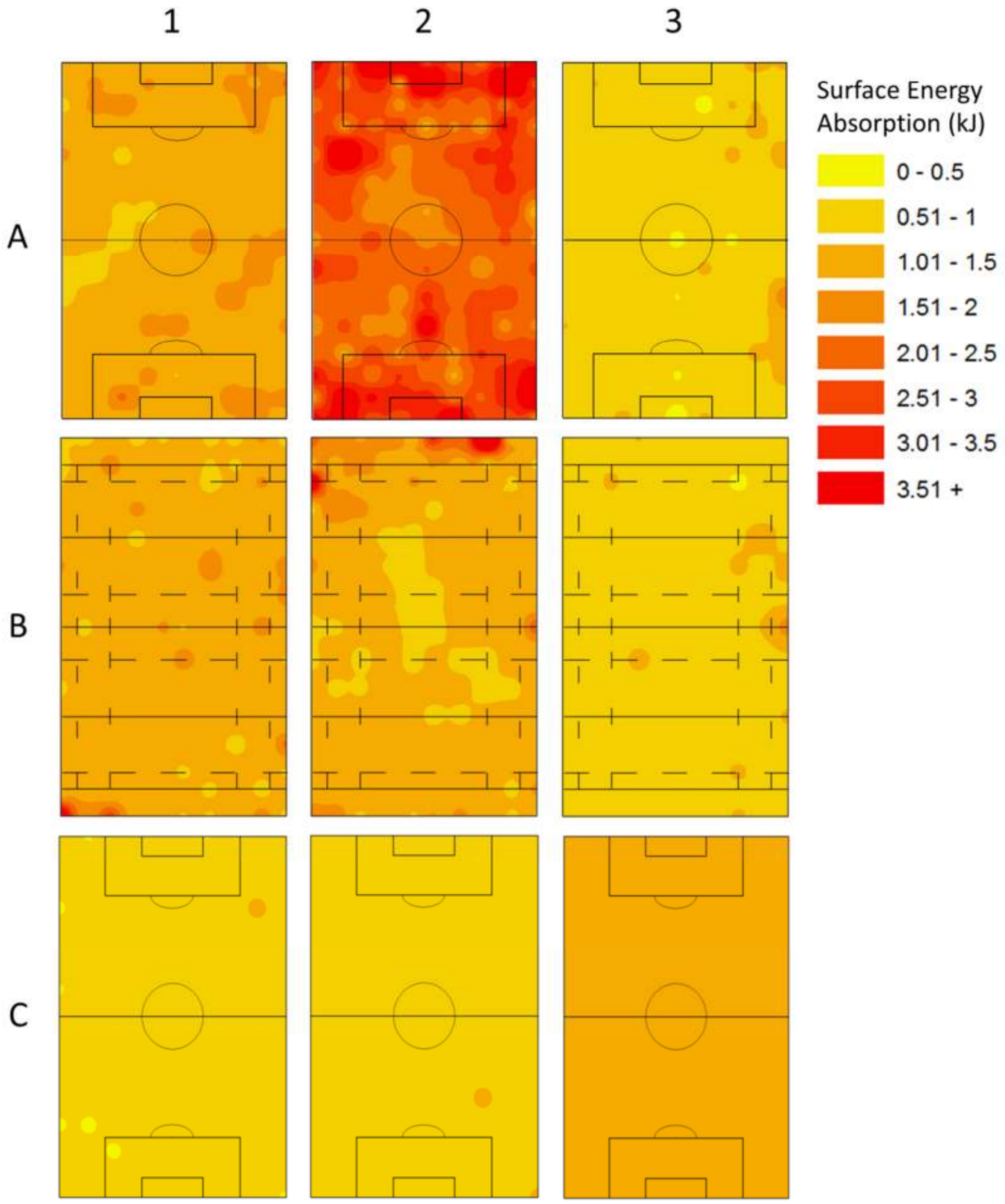

Figure 6-8 Inverse Distance Weighting (IDW) interpolation surface maps of surface energy absorption measured with the DST from the three pitches (A, B, and C) at three times across the season (1 = beginning of season, 2 = mid-season, 3 = end of season). See Table 6-2 for pitch dimensions.

6.4 DISCUSSION

Geostatistical theory dictates that pure nugget variograms determine a lack of spatial structure and that random variation dominates for the measured parameter (Webster and Oliver, 2007). This was confirmed with inspection of the IDW surface maps for these parameters. Pure nugget variation can be an indicator that the distance between sampling intervals is too large, with the scale of spatial dependency being evident in ranges less than the shortest sampling intervals (Isaaks and Srivastava, 1989). This was not considered applicable for these data, as the sampling scheme was considered to provide data to a high resolution, which aimed to detect variation at a small range (<10 m). However, it is acknowledged that variation can occur on pitches at even smaller ranges i.e. surface wear due to player or machinery entry points, but detecting this variation would require sampling at ~1 m intervals.

The mechanical properties quantified on the pitches provide different measurements of the resistance to deformation of the surface. Correlation coefficients between data from the testing devices was low ($r = 0.01$ to 0.64; $r = -0.03$ to -0.42), indicating the mechanical behaviour of the pitch at each test location was not ranked consistently across devices. This further emphasises the random variation that was detected on the pitches. Intuition suggests that spatial dependence of surface mechanical behaviour, if present, would be detected with all the devices. The function of the CIST device may explain this discrepancy: three consecutive drops are performed with the missile, with drop three data used for surface classification. Analysis of drop one data from the CIST (Appendix 11.6) indicated pure nugget variation. The correlation evident for the third drop data is attributed to the first two drops of the missile conditioning the surface (compacting or deforming), producing similar stress histories across the pitch and resulting in data being related. This effect has been considered, particularly the effect of the first two drops in flattening the grass leaves (Caple et al*,* 2011c).

Despite the perceived contribution of stress-history to the spatial dependency detected with the CIST, the range of spatial dependency did not bridge lag distance for all datasets on Pitches A and B, and in the end of season dataset on Pitch C. As sports pitches are managed consistently across the surface, this indicates that localised spatial dependency was detected with the device, and some conclusions can be drawn from the data. Strong spatial dependency (Cambardella et al., 1994) evident in the end of season datasets suggested this effect could be attributed to the effects of accumulated wear from play, previously hypothesised by Miller (2004). This spatial dependency also occurs within the smallest ranges throughout the season on Pitches B and C, emphasising the potential for concentrated spatially dependent areas of the surface. These effects can be seen visually in Figure 6-4 A3, B3, and C3. Strongly spatially dependent data were evident at the beginning of the season on Pitch A, and this may be explained by the low level of maintenance that is performed on this surface: well-maintained sports pitches in professional sport have extensive maintenance work performed (i.e. aeration, sand dressing) between seasons to relieve the effects of sporting wear, which were not performed on this pitch.

There was evidence in the descriptive statistics data to suggest that the engineered sand rootzone pitch (C) was more consistent temporally and spatially: the impact behaviour of the pitch did not vary as much over the season and had fewer instances of extreme values and large data spreads in comparison to Pitches A and B; the surface exhibited long range spatial dependency in the beginning and end of season datasets. Engineered sand rootzones overlying drainage systems are commonly selected for use in sports pitches at the elite level due to greater temporal consistency in their mechanical behaviour (Caple et al., 2011b). This consistency can be explained by sand soils exhibiting greater infiltration rates, greater resilient modulus, and shear strength that is less sensitive to changes in water content in comparison to soils containing greater proportions of clay (Gibbs and Baker, 1989; Guisasola et al., 2010a,b). During winter months in the UK when rainfall is higher than evapotranspiration (ET) levels, soil water content of clay soils increases because of the higher water retention of clay soils (Hillel, 1998), and strength reduces. This contributes to the greater temporal and spatial variations that have been shown on these sports surfaces (Holmes and Bell, 1986; Baker, 1991; Miller, 2004). Lower water retention of sand soils results in supplementary irrigation requirements to prevent the soil becoming too dry and losing strength; irrigation was applied on both the sandy pitches (B and C) in drier periods of the season when required. It was not possible to accurately quantify the inputs (irrigation, rainfall) and losses (ET, drainage) of water on the pitches in the study, but this aspect should be considered in future studies of temporal surface mechanical behaviour. Although a high ratio of sand (82%) was evident at the surface level (0-50 mm) in Pitch B, the pitch exhibited temporal variation in a similar magnitude to Pitch A, a clay loam soil. Water infiltration at the surface is high for this pitch, but greater ratios of clay at depth (200-300 mm) in the profile produces slower hydraulic conductivity, saturating the sand-ameliorated soil at the surface, and reducing the surface strength of the pitch.

Athlete performance and injury risks are considered to be influenced by mechanical surface properties such as stiffness and traction (Lambson et al., 1996; Dura et al., 1999; Naunheim et al., 2002). In regards to spatial variation of mechanical surface properties, it has not been fully explored how athletes would respond to unpredicted surface variations when in locomotion, or the variation in injury risk that may be posed. This type of biomechanical experiment is restricted by ethical constraints, but variation in surface condition has been cited as an injury risk in horses due to the need for biomechanical adaptation during locomotion (Stover, 2003). Similarly, athletes have been shown to produce biomechanical adaptations in running style when encountering surfaces of different stiffness (Dixon et al., 2000; Dixon et al., 2005). Currently, evidence linking surface condition and injury is often circumstantial, and few studies have significantly linked the two (Dixon et al., 1999). It is therefore difficult to define variation in surface properties that would significantly alter the risk of injury or affect athlete locomotion, although data presented here provides an important reference for the range of spatial variation that can occur, which may be matched against player performance and injury occurrence in future integrated studies.

Efforts have been made to define injury tolerances to the human body. Head impact severity tolerances have been established in the automotive and playground manufacturing industries and have been transferred for use on sports surfaces (Shorten, 2003; Theobald et al., 2010). Traction devices have also recently been developed that better replicate high injury risk situations, in order for safe limits of traction forces to be identified (Villwock et al., 2009; Grund and Senner, 2010). Due to their sophisticated designs, these types of devices are often cumbersome, lack portability, and are often built as ‘one-offs’, meaning it would not be feasible to collect data on a scale presented in this study. The devices used in the study were selected on the basis of portability and provision of a wide range of surface properties, epitomised by the use of the GoingStick over the more commonly used studded disc apparatus. Penetration resistance is also provided by the GoingStick, which has been quantified in numerous sports surface studies - most notably in the assessment of surface condition to injury rates (Orchard, 2001; Takemura et al., 2007). The CIST and GoingStick should be regarded as providing generic values of surface mechanical behaviour, as their functions do not replicate athlete-surface interactions (Nigg, 1990; Young and Fleming, 2007). Despite this, boot-surface traction is dependent upon turf shear resistance (Canaway and Bell, 1986) and the random variation detected for this parameter with the GoingStick suggests traction for athletes may also vary randomly across the surface.

The PQS natural turf framework and FIFA test standards for artificial surfaces (one star), stipulate that minimum torque values when using the studded disc apparatus should be 20 Nm and 25 Nm respectively (Bell and Holmes, 1988; FIFA, 2009a,b). Using the conversion factor of 0.8133 found between the GoingStick and studded disc apparatus (Caple et al., 2011b), minimum data values from the datasets only met the PQS benchmark in the beginning and end of season datasets on Pitch A, and values in the other datasets were below both minimum limits. Maximum values in the data did not exceed the 50 Nm value outlined by FIFA. Minimum values of impact hardness of the pitches were above the lower ‘acceptable’ benchmark values for football and rugby pitches (35 g and 30 g) outlined in the PQS framework (Baker et al., 2007). Maximum benchmark limits (120 g and 110 g) were exceeded by maximum values from 6 of the 9 datasets (Table 6-3). These findings highlights that the characterisation of the playing quality of the surface is dependent upon the location of the test performed. It must be noted that these surface standards are not based upon injury or performance risk associated to athlete-surface interaction, but rather upon player perceptions in the 1980s (Bell and Holmes, 1988), and may be obsolete for characterisation of modern sports pitches.

The DST device was used within the study as it is considered to be more biomechanically valid in its application of impact stresses and duration than the CIST device (Caple et al., 2011c), and is portable. A disadvantage of the device is that it is currently a prototype, limiting the quantity of data collected with the device to date. The large data ranges evident for surface energy absorption, additional to the random variation of this property, indicates the impact attenuation that athletes may receive when running on the surface could vary on a small spatial scale. Coefficients of variation measured with DST were high for the pitches, in comparison to coefficients in the range of 0 - 0.02 on the standardised rubber mat tested prior to data collection. Higher coefficients for the DST in comparison to the CIST and GoingStick data suggest the device may be more sensitive to detecting changes in surface condition. This aspect requires further exploration.

6.5 FUTURE SPATIAL ASSESSMENT OF SPORTS PITCHES

Geostatistical analysis provides the opportunity to comprehensively assess spatial variation of sports pitches: variograms allow statistical analysis of spatial dependency, and interpolation provides visual assessment of variation. The surface maps allowed the random variation and temporal variation of mechanical behaviour to be identified within this study. Some concentrated weaker and stronger areas of the pitches could be identified in the maps i.e. harder central areas of the three pitches in the end of season data sets measured with the CIST (Figure 6-4). By eye it is perhaps tempting to correlate these harder areas to drier areas identified in the IDW interpolation maps for soil water content (Figure 6-5) but correlation coefficients for these datasets were only in the range $r = -0.1$ to -0.33. Care must be exercised when using surface maps to assess spatial variation of sports surfaces, as the selection of the parameter intervals can significantly alter the appearance of the map; it is essential that descriptive statistics and geostatistical parameters of datasets are used to inform interpolation and interpretation of surface maps.

The presence of random variation in mechanical behaviour suggests that data could be collected at a lower resolution on the pitches to provide insight into the spatial variation of the surfaces. However, the results found here are specific to the pitches tested and for the time they were assessed, as spatial dependence may be detected at this testing resolution on other pitches or at other times of the year. At least 100 and ideally 150 locations are suggested for the reliable use of variograms (Webster and Oliver, 1992; Webster and Oliver, 2007), meaning studies assessing spatial structure of sports pitches should use a similar resolution of test locations that was used here. The time-consuming nature of sampling at this scale means that this type of methodology is largely restricted to research purposes and is not practical for grounds managers to undertake. To the author's knowledge, this is the highest density of locations used in the assessment of sports pitches. Previous studies have aimed to assess spatial variation (not spatial structure) of sports pitches by comparing data from a limited (3-12) amount of test locations (Baker and Bell, 1986; Holmes and Bell, 1986; Bell and Holmes, 1988; McClements and Baker, 1994). *In-situ* surface testing of synthetic sports fields by FIFA and the IRB also stipulates 6 test locations across the field (FIFA, 2009b; IRB, 2011). Studies assessing spatial variation to this scale have sampled in response to the perceived diamond pattern of wear from play that occurs on football pitches (Holmes and Bell, 1986). Sampling at a high resolution in this study determined random variation of mechanical behaviour, and it may be that the diamond wear pattern is valid for the cosmetic damage that occurs to the grass plant but not the mechanical behaviour of the surface. Pitches subjected to greater intensities of use should be assessed in future studies e.g. training pitches, which may indicate greater spatial dependency. It was not possible to quantify this variable on the pitches in this study, but communications with the grounds managers revealed playing hours were generally below the maximum use levels outlined for the different surface constructions by Baker and Gibbs (1989). Quantification of pitch use is suggested to be achieved through recording of hours of play and through the analysis of player movement patterns (Baker and Gibbs, 1989; Mohr et al., 2003; Andersson et al., 2008).

Work by Miller (2004) and Freeland et al. (2008) were the only previous studies to use geostatistical methods to characterise spatial structure of the mechanical behaviour of natural turf pitches, with only the CIST device used to quantify surface performance. It is therefore difficult to compare the findings of this study to previous work, in particular the determination of random variation on the pitches, which has not previously been considered in the literature. A more extensive number of pitches are required to be assessed in future research, as although efforts were made within this study to represent a range of soil textures and sporting levels, results cannot be extrapolated. Repetition should also be performed over a number of seasons, as surfaces may exhibit long term variation in their spatial structure. Synthetic turf sports surfaces are often used in locations where facilities are exposed to excessive climatic conditions or intensive use (Stiles et al., 2009). Previous studies indicated that mechanical behaviour of synthetic surfaces varies less spatially than natural turf (Baker and Bell, 1986; Kirby and Spells, 2006), and future work should use geostatistical analysis to compare the two surface types.

6.6 CONCLUSIONS

Variograms and interpolation were used to assess the spatial variation in mechanical behaviour of three sports pitches over a season of football/rugby union. With the exception of data collected with the CIST, the surfaces displayed random variation in mechanical behaviour, defined by pure nugget semi-variograms. The spatial dependence detected with the CIST was attributed to the comparative stress history applied by the first two drops of the missile. The engineered sand rootzone pitch was more consistent temporally for impact behaviour and data ranges were often smaller compared to the native soil pitches. This finding should be considered in further spatial analysis of sports pitches, as data from this study cannot be extrapolated to characterise other surfaces due to the number of intrinsic and extrinsic factors that contribute to mechanical behaviour. The random variation in the mechanical behaviour of the pitches should be placed in the context of surface performance applicable to athletes, as DST data suggests that the impact attenuation athletes receive will vary on a small spatial scale. Robust geostatistical techniques and methodologies are essential in future work on spatial variation of sports pitches.

6.7 ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from The Engineering and Physical Sciences Research Council (EPSRC) for this research, the sports clubs for allowing the study to be undertaken on the pitches, and David Bartlett for supplying and providing technical support for the DST.

6.8 REFERENCES

American Society for Testing and Materials (2000), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test for shock attenuation characteristics of natural playing surface systems using lightweight portable apparatus. F1702-96.* ASTM, West Conshohocken, PA.

Andersson, H., Ekblom, B. and Krustrup, P. (2008), Elite football on artificial turf versus natural grass: Movement patterns, technical standards, and player impressions, *Journal of Sports Sciences,* vol. 26, no. 2, pp. 113-122.

Baker, S. W. (1991), Temporal variation of selected mechanical properties of natural turf football pitches, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 83-92.

Baker, S. W. and Bell, M. J. (1986), The playing characteristics of natural turf and synthetic turf surfaces for association football, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 9-35.

Baker, S. W. and Gibbs, R. J. (1989), Levels of use and the playing quality of winter games pitches of different construction types: Case studies at Nottingham and Warrington, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 9-33.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F. and Konopka, A. E. (1994), Field-scale variability of soil properties in central Iowa soils, *Soil Science Society of America Journal,* vol. 58, no. 5, pp. 1501-1511.

Canaway, P. M. and Bell, M. J. (1986), An apparatus for measuring traction and friction on natural and artificial playing surfaces, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 211-214.

Caple, M. C. J., James, I. T., Bartlett, M. D. and Bartlett, D. I. (2011a), Development of a simplified dynamic testing device for turfed sports surfaces, *Journal of Sports Engineering and Technology,* vol. 225, pp. 103-109.

Caple, M. C. J., James, I. T., Bartlett, M. D. (2011b), Using the GoingStick to assess pitch quality. Submitted to *Journal of Sports Engineering and Technology.*

Caple, M. C. J., James, I. T., and Bartlett, M. D. (2011c), The effect of grass leaf height on the impact behaviour of natural turf sports field surfaces, *Sports Technology,* (Accepted)

Carrow, R. N., Krum, J. M., Flitcroft, I. and van Cline (2010), Precision turfgrass management: Challenges and field applications for mapping turfgrass soil and stress, *Precision Agriculture,* vol. 11, no. 2, pp. 115-134.

Chilés, J. P. and Delfiner, P. (1999), *Geostatistics: modeling spatial uncertainty,* John Wiley & Sons, Inc., New York.

Clark, I. (1979), *Practical Geostatistics,* Applied Science Publishers Ltd, Barking, England.

Clegg, B. (1976), An impact testing device for in situ base course evaluation, in: *Proceedings of the 8th ARRB Conference, vol. 8, no. 8*, Perth, Australia, pp. 1-6.

Clegg, B. (1980), Impact soil test as an alternative to California bearing ratio, in: *Proceedings of the Technical Association of the Pulp and Paper Industry,* vol. 1, pp. 225 - 230.

Dixon, S. J., Batt, M. E. and Collop, A. C. (1999), Artificial playing surfaces research: A review of medical, engineering and biomechanical aspects, *International Journal of Sports Medicine,* vol. 20, no. 4, pp. 209-218.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2000), Surface effects on ground reaction forces and lower extremity kinematics in running, *Medicine and science in sports and exercise,* vol. 32, no. 11, pp. 1919-1926.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2005), Compensatory adjustments in lower extremity kinematics in response to a reduced cushioning of the impact interface in heel-toe running, *Sports Engineering,* vol. 8, pp. 47-55.

Dixon, S. J., James, I. T., Blackburn, K., Pettican, N. and Low, D. (2008), Influence of footwear and soil density on loading within the shoe and soil surface during running, *Journal of Sports Engineering and Technology,* vol. 222, pp. 1-10.

Dufour, M. J. D. and Mumford, C. (2008a), The development and environmental applications of the Goingstick®, in: Fuss, F. K. Subic, A. and Ujihashi, S. (eds) *Impact of Technology on Sport II*; London: Taylor & Francis, pp. 149-154.

Dura, J. V., Hoyos, J. V. and Martinez, A. (1999), The effect of shock absorbing sports surfaces in jumping, *Sports Engineering,* vol. 2, no. 2, pp. 97-102.

Emery, X. and González, K. E. (2007), Incorporating the uncertainty in geological boundaries into mineral resources evaluation, *Journal of the Geological Society of India,* vol. 69, no. 1, pp. 29-38.

FIFA (2009a), *FIFA quality concept for football turf. Handbook of requirements.* FIFA, Geneva.

FIFA (2009b), *FIFA Quality Concept for Football Turf. Handbook of Test Methods,* FIFA, Geneva.

Freeland, R. S., Sorochan, J. C., Goddard, M. J. and McElroy, J. S. (2008), Using ground-penetrating radar to evaluate soil compaction of athletic turfgrass fields, *Applied Engineering in Agriculture,* vol. 24, no. 4, pp. 509-514.

Gibbs, R. J. and Baker, S. W. (1989), Soil physical properties of winter games pitches of different construction types: case studies at Nottingham and Warrington, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 34-54.

Grund, T. and Senner, V. (2010), Traction behavior of soccer shoe stud designs under different game-relevant loading conditions, in: *Proceedings of the 8th Conference of the International Sports Engineering Association,* Vol. 2, 12 - 16 July 2010, Vienna, pp. 2783-2783.

Guisasola, I. (2008), *Human-natural sports surface interaction* (unpublished PhD thesis), Cranfield University, .

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010a), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010b), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Hillel, D. (1998), *Environmental Soil Physics,* Academic Press, San Diego, CA.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

IRB (2011), *IRB Artificial rugby turf performance specification,* IRB, Dublin.

Isaaks, E. H. and Srivastava, R. M. (1989), *An Introduction to Applied Geostatistics,* Oxford University Press Inc., New York.

James, I. T. and Godwin, R. J. (2003), Soil, water and yield relationships in developing strategies for the precision application of nitrogen fertiliser to winter barley, *Biosystems Engineering,* vol. 84, no. 4, pp. 467-480.

Jian, X., Olea, R. A. and Yu, Y. -. (1996), Semivariogram modeling by weighted least squares, *Computers and Geosciences,* vol. 22, no. 4, pp. 387-397.

Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G. and Herr, H. M. (2002), Energetics and mechanics of human running on surfaces of different stiffnesses, *Journal of applied physiology,* vol. 92, no. 2, pp. 469-478.

Kirby, A. and Spells, S. J. (2006), Spatial characterisation of natural and third-generation artificial turf football pitches, *Sports Engineering,* vol. 9, pp. 59-64.

Krum, J. M., Carrow, R. N. and Karnok, K. (2010), Spatial mapping of complex turfgrass sites: Site-specific management units and protocols, *Crop Science,* vol. 50, no. 1, pp. 301-315.

Lambson, R. B., Barnhill, B. S. and Higgins, R. W. (1996), Football cleat design and its effect on anterior cruciate ligament injuries: A three-year prospective study, *American Journal of Sports Medicine,* vol. 24, no. 2, pp. 155-159.

Li, D., Minner, D. D. and Christians, N. E. (2009), Evaluation of factors contributing to surface stability of sand-based turf, *Agronomy Journal,* vol. 101, no. 5, pp. 1160-1167.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

McMahon, T. A. and Greene, P. R. (1979), The influence of track compliance on running, *Journal of Biomechanics,* vol. 12, no. 12, pp. 893-904.

Meyers, M. C. (2010), Incidence, mechanisms, and severity of game-related college football injuries on FieldTurf versus natural grass: a 3-year prospective study, *The American Journal of Sports Medicine,* vol. 38, no. 4, pp. 687-697.

Miller, G. L. (2004), Analysis of Soccer Field Hardness, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 287-294.

Mohr, M., Krustrup, P. and Bangsbo, J. (2003), Match performance of high-standard soccer players with special reference to development of fatigue, *Journal of sports sciences,* vol. 21, no. 7, pp. 519-528.

Naunheim, R., McGurren, M., Standeven, J., Fucetola, R., Lauryssen, C. and Deibert, E. (2002), Does the use of artificial turf contribute to head injuries?, *Journal of Trauma - Injury, Infection and Critical Care,* vol. 53, no. 4, pp. 691-694.

Nigg, B. M. (1990), The validity and relevance of tests used for the assessment of sports surfaces, *Medicine and science in sports and exercise,* vol. 22, no. 1, pp. 131-139.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Rogers III, J. N. and Waddington, D. V. (1990), Effects of management practices on impact absorption and shear resistance in natural turf, in: Schmidt, R. C., Hoerner, E.F., Milner, E. M. and Morehouse, C. A. (eds), *Natural and artificial playing fields: characteristics and safety features,* ASTM, PA., pp. 136-146.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. H., James, I. T., Dixon, S. J. and Guisasola, I. N. (2009), Natural turf surfaces: The case for continued research, *Sports Medicine,* vol. 39, no. 1, pp. 65-84.

Stover, S. M. (2003), The epidemiology of thoroughbred racehorse injuries, *Clinical Techniques in Equine Practice,* vol. 2, no. 4, pp. 312-322.

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British Journal of Sports Medicine,* vol. 41, no. 9, pp. 582-587.

Taylor, J. C., Wood, G. A., Earl, R. and Godwin, R. J. (2003), Soil factors and their influence on within-field crop variability, Part II: Spatial analysis and determination of management zones, *Biosystems Engineering,* vol. 84, no. 4, pp. 441-453.

Tengbeh, G. T. (1993), The effect of grass roots on shear strength variations with moisture content, *Soil Technology,* vol. 6, no. 3, pp. 287-295.

Theobald, P., Whitelegg, L., Nokes, L. D. M. and Jones, M. D. (2010), The predicted risk of head injury from fall-related impacts on to third-generation artificial turf and grass soccer surfaces: A comparative biomechanical analysis, *Sports Biomechanics,* vol. 9, no. 1, pp. 29-37.

Vanini, J. T., Henderson, J. J., Sorochan, J. C. and Rogers III, J. N. (2007), Evaluating traffic stress by the Brinkman Traffic Simulator and Cady Traffic Simulator on a Kentucky bluegrass stand, *Crop Science,* vol. 47, no. 2, pp. 782-786.

Villwock, M. R., Meyer, E. G., Powell, J. W. and Haut, R. C. (2009), Development and evaluation of a surrogate ankle for use with a rotational traction measurement apparatus, *Journal of Sports Engineering and Technology,* vol. 223, no. 4, pp. 151-158.

Webster, R. and Oliver, M. A. (1992), Sample adequately to estimate variograms of soil properties, *Journal of Soil Science,* vol. 43, no. 1, pp. 177-192.

Webster, R. and Oliver, M. A. (2007), *Geostatistics for Environmental Scientists,* Second ed, John Wiley & Sons Ltd, Chichester, England.

Young, C. and Fleming, P. R. (2007), A review of mechanical impact testing devices for sport surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

7. THE RESPONSE OF SOILS WITH ROOTS TO CYCLIC TRIAXIAL LOADING

Matt C. J. Caple, Iain T. James, and Mark D. Bartlett

ABSTRACT

The dynamic behaviour of soils with plant roots is not clearly defined. This study compared the effect of *Lolium perenne* grass roots on the behaviour of two soils (sand, clay loam) under cyclic loading using dynamic triaxial apparatus, an approach not previously undertaken. The presence of roots in the sand reduced the stiffness of the soil, which exhibited greater strain during loading, reduced elasticity, and greater permanent strain than the soil only treatment. The compressible nature of the roots was considered to produce this effect, compromising the frictional properties between particles. No differences in soil behaviour were found between soil with roots and soil only treatments for the clay loam soil. This behaviour was attributed to the greater adherence of the soil to the roots and the greater root density evident in the clay loam soil in comparison to the sand soil. The use of this novel approach to assess soils with roots to dynamic loading was considered successful for further implementation, although the difficulties in sample preparation, calculation of suitable confining stresses, and growing of the grass caused the process to be time consuming.

7.1 INTRODUCTION

The presence of vegetation roots in soil is widely recognised to increase shear strength. This process has been studied in a range of soil applications: wheel-soil interaction (Willatt & Sulistyaningsih, 1990; Cofie et al., 2000,) the conservation of soil from erosion (De Baets et al. 2008); and geotechnical applications of bearing capacity and slope stability (Frydman & Operstein, 2001; Ali & Osman 2008). Analytical models for soil-root interaction have also been used to quantify the contribution of roots to soil shear strength (Waldron & Dakessian, 1981; Wu & Watson, 1998). Some research has been performed using triaxial compression tests to assess the shear strength of rooted soils (Liu et al., 2006; Graf et al., 2009; Guisasola et al. 2010a; Zhang et al., 2010). The merits of using this equipment as opposed to direct shear tests for the assessment of soil physical properties has been considered by Zhang et al. (2010): the failure plane is not fixed or assumed; shear strength, stress-strain parameters, and volume changes can be studied within the entire loading process; field conditions and real loading conditions can be replicated more accurately; a range of different conditions (confining stress, sample drainage, consolidation) can be applied; modified tests such as dynamic cyclic or impact loading can be created with this equipment.

Dynamic cyclic loading of soil using triaxial equipment is commonly studied in a number of fields: the environmental effects of earthquakes, ecological risk assessments, the construction of off-shore structures, and traffic loading (O'Reilly & Brown, 1991; Cai & Wang 2008). Soil properties such as energy dissipation and damping, permanent and recoverable strain, pore pressures, and the variation of soil modulus (i.e. elastic modulus, shear modulus) are quantified using this equipment (Christakos, 2003; Okur & Ansel, 2007). Quasi-static shear strength tests performed with triaxial apparatus typically quantify the maximum stress the soil can withstand prior to yield failure, although they are also used in geotechnical engineering to determine overall stress-strain behaviour, soil stiffness and volumetric behaviour. In comparison, dynamic cyclic loading quantifies the stress-strain behaviour of soil under stresses that are smaller than those which cause sample failure. This behaviour owes much to the rate at which stress is applied, as soil does not have time to produce irreversible fracture mechanisms (sample failure) and dissipate pore pressures that are typical of quasi-static tests

(O'Reilly & Brown 1991). Both elastic and plastic strain occurs during loading and the magnitude of these is dependent upon properties of the soil, the characteristics of the applied stress, and the previous stress history of the soil (Brown et al., 1975; Wood 1980; O'Reilly & Brown, 1991; Karg & Haegeman, 2009).

The assessment of soils with plant roots using dynamic triaxial apparatus was not found in the literature, leaving uncertainty in the affect that roots have on the stiffness and elastic behaviour of soil-root composites (Guisasola et al., 2010b). The present study follows on from Guisasola et al. (2010a), which assessed the effect of Lolium perenne roots on the quasi-static triaxial compression strength of a sand soil. Shear strength was not found to be increased by the presents of roots, but axial deformation at failure was greater, and stiffness moduli were lower for the soil-with-roots treatment. This effect has also been shown by Michalowski & Čermák (2003) in triaxial tests of fibre-reinforced sand: the fibre-reinforced samples were more compressible (evident by volumetric changes), had reduced initial stiffness, and observed larger axial strain at failure in comparison to unreinforced samples. It was also noted that the addition of fibres to the sand, and an increase in fibre concentration increased the failure stress of the samples. The aim of the current study was to perform dynamic cyclic tests on soils with plant roots using the triaxial apparatus. Two soils were used (sand, clay loam) to prepare treatments with and without plant roots to assess the effect of *Lolium perenne* grass roots on the dynamic stress-strain behaviour of soil. A hypothesis was proposed that the soil with roots treatments would have lower stiffness and allow greater axial displacement during loading than the soil only treatments due to the compressive behaviour of plant roots in soils.

7.2 MATERIALS AND METHODS

7.2.1 Soil Characterisation and Sample Preparation

Two soils were selected for the study, a quarried sand and a clay loam (stripped stagnogley topsoil, supplied sieved to pass a 4 mm sieve), characterised in Table 7-1. These soils were representative of a soil evident within an elite level sand rootzone surface and a clay loam soil typical of a native soil amateur level facility respectively.

These soils were the same texture as those used in previous reported triaxial studies (Guisasola *et al.* 2010a; b). Soil texture, median particle size (D_{50}), coefficient of uniformity (C_u), and coefficient of gradation (C_c) was determined using the pipette method (BS7755-5.4:1998); plastic limit, liquid limit and plasticity index were determined using BS1377-2:1990; organic matter was determined by loss on ignition (BS EN13039:2000); Proctor soil compaction was determined using BS1377-4:1990. Soil only (NG) and soil with plant roots (G) treatments were prepared for each soil type (Table 7-2). Gravimetric water content, dry density and root density of the samples was determined post testing. Water content was determined by loss of sample mass after oven drying; density was determined by dry mass of soil by volume. Root density was characterised from separate sample replicates subjected to the same preparation and growing conditions. Dry mass of roots within the volume of soil was quantified by hand washing the roots from the soil, followed by drying and weighing them, as per the method of De Baets *et al.* (2006).

Table 7-1 Physical characterisation of the two soils used in the study.

Physical Property	**Soil**	
	Sand	Clay Loam
Particle size distribution		
Sand (%)	98	29
Silt (%)	1	45
Clay (%)	1	26
D_{50} (mm)	0.28 mm	
C_u	1.76	
C_c	0.94	
Organic matter (%)	1.3	4.1
Plasticity		
Plastic Limit (%)		18.1
Liquid Limit (%)		40
Index of Plasticity (%)		21.9
Proctor optimum compaction		
Maximum dry bulk density (g cm^{-3})	1.8	1.8
At gravimetric water content (%)	11.5	15
Saturation ratio at proctor optimum density (%)	15	25

Table 7-2 Characterisation of the soil only (NG) and soil with grass roots (G) treatments used in the study.

Treatment	**Dry density (g cm^{-3})**	**Gravimetric water content (%)**	**Root density (kg m^{-3})**
Sand (NG)	1.7 ± 0.004	14.3 ± 0.3	
Sand (G)	1.69 ± 0.003	14.5 ± 0.7	5.7 ± 0.6
Clay loam (NG)	1.5 ± 0.005	15.0 ± 0.4	
Clay loam (G)	1.5 ± 0.004	14.7 ± 0.2	19.9 ± 1.9

Soil with plant roots (G) samples were prepared from oven dried soils (24 h at 105°C), which were wetted to gravimetric water contents of 11.5% and 15.0% respectively for the sand and clay loam soils. These water contents corresponded to the water contents at which maximum dry density was achieved in Proctor tests, to enable ease of sample packing. The samples were packed in eight layers into plastic tubes (68 mm diameter, 136 mm length, 5 mm wall thickness), which acted as moulds. This procedure is similar to that described by Graf et al. (2009), who manually packed soil into PVC tubes to create soil with roots samples. Prior to packing, the tubes were cut lengthways in half and re-joined with cable ties. This technique allowed the samples to be removed from the tubes with minimal disturbance when fitting the latex membrane used in testing. To facilitate applying large forces to the samples without soil failure, it was decided at this stage to pack the soils at the highest achievable densities. The highest densities achieved by the manual packing procedure were 1.7 g cm^{-3} and 1.5 g cm^{-3} for the sand and clay loam soils respectively. Mechanically packing (fixed energy) the samples was not a reliable method, as damage to the moulds or misshaping of the samples occurred. Trial experiments indicated that it was necessary to slightly undercompact the bottom layers of soil to achieve uniform density along the length of the samples. This is a result of succeeding layers compacting the layers below, which has also been noted in the triaxial experiments undertaken by Christakos (2003). *Lolium perenne* cv Romance (Perennial ryegrass) seeds were applied to the surface of the samples at 50 g m^{-2} and samples were maintained with water as required under controlled conditions in a glasshouse (12°C ambient temperature, 16 hours daily light) for 18 weeks to ensure sufficient root growth (Figure 11-24, Appendix 11.7). As discussed in previous chapters, this grass specie is the most commonly used specie on UK sports pitches. Granular fertiliser (Sportsmaster Preseeder; The Scotts Company Ltd, Ipswich, UK) was applied twice to the samples (50 g m^{-2}), at initial germination and after 10 weeks of growth. For testing, the samples were rewetted to 11.5% and 15% for the sand and clay loam soils, corresponding to the Proctor optimum compaction. Regulating sample water contents was performed through calculation of gravimetric soil water content over specific time increments (every 24 hours) for each soil type, which was pre-determined from a drying cycle on the soils starting from saturation. Actual values determined post testing were shown to correspond well for the clay loam soil (14.7%), but were around 3% (m/m) higher for the sand soil (14.5%; Table 7-2). Immediately prior (~ 1 hour) to testing, the excess of grass (leaves and roots) was cut from both ends of the samples (Figure 11-25, Appendix 11.7).

Soil only treatments (NG) were tested after the G samples, in order for the densities and water contents to be matched accurately. These samples were prepared from oven dried soil and wetted to 14.5 % and 14.7 % water contents respectively for the sand and clay loam treatments. Actual values were determined as 14.3% and 15.0% post testing (Table 7-2). At this stage, the clay loam soil was left for 24 hours prior to packing to allow the water to equilibrate throughout the soil. The soil was packed into a standard triaxial mould (70 mm diameter, 140 mm length) in eight layers. No differences ($P>0.05$) were evident between G and NG treatments for gravimetric water content or dry density in both soil types (Table 7-2).

7.2.2 Test Apparatus and Procedure

Load-controlled dynamic cyclic tests were conducted using an electromechanical dynamic triaxial testing system (GDS DYNTTS 2 Hz 10 kN; GDS Instruments Ltd, Hampshire, UK). The basic components of the apparatus are outlined in Figure 11-26, (Appendix 11.7). Samples were removed from moulds prior to testing. Saturated porous plates were placed on the top and bottom of the samples, with a latex rubber membrane placed around the sample. Samples were docked in the chamber on a pedestal with a 70 mm Perspex cap fitted between the sample and the force transducer. Cell pressure was increased to a confining stress of 200 kPa in the consolidation stage of testing. The duration of this stage was dependent on the capability of the system to ramp the cell pressure, with pressure increasing at a rate of 5 kPa min^{-1} for the sand samples and 3 kPa min^{-1} for the clay loam samples. The consolidation process was completed when cell pressure remained at a steady 200 kPa pressure. It is recognised that 200 kPa confining stress is not representative of field conditions for the rootzone of this vegetation, and equates to soil conditions at greater depths (c. 10 m) with the absence of a water table. Calibration experiments on samples with grass roots resulted in soil failure at lower confining stresses. Samples did not fail at this magnitude of stress and was selected to produce initial data for this innovative method. In the second stage of testing, axial cycles were applied to the samples under undrained conditions at a rate of 0.5 Hz. and a target force of 0.5 kN; 100 cycles were applied, to ensure the samples reached a resilient stiffness. Load was determined from a 10 kN force transducer, and displacement (axial) determined from the loading ram position encoder, logged at 100 Hz. Treatments were replicated in triplicate.

7.2.3 Dynamic Soil Parameters

During dynamic cyclic loading, soil deformation occurs followed by a ratio of recovered strain when the load is removed (Figure 7-1). This ratio is lower for early cycles, as permanent plastic strain occurs and viscoplastic behaviour dominates. Increments of permanent strain reduce with each cycle as soil particles are orientated closer together (granular ratcheting), resulting in an increase in soil stiffness and elasticity with cycles. A resilient, equilibrium state is eventually reached for the applied load which is characterised by quasi-viscoelastic behaviour, where permanent strain becomes negligible compared to recovered strain.

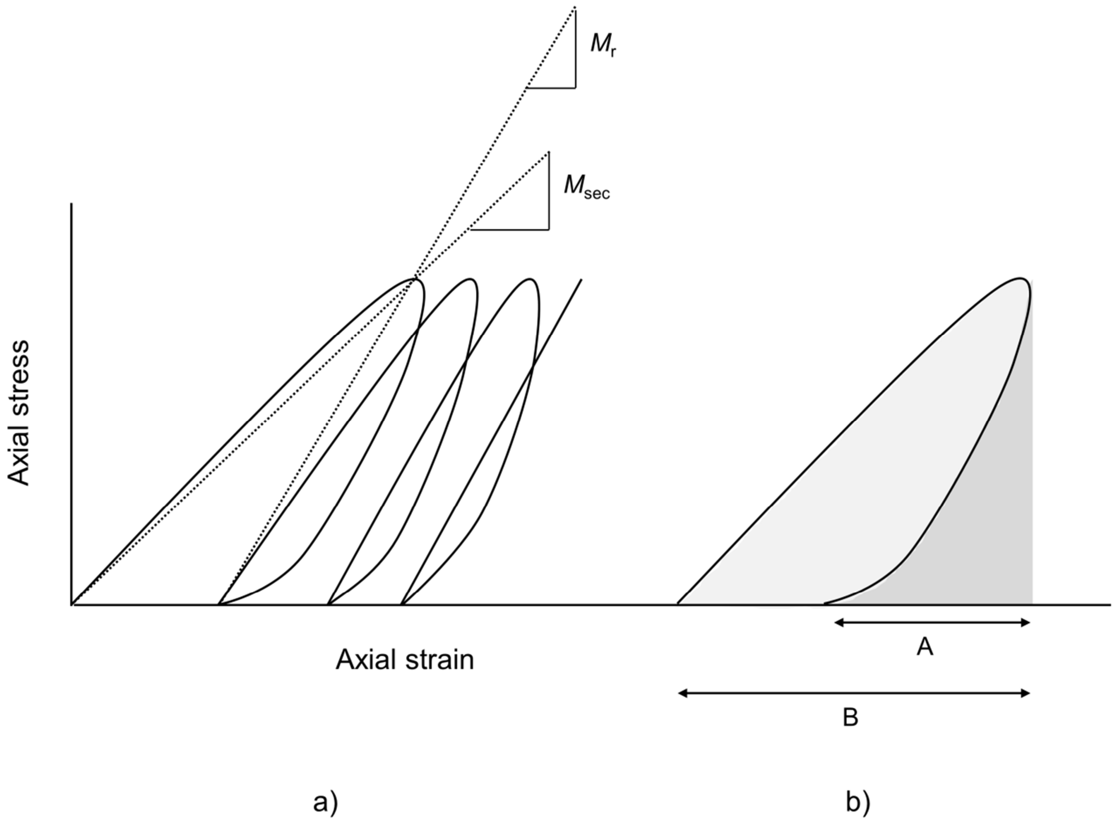

Figure 7-1 Typical behaviour of soil under cyclic loading: a) Early cycles exhibiting large plastic strain, M_{sec} (Equation 7.1) and M_r (Equation 7.2) modulus indicated for first cycle; b) Calculation of R (Equation 7.3) – A represents strain recovered, B represents total strain.

A number of parameters were calculated from the force-displacement curves. Secant modulus M_{sec} (MPa) was determined by:

$$M_{sec} = \frac{\sigma_a^{max}}{\varepsilon_a} \tag{7.1}$$

where σ_a^{max} is the maximum axial stress, and ε_a is axial strain at the maximum axial stress.

Resilient modulus M_r (MPa) is given by:

$$M_r = \frac{\sigma_a^{max}}{\Delta\varepsilon_{rec}} \tag{7.2}$$

where $\Delta\varepsilon_{rec}$ is the portion of recovered strain. Values of M_{sec} approach M_r as the soil becomes more resilient. The proportion of strain recovery (R) was determined by:

$$R(\%) = \frac{A}{B} \times 100 \tag{7.3}$$

where A is the recovered strain determined by the increment under the unloading curve in Figure 7-1, and B is the total strain. This parameter increases as the soil becomes more resilient, and a resilient state for the soil was defined when R = >97.5%. Calculation of dynamic parameters was performed in MATLAB 7.10.0 (Mathworks, Natick, MA, USA).

7.2.4 Statistical Analysis

The treatments were assessed for the effect of grass roots on their dynamic behaviour. Secant modulus, resilient modulus, R, maximum axial strain, recovered strain, and accumulated axial plastic strain were calculated for the 1st, 10th and 100th cycles of loading. Differences between treatments were determined using one-way ANOVA and Fisher LSD ($P<0.05$) in Statistica 9 (Statsoft Inc., Tulsa, OK., USA).

7.3 RESULTS

The behaviour of the treatments under cyclic loading is illustrated in Figure 7-2 for the 1st, 10th, and 100th cycles. In early cycles (1st and 10th), the target force (0.5 kN) applied is not reached as a result of plastic behaviour of the soil dominating. The target force is invariably achieved in later cycles (100th) as soil stiffness increases. The dynamic behaviour of the sand soil was affected by the presence of grass roots. The G samples exhibited significantly lower values for M_{sec} than the NG samples and produced greater maximum strain during loading for all cycles ($P<0.05$; Table 7-3, Figure 7-2a, b). Although M_{sec} indicates stiffness of the soil during loading, the target force was not achieved for the sand NG treatment in early cycles (1st and 10th), indicating that the soil exhibited lower strength and reached conditions closer to failure. The resilient modulus (M_{r}) was similar ($P>0.05$) for the 1st cycle of loading between sand NG and G treatments, but was significantly greater for the NG treatment in the 10th and 100th cycles. Despite the comparable values for M_{r} in the first cycle, inspection of strain recovery (R) highlighted the sand NG treatment was more elastic compared to the sand G treatment, and this was the case for all cycles ($P<0.05$; Table 7-3). Absolute recovered displacement (mm) was comparable between the sand G and NG treatments in the first and 100th cycles of loading, but was higher for the G treatment in the 10th cycle ($P<0.05$; Table 7-3). A resilient state was reached (R = >97.5 %) in an earlier mean cycle (27) in the sand NG treatment in comparison to the sand G treatment (69), which was statistically significant ($P<0.05$).

Values of R were significantly different for the G and NG treatments for both soils in the 100th cycle ($P<0.05$; Table 7-3). These differences were attributed to the small variation between the replicates, highlighted with low standard error of the mean values (Table 7-3). With the exception of this parameter in the 100th cycle, no other differences were detected between clay loam G and NG treatments for stiffness or displacement parameters in all cycles ($P>0.05$; Table 7-3; Figure 7-2c, d). However, the resilient state was reached in an earlier mean cycle for the clay loam NG treatment (47) compared to the G treatment (86), which was statistically significant ($P>0.05$).

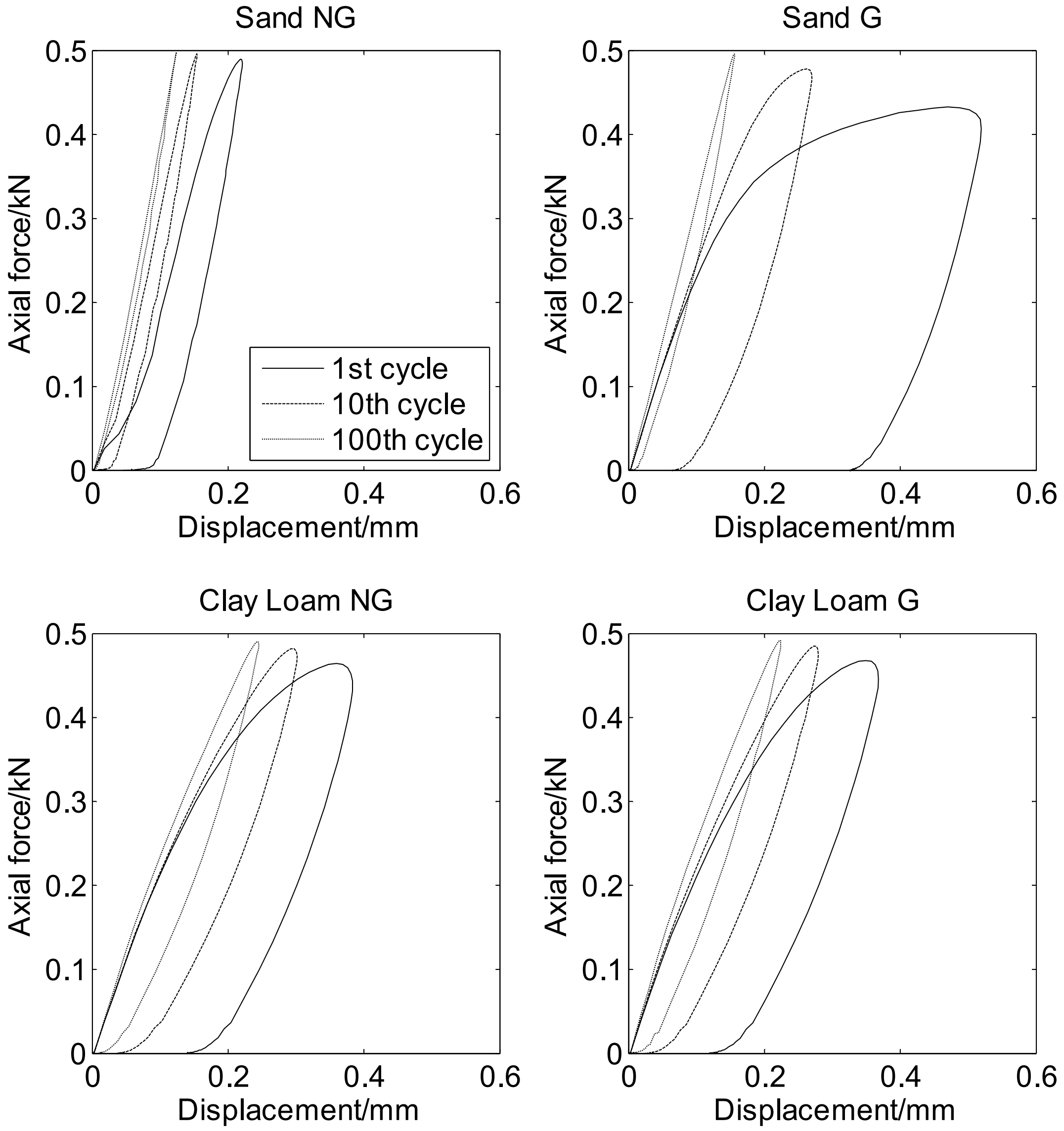

Figure 7-2 Mean force-displacement curves of the 1st, 10th, and 100th loading cycles of the sand and clay loam soil only (NG) and soil with grass roots (G) treatments defined in Table 7-2

Table 7-3 Mean (± standard error) dynamic soil parameters determined from cyclic triaxial loading for soil only (NG) and soil with grass roots (G) treatments of a sand and clay loam soil for the 1st, 10th, and 10th cycle of loading. Letters indicate homogenous groups between NG and G treatments tested with one-way ANOVA and Fisher LSD (P<0.05); data without letters belonged to the same homogenous groups.

Cycle/Treatment	**M_{sec} (MPa)**	**M_r (MPa)**	**R (%)**	**Cycle at which R ≥97.5%**	**Maximum displacement (mm)**	**Recovered displacement (mm)**	**Accumulated plastic displacement (mm)**
1st Cycle							
Sand NG	87.4 ± 11.9a	109.4 ± 16.1	79.2 ± 1.1a		0.22 ± 0.03a	0.18 ± 0.023	0.04 ± 0.003a
Sand G	38.3 ± 10.1b	96.9 ± 3.0	36.1 ± 11.1b		0.52 ± 0.11b	0.20 ± 0.005	0.35 ± 0.09b
10th Cycle							
Sand NG	123.9 ± 9.0a	130.0 ± 9.9a	94.6 ± 0.5a		0.15 ± 0.01a	0.15 ± 0.011a	0.17 ± 0.01a
Sand G	72.6 ± 7.1b	90.8 ± 4.6b	75.9 ± 4.5b		0.26 ± 0.02b	0.20 ± 0.009b	1.65 ± 0.53b
100th cycle							
Sand NG	151.9 ± 5.9a	152.7 ± 6.2a	99.5 ± 0.1a	27a	0.12 ± 0.005a	0.12 ± 0.005	0.34 ± 0.01a
Sand G	119.7 ± 1.1b	121.5 ± 1.1b	98.4 ± 0.1b	69b	0.16 ± 0.002b	0.15 ± 0.003	2.24 ± 0.53b
1st Cycle							
Clay Loam NG	48.8 ± 2.2	76.3 ± 2.9	61.4 ± 0.9		0.38 ± 0.02	0.24 ± 0.010	0.14 ± 0.008
Clay Loam G	50.6 ± 1.4	73.8 ± 2.3	66.2 ± 0.9		0.38 ± 0.002	0.25 ± 0.008	0.12 ± 0.004
10th Cycle							
Clay Loam NG	62.2 ± 3.2	69.0 ± 3.5	87.8 ± 1.3		0.3 ± 0.02	0.27 ± 0.014	0.62 ± 0.05
Clay Loam G	67.6 ± 3.0	72.6 ± 3.2	91.3 ± 0.5		0.29 ± 0.01	0.26 ± 0.011	0.49 ± 0.01
100th cycle							
Clay Loam NG	76.6 ± 4.7	77.7 ± 4.4	97.8 ± 0.1a	86a	0.25 ± 0.01	0.24 ± 0.015	1.62 ± 0.15
Clay Loam G	83.6 ± 3.5	84.1 ± 3.5	98.7 ± 0.2b	47b	0.23 ± 0.01	0.22 ± 0.009	1.08 ± 0.01

7.4 DISCUSSION

The use of triaxial apparatus to assess dynamic properties of rooted soils has not been previously reported in the literature, with this work considered novel in its application. Although the addition of roots in soil compromises the homogenous and isotropic assumption of triaxial loading by providing planes of failure in a particular orientation, the use of the equipment provides an opportunity to quantify the effect of roots on dynamic soil behaviour in more detail than other equipment. In cyclic loading of dense soils (such as those used in the experiment), pore pressure often follows a negative trend of build-up. It is possible that the increase in stiffness measured with cyclic number may be due to the densification of the soil matrix, a result of air compressibility in unsaturated conditions. However, the lack of pore pressure measurements (suction) recorded within this study means that this is not confirmed, but requires a complex test set-up for unsaturated samples. Future cyclic triaxial experiments on grass with roots samples should consider these measurements.

Operation of triaxial equipment is time consuming and demanding, which reduces replication of different soil and loading conditions (Graf et al., 2009), and limited the treatment number to four in this study. Guisasola et al. (2010b) reported dynamic loading at a force of 2 kN, a rate of 1 Hz, and a confining stress of 250 kPa. When these conditions were used for the G samples in this study, complete sample failure occurred and the cycle rate was considered too fast. A range of conditions were tested before the current conditions were accepted (0.5 kN, 0.5 Hz and 200 kPa), which allowed behaviour of the soils to be studied without failure of the sample. It is acknowledged that soil behaviour is dependent upon loading rate, confining stress, soil dry density and water content in both triaxial cyclic loading and in quasi-static triaxial compression (Assimaki et al., 2000; Puppala et al., 2004; Okur & Ansal, 2007; Guisasola et al. 2010a; b; Okur & Ansal 2011). Therefore it is considered that the results presented here can only be considered valid for the particular conditions tested. Further work is required in assessing dynamic behaviour of rooted soils with a greater range of soil physical conditions, loading conditions, and confining stresses.

The load is applied by the triaxial apparatus within 0.56 s at this cycle rate (0.5 Hz.), and deformation of samples was small in each cycle (≤0.52 mm). A strain rate of 0.93 mm s^{-1} is therefore applied to the soil, which is very small when comparing to the CIST or DST devices (1257 mm s^{-1} and 300 mm s^{-1} respectively). However, in dynamic triaxial loading of soils, it is more important to apply loading conditions to the soil that allow the target force (0.5 kN) to be achieved without resulting in complete sample failure, rather than produce large strain rates. This approach allows the dynamic behaviour of the soil during loading and unloading to be studied, and was particularly important to be able to quantify the effect of grass roots on soil behaviour. This makes comparison between these tests and the *in-situ* surface testing devices used in other experiments difficult, as all are dominated by plastic soil behaviour.

A trade-off was necessary in the selection of soil physical conditions for the rooted treatments - samples were required to be of sufficient strength to allow dynamic loading without soil failure, yet bulk densities were limited by the manual packing procedure of the soil into the plastic moulds. Controlling variation that occurred for root density between the two soil textures was also not feasible. The higher root density evident in the clay loam samples can be attributed to the greater cation exchange capacity of the clay soil providing nutrients for the roots to grow more abundantly, and the difference in pore size distributions compared to the more compacted sand. It is logical to suggest that the increased density of the sand soil also contributed to the lower density of grass roots by means of limiting root length and distribution during the growing period (Shierlaw & Alston, 1984).

The effect of grass roots in increasing the strength of soils in the horizontal direction is well established, where shear stresses are applied perpendicular to the orientation of the majority of the roots. Roots adhere to soil particles forming a composite material, and during shear, axial tensile forces are built up as the root is stretched (De Baets et al. 2008). Failure occurs at these interfaces when slippage between roots and particles occur, or the tensile force reaches its ultimate value and the root fails (Makarova et al., 1998). Soils with plant roots can typically exhibit greater shear displacements before failure compared to soils without roots due to this mechanism (Comino & Druetta, 2010; Guisasola et al., 2010a). Less research has been performed on assessing the shear strength of grass rooted soils under vertical compression stresses, where the majority of roots are in the same orientation as the applied stress. Under triaxial compression, tree roots have been shown to increase shear strength of soils (Graf et al., 2009; Zhang et al., 2010), while Pu et al. (2009) performed triaxial compression tests on grass rooted soils finding shear strength was correlated with the number of vertical roots placed in the soil. The results presented here for dynamic cyclic loading of rooted soils showed that in the sand soil, the grass treatment produced more axial strain and was weaker during loading than the soil only treatment. The hypothesis that the G treatments would have lower stiffness and allow greater axial displacement during loading than the NG treatments was therefore accepted for the sand soil. The independence of soil behaviour to the presence of roots resulted in a rejection of the hypothesis for the clay loam soil.

Soil is high in compressive strength, but low in tensile strength; while roots are high in tensile strength and low in compressive strength. The energy-absorbing potential of compressible materials mixed with sand soils has previously been recognised, as energy is consumed and dissipated in the soil mass when strain occurs (Feng & Sutter, 2000). Soils with grass roots have also been shown to compress more than soil only treatments in dynamic roller experiments on clay loam soil (James & Shipton, 2011). In the NG sand soil, only a small increment of maximum displacement occurred (≤0.22 mm; Table 7-3) owing to the stiff nature of sand particles and frictional forces acting between particles, resulting in low energy dissipation. It is proposed that under dynamic loading, the low compression strength of the vertical roots compromised the frictional forces acting between sand particles, and resulted in greater sample displacement and reduced stiffness under load.

The micro-mechanical interaction of soil and grass roots should be considered in the explanation of the presented data. Research detailing plastic fibre-root interaction has shown that the adherence of soil particles to fibres is attributed to friction in sandy soils (Michalowski & Čermák, 2003), while the cohesive properties of clay minerals have been shown to bond to fibres in clay-fibre composites (Tang et al. 2007). Reinforcement effects of soil-fibre mixes can also be greater when the fibre-particle size ratio is larger, due to increased effective contact area (Michalowski & Čermák, 2003). These two components suggest that the adherence of soil particles to roots would be stronger for the clay loam soil than the sand soil. This phenomenon was encountered when separating roots from the soil in the root density tests. Zhang et al. (2010) described that the difference between the deformation moduli of roots and soil causes a trend of dislocation between them when vertical loads are applied. This dislocation is prevented by the strength of the adhesion between roots and soil, which subsequently reduces soil failure. This concept may explain the dynamic stress-strain behaviour of the soils in the study – less comparative plastic displacement was evident in the G clay loam soil compared to the G sand soil, and this is attributed to the increased adherence of soil and roots.

The effect of a greater root density in the clay loam soil (19.9 kg m^{-3}) compared to the sand soil (5.7 kg m^{-3}) may have contributed to the independence of soil behaviour with roots. The compressible nature of the grass roots may have been counteracted by the reinforcement effects the roots provide to the soil, which increases with root density in soils (Tengbeh, 1993). The reinforcement effect of roots in soils has been likened to the behaviour of a higher density soil without roots through the concept of 'virtual density' increasing the soils resistance to displacement (Graf et al., 2009). Additionally, the volume of soil a root occupies is accommodated by a loss of equal volume of pore space surrounding the root (Dexter, 1987). It must therefore be considered that high root density soils may not produce increased displacement owing to restrictions on available pores spaces into which particles can move.

It has previously been considered that increase in soil strength and reinforcement provided by plant roots in soils is due to the combination of both horizontal and vertical fibres to absorb the applied stress (Wu et al., 1988; Zhang et al., 2010). The growth of the roots in this study was limited to mostly vertical growth, due to the small diameter of the samples (68 mm) and their confinement in the plastic moulds. Graf et al. (2009) have considered that the effect of roots on the behaviour of soils *in-situ* is probably underestimated using the results from triaxial tests due to the restrictions placed upon the roots. Therefore, care must be exercised in modelling data from soils with roots under cyclic loading to field situations.

As behaviour of soils with roots under dynamic stresses is not clear, so is the behaviour of these soils after stresses are removed, as understanding of the elastic behaviour of roots is limited. The behaviour of woody roots of beech and larch trees has been investigated under cyclic loading by Makarova et al. (1998) and Cofie et al. (2000). It was shown that elastic as well as plastic strain was exhibited by the roots, however stiffness was low, and plastic strain in the first cycle was high. In the roller compaction experiment of James & Shipton (2011), the soil with grass roots treatment was shown to be more elastic by producing higher maximum axial strain but similar permanent strain compared to a soil-only treatment. This suggests that the tensile strength of these fibrous roots can transfer to elastic behaviour when load is removed. There was no evidence of soil elasticity produced from the effects of grass roots in the current study, as recovery of strain ratio was similar for the clay loam treatments, and higher for the NG treatment in the sand soil. However, it must be considered that the recovery of strain for the rooted soils may be considered time dependent (viscous), and the roots may have returned a greater ratio of strain given longer time between loads than the cycle rate (0.5 Hz) allowed. This should be explored further in future research, as the triaxial apparatus provides the opportunity to vary the cycle rate and study the recoverable strain in rooted soil samples more closely.

7.5 CONCLUSIONS

Issues with undertaking dynamic triaxial tests of soils with roots include difficulties in preparing and handling samples, and determination of suitable loading and confining test conditions. The methodology used in the study successfully allowed treatments of a sand and clay loam soil with and without roots to be assessed, albeit with the physical conditions of the soil limited by the preparation procedure. The soil with roots treatment of the sand soil exhibited a reduction in secant stiffness when loaded, greater displacement during loading, greater permanent displacement, and reduced elasticity than the soil only treatment. No differences were found between treatments for the clay loam soil. Based on behaviour of soil-root composites and soil-plastic composites under triaxial compression, it was considered that the compressible nature of roots were responsible for this behaviour in cyclic loading of the sand soil. The independence of soil behaviour to roots evident in the clay loam was attributed to the greater cohesion between the soil and roots which prevented the soil from straining, and the greater root density of the soil in comparison to the sand. The results of this preliminary study show that the dynamic behaviour of soils with roots to cyclic loading is complex and may not be explained by a single mechanism. Rather, a combination of mechanisms may affect soil behaviour, owing to a number of intrinsic and extrinsic factors, which require further investigation.

7.6 ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from the UK Engineering and Physical Sciences Research Council (EPSRC) for this research.

7.7 REFERENCES

Ali, F. H. and Osman, N. (2008), Shear strength of a soil containing vegetation roots, *Soils and Foundations,* vol. 48, no. 4, pp. 587-596.

Assimaki, D., Kausel, E. and Whittle, A. (2000), Model for dynamic shear modulus and damping for granular soils, *Journal of Geotechnical and Geoenvironmental Engineering,* vol. 126, no. 10, pp. 859-869.

Brown, S. F., Lashine, A. K. F. and Hyde, A. F. L. (1975), Repeated load triaxial testing of a silty clay, *Geotechnique,* vol. 25, no. 1, pp. 95-114.

BS EN13039:2000 (2000), *Soil improvers and growing media. Determination of organic matter content and ash,* British Standards Institute, London.

BS1377-2:1990 1990. Methods of test for soils for civil engineering purposes - part 2: classification tests. British Standards Institute, London.

BS1377-4:1990 (1990), *Methods of test for soils for civil engineering purposes. Compaction-related tests,* British Standards Institute, London.

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

Cai, Y. and Wang, J. (2008), Modeling of stress-strain behavior of soft clay under cyclic loading, in: *2nd International Conference on Geotechnical Engineering for Disaster Mitigation and Rehabilitation, GEDMAR08,* 30 May - 2 June 2008, Nanjing, China, pp. 277-283.

Christakos, G. (2003), Soil behaviour under dynamic loading conditions: Experimental procedures and statistical trends, *Stochastic Environmental Research and Risk Assessment,* vol. 17, no. 3, pp. 175-190.

Cofie, P., Koolen, A. J. and Perdok, U. D. (2000), Measurement of stress-strain relationship of beech roots and calculation of the reinforcement effect of tree roots in soil-wheel systems, *Soil and Tillage Research,* vol. 57, no. 1-2, pp. 1-12.

Comino, E. and Druetta, A. (2010), The effect of Poaceae roots on the shear strength of soils in the Italian alpine environment, *Soil and Tillage Research,* vol. 106, no. 2, pp. 194-201.

De Baets, S., Poesen, J., Gyssels, G. and Knapen, A. (2006), Effects of grass roots on the erodibility of topsoils during concentrated flow, *Geomorphology,* vol. 76, no. 1-2, pp. 54-67.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J. and Muys, B. (2008), Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength, *Plant and Soil,* vol. 305, no. 1-2, pp. 207-226.

Dexter, A. R. (1987), Compression of soil around roots, *Plant and Soil,* vol. 97, no. 3, pp. 401-406.

Feng, Z. and Sutter, K. G. (2000), Dynamic Properties of Granulated Rubber/Sand Mixtures, *Geotechnical Testing Journal,* vol. 23, no. 3, pp. 338-344.

Frydman, S. and Operstein, V. (2001), Numerical simulation of direct shear of root-reinforced soil, *Ground Improvement,* vol. 5, no. 1, pp. 41-48.

Graf, F., Frei, M. and Böll, A. (2009), Effects of vegetation on the angle of internal friction of a moraine, *Forest Snow and Landscape Research,* vol. 82, no. 1, pp. 61-77.

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010a), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010b), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

James I.T., and Shipton P.M.R. (2011), Quantifying compaction under rollers using marker tracing image analysis, *Soil and Tillage Research,* (in review).

Karg, C. and Haegeman, W. (2009), Elasto-plastic long-term behavior of granular soils: Experimental investigation, *Soil Dynamics and Earthquake Engineering,* vol. 29, no. 1, pp. 155-172.

Liu, X. , Chen, L. and Song, W. (2006), Study on the shear strength of forest root-loess, *Beijing Linye Daxue Xuebao/Journal of Beijing Forestry University,* vol. 28, no. 5, pp. 67-72.

Makarova, O. V., Cofie, P. and Koolen, A. J. (1998), Axial stress-strain relationships of fine roots of Beech and Larch in loading to failure and in cyclic loading, *Soil and Tillage Research,* vol. 45, no. 1-2, pp. 175-187.

Michalowski, R. L. and Čermák, J. (2003), Triaxial compression of sand reinforced with fibers, *Journal of Geotechnical and Geoenvironmental Engineering,* vol. 129, no. 2, pp. 125-136.

Okur, D. V. and Ansal, A. (2007), Stiffness degradation of natural fine grained soils during cyclic loading, *Soil Dynamics and Earthquake Engineering,* vol. 27, no. 9, pp. 843-854.

Okur, D. V. and Ansal, A. (2011), Evaluation of cyclic behaviour of fine-grained soils using the energy method, *Journal of Earthquake Engineering,* vol. 15, pp. 601-619.

O'Reilly, M. P. and Brown, S. F. (1991), Cyclic loading in geotechnical engineering, in: O'Reilly, M. P. and Brown, S. F. (eds.), *Cyclic loading of soils: from theory to design,* Blackie & Son Ltd., London, pp. 1-18.

Pu, Y., Zhihai, X., Xiasong, H., Guorong, L., Haili, Z., Xiaoqin, M. and Zhangzhi, C. (2009), Limit load of soil-root composites, *Computers, Materials and Continua,* vol. 10, no. 2, pp. 117-137.

Puppala, A. J., Chomtid, S. and Wattanasanticharoen, E. (2004), Plastic deformation potentials of sandy clay from repeated load triaxial test in: Yegian M.K. & Kavazanjian E. (eds), *Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans 2004*, 27 - 31 July 2004, pp. 938-947.

Shierlaw, J., & Alston, A. M. 1984. Effect of soil compaction on root growth and uptake of phosphorous. Plant and Soil, 77, 15-28.

Tang, C., Shi, B., Gao, W., Chen, F. and Cai, Y. (2007), Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil, *Geotextiles and Geomembranes,* vol. 25, no. 3, pp. 194-202.

Tengbeh, G. T. (1993), The effect of grass roots on shear strength variations with moisture content, *Soil Technology,* vol. 6, no. 3, pp. 287-295.

Waldron, L. J. and Dakessian, S. (1981), Soil reinforcement by roots: calculation in increased soil shear resistance from root properties, *Soil Science,* vol. 132, no. 6, pp. 427-435.

Willatt, S. T. and Sulistyaningsih, N. (1990), Effect of plant roots on soil strength, *Soil and Tillage Research,* vol. 16, no. 4, pp. 329-336.

Wood, D. M. (1980), *Laboratory investigations of the behaviour of soils under cyclic loading: a review,* CUED/D-Soils/TR 84, Cambridge University, Cambridge.

Wu, T. H., McOmber, R. M., Erb, R. T. and Beal, P. E. (1988), Study of soil-root interaction, *Journal of Geotechnical Engineering,* vol. 114, pp. 1351-1375.

Wu, T. H. and Watson, A. (1998), In situ shear tests of soil blocks with roots, *Canadian Geotechnical Journal,* vol. 35, no. 4, pp. 579-590.

Zhang, C. , Chen, L., Liu, Y., Ji, X. and Liu, X. (2010), Triaxial compression test of soil-root composites to evaluate influence of roots on soil shear strength, *Ecological Engineering,* vol. 36, no. 1, pp. 19-26.

8. THE EFFECT OF GRASS LEAF HEIGHT ON THE IMPACT BEHAVIOUR OF NATURAL TURF SPORTS PITCHES

Matt C. J. Caple, Iain T. James, and Mark D. Bartlett

ABSTRACT

The effect of three grass leaf height treatments (50 mm, 25 mm, <1 mm) of two sports pitch rootzones (clay loam, sand) was assessed under controlled conditions using the 0.5 kg and 2.25 kg Clegg Impact Soil Testers (CIST) and the Dynamic Surface Tester (DST) device. Results were dependent upon the test device, impact energy, and drop number of the impact. The presence of grass was shown to be more important than specific grass heights in regulating impact behaviour, with no differences ($P>0.05$) detected between 50 mm and 25 mm treatments. Peak deceleration was reduced ($P<0.05$) by the presence of grass (50 mm and 25 mm treatments) for drop one, but not drop three of the 0.5 kg CIST missile, indicating grass leaves absorb some impact energy on lower energy single impacts but not when leaves are flattened under repeated loading. There was no difference ($P>0.05$) in peak deceleration of the higher energy 2.25 kg CIST among leaf treatments for first drop, but was significantly lower ($P<0.05$) for third drop on the <1 mm treatment where the soil exhibited greater ($P<0.05$) plastic displacement. Surface loading rate and energy absorption did not differ ($P>0.05$) across treatments under athlete-specific impact stresses measured with the DST, suggesting grass leaves may not affect athlete impacts. Greater consideration is required for future impact testing to assess surfaces to specific impacts that occur in game situations through the use of appropriate test devices.

8.1 INTRODUCTION

The behaviour of sports surfaces in response to vertical impact is widely quantified, with a range of devices and standards evident globally (Murphy et al., 1996; American Society for Testing and Materials, 2000; Baker et al., 2007; Young and Fleming, 2007). The motivation for quantification of surface response to vertical impact is driven by proposed links between the absorption and return of impact forces and performance and injury potentials of athletes. The return of impact energy from sports surfaces is considered desirable to provide adequate ball bounce and to allow athletes to perform efficient movements (Dura et al., 1999; Stefanyshyn and Nigg, 2003). However, excessively stiff surfaces are assumed to reduce the cushioning provided to players on impact by increasing the loading rate of impact forces (Stiles and Dixon, 2007), which have been linked to increased injury risks such as overuse and impact injuries (James et al., 1978; Naunheim et al., 2002)

Natural turf sports pitch surfaces consist of grass plants within a soil rootzone. Grass plant species are predominantly selected for resistance to wear and tolerance to shade characteristics (Canaway, 1981; Newell et al., 1999). Plant leaves are typically maintained at heights of between 18 - 50 mm for elite level surfaces, with heights varying with sport played and quality of maintenance (Baker and Canaway, 1991; McClements and Baker, 1994; Mooney and Baker, 2000). The soil component of this system provides the mechanical characteristics of the surface: shear and compressive strength, elasticity, stiffness, traction, and durability; and the edaphic environment for the grass plant by providing water, nutrients, and oxygen (James, 2011). Response of these surfaces during impact is dominated by non-linear soil stress-strain behaviour; with both elastic and plastic deformation evident during impact. This behaviour is dependent on physical soil parameters (soil texture, soil water content, bulk density), the magnitude and rate of applied stress, the stress history of the soil, and climatic conditions (Guisasola et al., 2010a,b). Elastic deformation is limited to a small proportion of strain (~0.5%) and is loading rate dependent (Guisasola et al., 2010b).

The most commonly assessed impact property of natural turf sports pitch surfaces is hardness - the resistance of the surface layer to plastic deformation when loaded. This property is quantified with drop devices that determine peak deceleration of an accelerometer mounted in a free falling weighted missile dropped from a standard height. The Clegg Impact Soil Tester (Clegg, 1976) is the most common of this type of device, consisting of a 50 mm diameter missile of typically 0.5 kg or 2.25 kg dropped from heights of 0.55 m and 0.45 m respectively in the UK; although the 0.5 kg missile has been previously dropped from 0.3 m height (Canaway, 1985; Baker et al., 1988; Bell and Holmes, 1988). Higher peak deceleration values equate to a harder surface, as the deceleration of the missile is greater when surface deformation is reduced. Lower peak deceleration values are as a result of longer ground contact times predominantly due to greater plastic displacements (Rogers III and Waddington, 1990a Baker et al., 2007). The CIST is utilised to quantify impact hardness of sports pitches under the performance quality standard (PQS), with acceptable and preferred benchmark limits evident (Bell and Holmes, 1988; Baker et al., 2007).

The effect that the grass plant has on the impact behaviour of sports pitch soils is unclear. While the contribution of roots to the stiffness and damping of soils is harder to quantify, previous research has aimed at quantifying the role of grass leaves in altering the peak deceleration of drop devices when impacting the surface. A review of the literature indicates that grass leaves have the potential to absorb some impact energy of low energy impacts, although contrasting findings have been presented. Impact energy of drop missiles can be altered by changing the mass of the missile or its drop height (assuming all potential energy is transferred to kinetic energy). Rogers III and Waddington (1989) compared grass treatments to bare soil treatments and found lower peak deceleration values measured with the 0.5 kg CIST missile from 0.55 m drop height (2.7 J). This effect was not present for the 2.25 kg missile from a drop height of 0.45 m (9.9 J). The effect that grass leaf height has on peak deceleration has also been studied. Zebarth and Sheard (1985) assessed horse racing surfaces of three leaf heights (30, 90, and 150 mm) to higher energy impacts (141 J) and found no differences in peak deceleration among treatments. Grossi et al. (2004) showed ball rebound and peak deceleration were negatively correlated with grass height in the range 10 - 25 mm when using the 0.5 kg missile dropped from 0.3 m (1.5 J). A negative correlation between leaf height (14 mm - 65 mm) and peak deceleration was also shown in an i*n-situ* study of 43 rugby pitches with the 0.5 kg missile from heights of 0.3 m and 0.55 m (McClements and Baker, 1994). Peak deceleration of a 2.5 kg missile was not affected by grass height in this study from a drop height of 1 m (24.5 J). In contrast to these findings, Mooney and Baker (2000) showed that peak deceleration of the 0.5 kg CIST missile and ball rebound heights were not significantly different across four grass leaf heights between 18 and 30 mm at a 0.55 m drop height. Baker et al. (2007) recommended the use of the heavier 2.25 kg missile in the determination of impact hardness of sports surfaces because of the potential for the lighter 0.5 kg missile to be affected by variation in grass cover or leaf height.

It is difficult to isolate grass leaf effects from grass root-soil rootzone interaction effects in the surface hardness data reported. Grass root systems grow proportionally to the maintained height of cut of the leaves, in terms of root length and mass, i.e. mowing at a greater height of cut results in a deeper and more extensive root system *c.f.* shorter mowing (Liu and Huang, 2002; Issoufou et al., 2008). These root properties could contribute to the impact behaviour of soil, creating uncertainty as to the relative contributions of the two main components of the grass plant (leaves and roots) in attributing to the impact performance of natural turf surfaces. Penetrometer devices are commonly used in Australia and New Zealand to quantify penetration resistance of natural turf sports pitches (Orchard et al., 2005; Takemura et al., 2007). Readings are considered to be unaffected by surface organic matter content (thatch) and above ground leaves, providing a means to assess the mechanical strength of surfaces without the influence of grass leaves (Orchard, 2001). Research that separates grass leaf and root components is required to provide a better understanding of the role of the grass plant in determining surface hardness and other impact behaviour.

Drop devices are considered to provide generic insights into the impact properties of sports surfaces due to deficiencies of the devices to replicate loading and boundary conditions of athletes (Nigg and Yeadon, 1987; Nigg, 1990; Young and Fleming, 2007). In particular, the duration of loading of the missiles is too short, 5.3 – 9.1 ms (Rogers III and Waddington, 1990a) compared to *ca*. 120 ms for athletes when running at 3.8 m s^{-1} (Stiles et al., 2011). These devices are also limited by the single data value that is provided (peak deceleration), although some studies have calculated other impact parameters such as impact time, time to peak deceleration, force, and displacement (Rogers III and Waddington, 1989; Rogers III and Waddington, 1990a; Rogers III and Waddington, 1990b; Carré and Haake, 2004). Impact parameters such as surface deformation, loading rate, and impact time are quantified in biomechanical studies of athletes impacting surfaces when running. The Dynamic Surface Tester (DST) device was developed recently to replicate the vertical dynamic stress an athlete imparts during running, and produces data for these parameters (Caple et al., 2011). The device represents an opportunity to investigate the response of a surface to stresses of similar magnitude and duration to those of an athlete, including the relative contribution of grass leaves in the energy absorption of athlete-specific impacts.

This study assessed the vertical impact behaviour of two sports pitch rootzones at three grass leaf heights (50 mm, 25 mm, and <1 mm), with the aim of normalising the effect of the root system in impacts. Surface impact behaviour was measured with a 0.5 kg CIST, a 2.25 kg CIST, and the DST. Penetration resistance and shear resistance of the surfaces was quantified with the GoingStick. A proposed hypothesis was that the height of the grass leaves will affect impact data for the lower energy 0.5 kg CIST missile due to the impact energy being absorbed by the grass leaves; data from the 2.25 kg CIST missile would not be affected due to the mechanical properties of the soil dominating over the effect of the grass leaves in higher energy impacts.

8.2 METHODS

8.2.1 Surface Preparation

Two sports pitch surfaces were prepared for laboratory testing on contrasting rootzones: a clay loam (24% sand, 44% silt, 32% clay) representative of soils found at amateur and community level surfaces (comparable to Pitch D-MP, Chapter 5); a sand soil (98% sand, 1% silt, 1% clay) representative of an elite level sports pitch rootzone (such as Pitches A-MP and B-MP, Chapter 5). Soil texture was determined using the pipette method (BS7755-5.4:1998). Each soil was packed in layers into a self-contained soil tank (internal dimensions: depth 350 mm, width 500 mm, length 3500 mm) to a depth of 300 mm. The soils were sown with *Lolium perenne* cv Romance (Perennial ryegrass), the most popular specie for use on natural turf sports pitches in the UK owing to its high wear and shade tolerance. The surfaces were established and maintained outside for four months from August – November 2010 at Cranfield University, Bedfordshire, UK (Lat. 52° 04' 12.68" N, Lon. 0° 37' 46.01" W). Mean day and night temperatures for this period were 13.5°C and 9.6°C respectively. The grass leaves were maintained outdoors with water as required at 50 mm height during this growing period.

8.2.2 Experimental Design

Impact parameters of the surfaces were assessed for three treatments. The treatments were created by altering the height of the grass leaves on the surface, maintaining a consistent soil-root system across the treatments. Grass leaf heights of 50 mm, 25 mm and <1 mm were selected. Leaf heights of 50 mm and 25 mm corresponded to typical leaf heights evident on rugby and football sports field surfaces respectively (Baker and Canaway, 1991; McClements and Baker, 1994), and the <1 mm treatment provided data for surfaces without the effect of leaves.

Testing was performed in descending leaf height order. When testing was completed at the 50 mm treatment, the grass leaves were cut with a pair of shears to a height of 25 mm, creating the second treatment. Grass leaf clippings were blown with compressed air from the surface to remove the potential effect they may have on dampening impacts. This procedure was repeated after testing was completed on the 25 mm treatment, where leaves were removed by cutting to the crown of the plant, producing the final treatment (<1 mm). All tests were performed on new areas of turf within the tanks to ensure data were not affected by previous tests. All testing was performed within six hours.

Within each treatment, a randomised block design was used by splitting the surface into three blocks (1170 mm length, 500 mm width), illustrated in Figure 8-1. Three replicates of each test were performed within each block, resulting in nine replicates per treatment. Data were analysed for differences between grass height treatments within each soil type, and for differences in grass height treatments between soil types using two-way ANOVA and Fisher LSD (*P*<0.05). Analysis was performed using Statistica 9 software (Statsoft Inc., Tulsa, OK., USA).

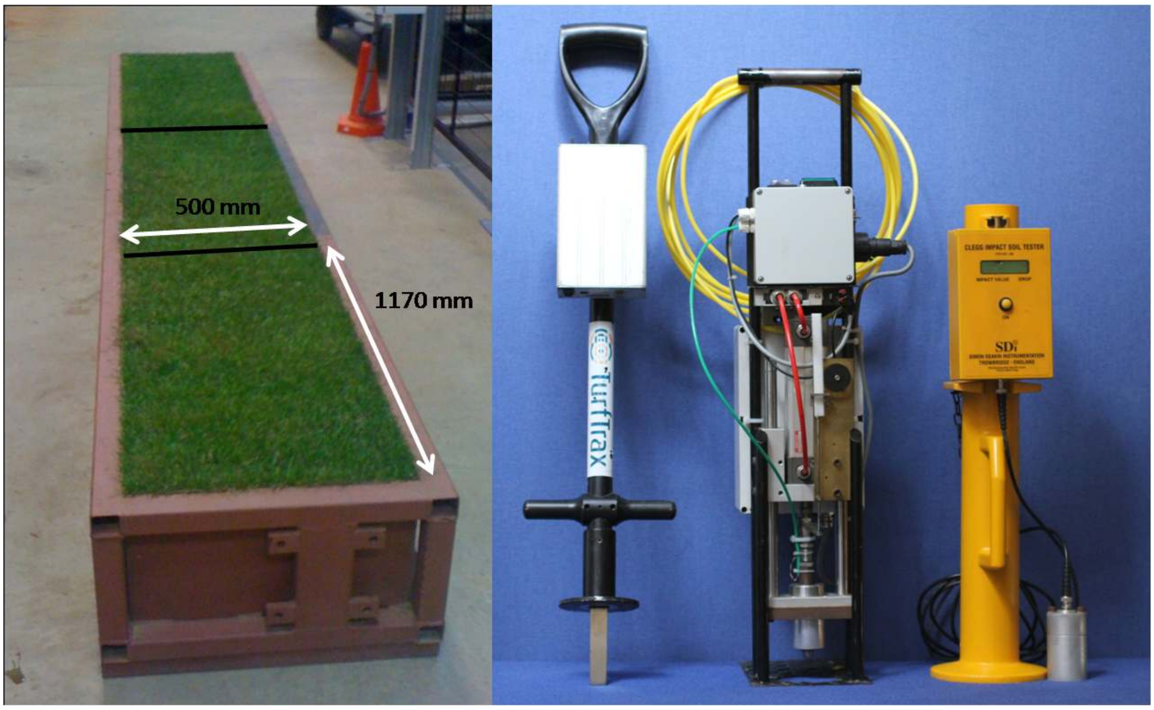

Figure 8-1 Left: the sand rootzone sports surface in the self-contained soil bin (internal dimensions: depth 350 mm, width 500 mm, length 3500 mm) prior to testing, with plots indicated. Right: Three of the test devices - (L-R) the GoingStick, The Dynamic Surface Tester (DST), and the 0.5 kg Clegg Impact Soil Tester (CIST).

8.2.3 Surface Testing

The impact devices used were a 0.5 kg and 2.25 kg CIST (both SDi Instrumentation Ltd., Bath, UK) and the DST device (Caple et al., 2011). Both CIST devices were dropped three times on the surface from heights of 0.55 m and 0.45 m for the 0.5 kg and 2.25 kg missiles respectively. It is common to use the third drop of the CIST in comparison to standard values of surface hardness in routine pitch testing (Barton et al., 2009; James and McLeod, 2010). In this study the third drop was considered but also the first drop as this represents an initial condition where the difference in turf leaf height is greatest (i.e. prior to leaf compaction from prior drops). The DST uses compressed air to displace a 100 mm stroke ram attached to a single-studded cylindrical (41 mm diameter, 38 mm height) test foot into the surface. Testing terminates when the soil resistance brings the foot to rest. The regulator pressure of the DST was set at 0.58 MPa, producing an impacting force of 682 N ± 1.9 on a reference styrene butadiene rubber shockpad (15mm thick) over concrete. This resulted in an actual vertical impact stress of 0.52 MPa, 93% of the mean stress value calculated for players running at 3.8 m s^{-1} (Guisasola, 2008). DST parameters selected to assess the rootzones were loading rate in the first 50 ms of impact (dFz_{50}), surface displacement, and surface energy absorption.

The standard CIST devices were modified to log accelerometer output over time, as per the method of Carré and Haake (2004). Accelerometer output was amplified using a Brüel & Kjær Charge Amplifier (Type 2635) and logged through a digital/analogue convertor (Tektronix 2211) at 50 kHz and stored on a laptop computer. Post processing of the signal data identified the peak deceleration in the unfiltered output. Filtering was undertaken manually as the noise in the signal occurred at a similar frequency to the actual data. The datum was defined by calculating the maximum acceleration point within a window of 1000 data points positioned 4000 data points prior to and post impact. The impact was determined as starting and ending when the acceleration signal passed through these maximum values of acceleration (see Appendix 11.8 for further details of signal filtering). Capturing the data by this method meant that there was a potential error of 7.4 % and 5.8 % in the 0.5 kg and 2.25 kg CIST devices (the ratio of the noise to the actual impact). From the acceleration-time histories, peak acceleration, time to peak acceleration, and duration of impact (contact time) were calculated. As per the method of Carré and Haake (2004), the processed accelerometer signal was integrated to determine velocity and double integrated to determine displacement. These calculations were based on the assumption that the impact velocity was 95% of the velocity determined by conversion of potential energy into kinetic energy, i.e. an assumption that there were 5% losses due to friction and air compression in the guide tube. The effect that using 100% and 90% is shown graphically in Figure 11-30 (Appendix 11.8). Using the 95% value resulted in initial impact velocities of 3.12 m s^{-1} and 2.82 m s^{-1} for the 0.5 kg and 2.25 kg missiles respectively; the 0.5 kg value is similar to the -3.1 m s^{-1} reported graphically by Carré and Haake (2004). Using ($F = ma$), force-displacement histories were produced which allowed for secant and maximum loading stiffness parameters to be calculated. All data analysis was performed in MatLab 7.1 (Mathworks, Natick, MA, USA).

Penetration and shear resistance of the rootzones were determined using the GoingStick (Dufour and Mumford, 2008). The device comprises a 100 mm long, flat steel tip that is pushed into the ground to determine penetration resistance and then pulled back along the plane of the tip to determine translational shearing resistance.

8.2.4 Surface Characterisation

Soil dry density, volumetric water content, root density and grass cover were determined for each rootzone (Table 8-1). Dry density of the soil was quantified using the core sampling method (60 mm diameter, 51.5 mm height; BS7755-5.6:1999). Dry density was greater for the sand surface, which is typical for soils of this type in the field. Volumetric water content of the soil was determined nine times per treatment using a soil water content impedance probe (type ML2x, Delta-T Devices Ltd., Cambridge, UK) and differed between surfaces due to the soil water retention characteristics of the soils – clay soils contain greater ratios of smaller pores that retain more water than sandy soils (Hillel, 1998). Saturation ratios of the soils were 0.4 for sand and 0.87 for the clay. Conversion of gravimetric water content measured with the core sampling method to volumetric water content determined the sand rootzone as 15.3% and the clay loam rootzone as 37.8%, similar to data obtained with the impedance probe (Table 8-1). Root density was determined by calculating the dry mass of roots within a core of the same dimensions used for dry density. The procedure involved hand washing and drying the samples, similar to the procedure outlined by De Baets et al. (2006). Nine replicates of dry density and root density were collected per surface at the end of testing. Grass cover percentage was quantified three times per surface prior to testing by using the frame quadrat method (BS 7370-3:1991). Grass cover was high for both surfaces (>90%; Table 8-1) and was considered to replicate the cover evident for sports pitch surfaces (Baker et al., 1992).

Table 8-1 Mean (± standard error) surface characterisation of the sand and clay loam sports pitch rootzones used in the study.

	Clay loam	**Sand**
Dry density (kg m^{-3})	1450 ± 20	1700 ± 40
Volumetric water content (%)	36.8 ± 0.2	15.1 ± 0.1
Root density (kg m^{-3})	3.8 ± 0.2	2.6 ± 0.3
Grass cover (%)	95	90

8.3 RESULTS

8.3.1 Differences between Soil Rootzones

With the exception of the first drop of the 0.5 kg CIST missile (which did not show any soil effect), the clay loam rootzone was significantly softer ($P<0.05$) than the sand rootzone. This was indicated with lower peak deceleration measured with the CIST devices (Tables 8-2 and 8-3) and lower loading rates, higher surface displacements, and greater energy absorption measured with the DST (Table 8-4). The sand rootzone was stiffer for these impacts, indicated with higher ($P<0.05$) secant stiffness and peak stiffness values measured with both CIST missiles (Tables 8-2 and 8-3). This trend was also evident in the force-displacement curves with steeper loading, higher peak force values, and lower displacements for the sand rootzone (Figure 8-2). In contrast to impact data, penetration and shear resistance of the sand rootzone measured with the GoingStick were significantly lower than the clay loam rootzone for each treatment ($P<0.05$; Table 8-4).

Using data from Tables 8-2 and 8-3, the maximum strain rates applied by the CIST missiles was 1867 mm s^{-1} and 1557 mm s^{-1} for the 0.5 kg and 2.25 kg missiles respectively. This is slightly greater than the 1333 mm s^{-1} and 1257 mm s^{-1} calculated from Rogers and Waddington's (1990) data, as a result of the surfaces deforming greater in this study.

Table 8-2 Mean (± standard error) impact data of three grass leaf height treatments (50 mm, 25 mm, <1 mm) measured with drops one and three of the 0.5 kg and 2.25 kg CIST on the clay loam sports pitch surface. Letters indicate homogenous groups tested with one-way ANOVA and Fisher LSD (*P*<0.05; between grass treatments, within same drop). Unlettered data belonged to the same homogenous group (between grass treatments).

	0.5 kg						**2.25 kg**					
	Drop 1			**Drop 3**			**Drop 1**			**Drop 3**		
Impact Parameter	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**
Peak deceleration (g)	82 ± 3 a	83 ± 2 a	100 ± 7 b	96 ± 2.3	103 ± 3.6	102 ± 2.5	29 ± 1	27 ± 1	27 ± 1	38 ± 2 a	35 ± 1 a	29 ± 1 b
Time to peak deceleration (ms)	2.1 ± 0.2	1.9 ± 0.1	1.7 ± 0.3	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.2	4.4 ± 0.4	5.2 ± 0.4	4.5 ± 0.4	4.8 ± 0.3	4.1 ± 0.1	4.0 ± 0.4
Contact time (ms)	7 ± 0.3	6.4 ± 0.2	6.9 ± 0.3	6.4 ± 0.2	6.2 ± 0.1	6.3 ± 0.1	12.9 ± 0.3 a,b	13.6 ± 0.3 a	12.7 ± 0.2 b	11.6 ± 0.3	11.7 ± 0.2	12.3 ± 0.4
Peak displacement (mm)	10.1 ± 0.7	9.4 ± 0.3	8.5 ± 0.3	8.1 ± 0.2	7.9 ± 0.3	7.7 ± 0.3	19.1 ± 0.6	20.2 ± 0.7	19.7 ± 0.5	15.4 ± 0.7 a	16.3 ± 0.6 a	19.1 ± 0.7 b
Secant stiffness (N mm^{-1})	72 ± 5 a	81 ± 7 a,b	110 ± 13 b	159 ± 9 a	203 ± 21 b	214 ± 26 b	63 ± 5	51 ± 3	56 ± 3	78 ± 5	78 ± 3	67 ± 5
Peak stiffness (N mm^{-1})	144 ± 20	143 ± 12	249 ± 50	299 ± 33	323 ± 41	325 ± 48	257 ± 11 a	224 ± 15 a	341 ± 42 b	409 ± 85	438 ± 31	474 ± 47

Table 8-3 Mean (± standard error) impact data of three grass leaf height treatments (50 mm, 25 mm, <1 mm) measured with drops one and three of the 0.5 kg and 2.25 kg CIST on the sand sports pitch surface. Letters indicate homogenous groups tested with one-way ANOVA and Fisher LSD (*P*<0.05; between grass treatments, within same drop). Unlettered data belonged to the same homogenous group (between treatments).

	0.5 kg						**2.25 kg**					
	Drop 1			**Drop 3**			**Drop 1**			**Drop 3**		
Impact Parameter	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**	**50 mm**	**25 mm**	**<1 mm**
Peak deceleration (g)	71 ± 8 a	81 ± 7 a	99 ± 8 b	142 ± 5.1	142 ± 5.6	143 ± 4.4	44 ± 2	42 ± 2	44 ± 2	63 ± 2 a	62 ± 1 a	52 ± 1 b
Time to peak deceleration (ms)	1.8 ± 0.2	1.7 ± 0.2	1.4 ± 0.1	1.2 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	2.9 ± 0.2	3.2 ± 0.2	2.5 ± 0.3	1.8 ± 0.1	1.9 ± 0.1	2.0 ± 0.1
Contact time (ms)	7.1 ± 1.2	6 ± 0.3	5.8 ± 0.6	5.0 ± 0.3 a	4.9 ± 0.3 a	4.3 ± 0.3 b	9.1 ± 0.3	9.4 ± 0.3	9.3 ± 0.3	8.0 ± 0.3	8.0 ± 0.2	8.2 ± 0.2
Peak displacement (mm)	12.5 ± 1.0 a	11.2 ± 0.5 a	9.4 ± 0.9 b	7.5 ± 0.5 a	7.6 ± 0.4 a	6.4 ± 0.5 b	13.4 ± 0.6	13.7 ± 0.4	13.5 ± 0.6	10.0 ± 0.4 a	10.2 ± 0.2 a	12.1 ± 0.5 b
Secant stiffness (N mm^{-1})	77 ± 19 a	87 ± 12 a,b	117 ± 12 b	216 ± 18	233 ± 21	223 ± 19	142 ± 16	123 ± 9	181 ± 45	301 ± a	287 ± 10 a	241 ± 14 b
Peak stiffness (N mm^{-1})	195 ± 21	189 ± 10	224 ± 28	336 ± 32	371 ± 44	425 ± 49	344 ± 39 a	312 ± 30 a	496 ± 52 b	668 ± 67	630 ± 32	649 ± 43

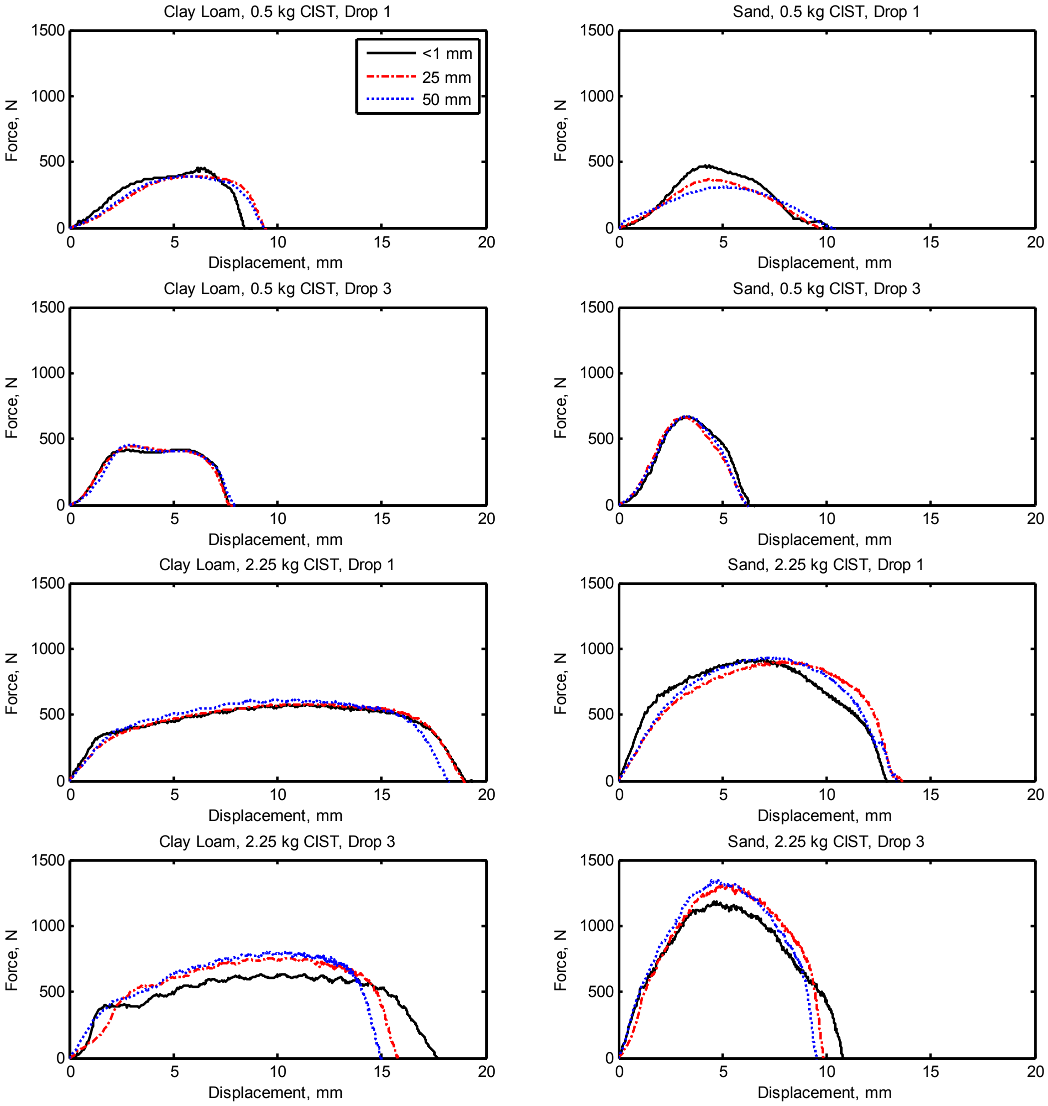

Figure 8-2 Mean force-displacement curves from drops one and three of the 0.5 kg and 2.25 kg CIST devices (derived from integration of acceleration data) for the clay loam and sand sports pitch rootzones at three grass heights (<1 mm, 25 mm, 50 mm).

Table 8-4 Mean (± standard error) penetration resistance and shear resistance measured by the GoingStick; dFz_{50} (loading rate in first 50 ms of impact), displacement, and energy absorption measured with the DST device of the two sports pitch surfaces at different grass leaf height treatments (50 mm, 25 mm, <1 mm). Letters indicate homogenous groups tested with two-way ANOVA and Fisher LSD ($P<0.05$).

	50 mm	**25 mm**	**0 mm**
GoingStick			
Penetration resistance (MPa)			
Clay loam	4.7 ± 0.2a	4.5 ± 0.2a	5.1 ± 0.2a
Sand	4.2 ± 0.1b	4.1 ± 0.3b	3.7 ± 0.1b
Shear resistance (Nm)			
Clay loam	26.0 ± 0.5a	25.0 ± 1.4a	24.7 ± 0.8a
Sand	7.0 ± 0.2b	8.6 ± 0.6b	7.7 ± 0.3b
DST			
Loading rate (kN s^{-1})			
Clay loam	9.1 ± 0.1a	9.1 ± 0.1a	8.8 ± 0.1a
Sand	10.4 ± 0.2b	10.1 ± 0.9b	10.2 ± 0.1b
Displacement (mm)			
Clay loam	39.3 ± 0.6a	40.4 ± 0.8a	41.4 ± 0.6a
Sand	24.9 ± 0.9b	25.6 ± 0.7b,c	28.1 ± 1.6c
Energy absorption (kJ)			
Clay loam	4.35 ± 0.33a	4.37 ± 0.18a	4.50 ± 0.09a
Sand	1.38 ± 0.35b	1.49 ± 0.46b	1.70 ± 0.18b

The majority of peak deceleration data measured with the CIST devices were within the ‘acceptable’ ranges of values for impact hardness of sports pitch surfaces outlined in the PQS framework (30-180 g for rugby and 35-200 g for football with the 0.5 kg missile; 30-110 g for rugby and 35-120 for football with the 2.25 kg missile; (Baker et al., 2007). The exception to this was drop one data of the 2.25 kg CIST missile in all treatments on the clay loam, and drop three data of the 2.25 kg missile in the <1 mm treatment on the clay loam, which had lower peak decelerations than these benchmarks (Tables 8-2 and 8-3).

8.3.2 The Effect of Changing Grass Leaf Height

Peak deceleration measured from the first drop of the 0.5 kg CIST was lower (*P*<0.05) in the 50 mm and 25 mm leaf height treatments than the <1 mm treatment (Tables 8-2 and 8-3). This effect of grass was also evident in the secant loading stiffness, which was lower (*P*<0.05) in the 50 mm treatment than the <1 mm treatment for both rootzones on the first drop. However, no differences (*P*>0.05) were found between treatments for the third drop data of the 0.5 kg CIST on both rootzones (Tables 8-2 and 8-3).

There was no significant differences (*P*>0.05) in peak deceleration of the 2.25 kg CIST among leaf height treatments on the first drop, indicating the effect of leaves was negligible for this heavier missile. Peak deceleration was significantly lower in the <1 mm treatment for both rootzones on the third drop however, and was accompanied by greater peak displacement in this treatment for both rootzones (*P*<0.05; Tables 8-2 and 8-3). Greater (*P*<0.05) displacement was produced in the first drop for both missiles in comparison to the third drop on both rootzones and in all treatments. Stiffness was also greater (*P*<0.05) for the third drop than the first (Figure 8-2; Tables 8-2 and 8-3).

There was no significant difference (*P*>0.05) in DST data among leaf height treatments, with the exception of surface displacement being greater in the <1 mm treatment than in the 50 mm treatment for the sand rootzone (*P*<0.05; Table 8-4). There were no significant differences (*P*>0.05) in penetration resistance or shear resistance among the height of cut treatments for both rootzones (Table 8-4).

8.4 DISCUSSION

The study assessed impact parameters of sports pitch rootzones with the effect of the root system normalised (i.e. without root adaptation to cutting height), an approach which has not previously been reported. It must be noted that the morphology of the plants at the 25 mm and <1 mm treatments were that of a 50 mm plant reduced to lower heights of cut. This is a limitation of the study, as shoot numbers per area are typically higher for lower heights of cut on turf when maintained continuously at these heights (Grossi et al., 2004), and may contribute to the effect that grass has to absorb impacts

(Baker et al., 2007). Only one soil mechanical condition per soil type has been considered. Variation in root density, soil water content, dry density, or grass species have been shown to contribute to soil strength and impact behaviour (Rogers III and Waddington, 1990a; Tengbeh, 1993; McNitt et al., 1997; Guisasola et al., 2010b). Future work should determine whether or not variation in these parameters interacts with grass leaf height to affect impact behaviour of surfaces *in situ*.

The contrasting ranking of the rootzones by the impact devices and the GoingStick highlights the difference between relatively dynamic vertical impact testing and slower loading rate/strain rate shear testing. Sand sports pitch soils have been shown to have higher dynamic stiffness than clay dominated soils both in mechanical and biomechanical tests (Guisasola et al., 2010b; Stiles et al., 2011). The lower dynamic strength of the clay loam rootzone, indicated with higher plastic deformation and lower peak deceleration values, can be explained by the high saturation ratio evident for the soil (0.87). The shear resistance of sand soils is less sensitive to water content, which has driven the selection of sand rootzones for sports pitch surfaces (Guisasola et al., 2010a). However, the shear resistance of sand rootzones is often increased *in-situ* with the addition of synthetic fibres mixed or woven into the soil (Baker and Woollacott, 2005; Spring and Baker, 2006), which was not replicated in this study.

Baker et al. (2007) proposed, based on peak deceleration alone, that some of the impact energy of 0.5 kg CIST missile is absorbed by the grass leaves before contact with the soil is made. This effect was evident in the data, with the derived force-displacement histories (Figure 8-2) showing that work was done on deforming the grass leaf in the first drop which slowed the missile and reduced peak deceleration in the 50 mm and 25 mm treatments. Deformation of the grass leaf is not recovered in the less than 20 s between the first and third drops however, so the attenuation effect of the grass is not observed in the third drop. This is considered time-dependent, as leaves would be expected to recover over a longer period of time (not measured but greater than one hour).

The surfaces exhibited an increased resilience to loading under repeated impacts with both CIST missiles, which was evident through greater displacement and lower stiffness in the first drop data compared to the third. This is typical behaviour of soils under repeated loading due to increased packing and optimised orientation of particles which increases shear resistance (O'Reilly and Brown, 1991). This behaviour was shown in the cyclic loading of soils in Chapter 7. The effect of leaves was negligible for the heavier 2.25 kg missile in the first drop. Inspection of Figure 8-2 shows that there is work done on the grass leaf but that this is a small proportion of the energy of the impact and the total work done on the soil, which is greater for the 2.25 kg CIST in comparison to the 0.5 kg missile. Greater displacement of surfaces under impact reduces the impact impulse, which reduces peak deceleration of the CIST missiles (assuming Newton's second law). This was evident for the third drop of the 2.25 kg missile on the rootzones. For this missile, the turf leaves (25 mm and 50 mm) do not reduce peak deceleration by attenuating the missile (as evident for the 0.5 kg missile), but actually increase peak deceleration by reinforcing the soil and reducing penetration.

The data obtained with the DST provides an insight into the behaviour of the rootzone surfaces to athlete-specific impacts, due to the replication of the vertical stress component of athlete loading over a longer time period (Caple et al., 2011). The results showed that grass leaves did not influence surface loading rate and energy absorption of the rootzones, and may not affect the energy absorption athletes receive from surfaces during loading whilst running (in the range of leaf heights tested). Insensitivity to grass length has previously been cited as an advantage of using penetrometer type devices over dynamic drop devices in the quantification of rootzone soil strength (Orchard, 2001). In addition, shear resistance of sports pitch rootzones is closely linked to traction of athletes wearing studded footwear (Canaway and Bell, 1986). Rogers III and Waddington (1989) reported that shear resistance of rootzones is reduced when leaves are removed from the surface but there is no evidence to support that in this study.

The production of a variety of CIST impact parameters allowed the role of grass leaves in absorbing impacts to be explored in greater detail than would be provided with peak deceleration values alone. Production of other impact parameters from CIST devices has been employed in studies previously. In the assessment of synthetic cricket surfaces, Carré and Haake (2004) found that surfaces were considered to 'play' similarly despite variations in peak deceleration data, suggesting this variable alone is not sufficient to characterise surfaces. Rogers and Waddington (1990b) found high correlation coefficients between impact parameters for turfed surfaces, but suggested both peak deceleration and time increments such as total and peak impact times should be used when comparing between turfed and bare soil treatments. In the data presented, statistical differences ($P<0.05$) were detected between some treatments. However, consistent trends were not evident across parameters or between missiles, limiting the conclusions that can be drawn from the data. Determination of these further parameters by integration in the study helped to characterise the nature of the loading for the CIST test but based on the data presented, peak deceleration alone provided insight into the effect of grass leaf height on the relative hardness of sports pitch rootzones. It is hypothesised that some elastic surface recovery should be measured with the CIST devices (assuming the missile remains in contact with the surface as it is unloaded). Evidence of this was not present in the raw acceleration signals, and would be indicated by a spike of acceleration after the impact. Due to the noise in the signal (presumably due to cable quality), the method in which the impact was filtered (Appendix 11.8) meant that elastic recovery would not have been measurable in any case. Therefore, it is evident that in its current set-up, the CIST is not able to accurately measure elastic surface properties on natural turf surfaces.

The contrasting categorisation of the grass leaf treatments with CIST drop number is an important finding that must be considered in the context of surface performance and future surface testing. Utilising the data presented, the sand and clay loam rootzones would be categorised as performing similarly if data from the first drop of the 0.5 kg CIST was used in isolation. Drops one, three and four of the 0.5 kg CIST have been used in the past to classify surfaces (Gibbs et al., 2000; Chivers and Aldous, 2003), with many research studies presented in the literature failing to state which drop number was selected for use. This restricts comparison of data across studies and it must be regarded as essential for researchers to provide details of drop number used in all research, as data presented here show that drops one and three differ due to the stress histories of surfaces. Gibbs et al. (2000) suggested that the consecutive drops of the CIST measure the behaviour of different surface profiles of turf surfaces (with increasing drop numbers corresponding to deeper rootzone layers). This would be restricted to rootzone depths <100 mm (Dixon et al., 2008). The data presented suggest that data from the first drop provide an insight into single impacts occurring on the turf surface, while subsequent drops are affected by compaction of both grass and soil, and thus represent the mechanical behaviour of the rootzone, which is likely to be significant in high wear areas on sports pitch surfaces.

A variety of impacts can occur on sports pitches within games – ball impacts, athlete impacts during running, athlete impacts from falls or to the head. An important aspect of sport surface testing is for specific research objectives and parameters to be identified, with appropriate devices selected to assess these parameters (Bartlett et al., 2009). This is particularly important in surface impact testing of natural turf sports pitches due to the non-linear stress-strain behaviour of soil that has been highlighted in this study and previous chapters. Loading conditions (force, stress, loading rate, contact time, strain rate) from specific impacts are required to be replicated with mechanical devices in order for specific types of impacts to be assessed. This was identified in the development of the DST device (Caple et al., 2011). Table 8-5 illustrates the difference in peak force and loading duration for the two CIST missile masses and the DST. Comparing these impacts, peak forces were 659 N and 1180 N, with contact times of 211 ms and 8.2 ms for the DST and third drop of the 2.25 kg CIST respectively in the 25 mm treatment on the sand surface. The longer ground contact time of the DST device is a consequence of its design, the compressed-air regulated system of the DST device drives the test foot into the surface until it stops moving (i.e. when soil resistance is equal to the stress generated by regulated pressure in the ram), as opposed to being dropped and rebounding from the surface like the CIST missiles. The function of the devices also causes strain rates to vary significantly – up to 300 mm s^{-1} for the DST and up to 1557 mm s^{-1} for the 2.25 kg CIST. Comparing the impact devices to athlete loading (Guisasola, 2008; Stiles et al., 2011), both the 2.25 kg CIST and DST devices provided similar peak stress values, but only the DST provided a similar contact time (Table 8-5). In this respect, the DST can therefore be considered to provide a better replication of the loading conditions of athletes than the CIST devices. Future biomechanical studies should aim to quantify the strain rate of athlete-surface interaction on natural turf.

Table 8-5 Comparison of impact data for drop three of the CIST devices and DST for the 25 mm treatment on the sand rootzone, and a 80 kg human running at 3.8 m s^{-1} (from Guisasola, 2008; Stiles et al., 2011).

Device	**Peak force (N)**	**Peak stress (kN m^{-2})**	**Duration of loading (ms)**
CIST (0.5 kg)	673	343	4.3
CIST (2.25 kg)	1180	600	8.2
DST	659	499	211
Human (80 kg) running at 3.8 m s^{-1}	2100	553	120

Bell and Holmes (1988) and Fleming et al. (2004) have suggested that the 0.5 kg CIST should be used for the assessment of surfaces with respect to ball impact and ball rebound height. An implication from this study is that ball rebound would have been lower on the 50 mm and 25 mm treatments compared to the <1 mm treatment on both surfaces. The 2.25 kg CIST missile has not as yet been shown to replicate any specific impacts that occur on sports pitches, and must be regarded solely as a device providing a generic value of surface condition (Young and Fleming, 2007). Further research is also required into head impact injury potentials on natural turf sports pitches. More sophisticatedly designed drop devices are often used for this purpose on playground surfaces, which replicate the loading and boundary conditions of head-surface interaction (Shorten, 2003). The use of this type of device on natural turf sports pitch surfaces has been limited largely to comparisons between natural turf and artificial sports surfaces (Theobald et al., 2010), without consideration of the mechanisms that affect impact absorption on natural turf.

8.5 CONCLUSIONS

The effect of grass leaf height on absorbing impacts on natural turf sports pitch surfaces was shown to be dependent upon the testing device used (impact mechanism), the impact parameter measured, the energy of the impacting object, and the number of impacts performed. Grass leaves were shown to absorb some of the impact energy from the lighter 0.5 kg CIST missile, which may affect impacts occurring from balls on these surfaces. However, this effect may be removed once the grass leaves are flattened from repeated impacts which can occur in game situations. In higher energy impacts from the 2.25 kg CIST, impact absorption by the grass was insignificant and was dominated by the soil-root system for single impacts. Under repeated high energy impacts, the grass leaves reinforced the soil, preventing plastic deformation which resulted in greater peak deceleration in the <1 mm treatment. Under impacts of longer duration that are more typical of those encountered in athlete-surface interaction, grass leaf treatments were not significant in determining surface loading rate or energy absorption, suggesting that grass leaves may not influence the impacts encountered in athlete-surface interaction. Surface management should aim to maintain grass cover of sports pitch rootzones to provide consistency in impact behaviour, with the presence of grass leaves (between 25 – 50 mm) shown to be more important than specific heights of leaves in regulating impacts. It is important that future surface impact testing ensures research objectives are determined and devices are used which replicate the loading conditions of specific impacts occurring on sports pitch surfaces. Future use of the CIST devices should also consider the effect of impact energy and drop number on surface classification, which should be stated clearly in the research.

8.6 ACKNOWLEDGEMENTS

The authors would like to acknowledge David Bartlett for supplying and providing technical assistance of the DST device, and the UK Engineering and Physical Sciences Research Council (EPSRC) for funding this research.

8.7 REFERENCES

American Society for Testing and Materials (2000), *Annual book of ASTM standards. Vol. 15.07. End use products. Standard test for shock attenuation characteristics of natural playing surface systems using lightweight portable apparatus. F1702-96.* ASTM, West Conshohocken, PA.

Baker, S. W. and Canaway, P. M. (1991), The cost effectiveness of different construction methods for association football pitches. I. Soil physical properties, *Journal of the Sports Turf Research Institute,* vol. 66, pp. 8-20.

Baker, S. W., Cole, A. R. and Thornton, S. L. (1988), Performance standards and the interpretation of playing quality for soccer in relation to rootzone composition, *Journal of the Sports Turf Research Institute,* vol. 64, pp. 120-132.

Baker, S. W., Gibbs, R. J. and Adams, W. A. (1992), Case studies of the performance of different designs of winter games pitches. I. Playing quality and usage, *Journal of the Sports Turf Research Institute,* vol. 68, pp. 20-32.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Baker, S. W. and Woollacott, A. R. (2005), Comparison of the playing performance of third generation artificial grass with natural turf used for professional soccer, *International Turfgrass Society Research Journal,* vol. 10, no. 1, pp. 15-26.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

Barton, L., Wan, G. G. Y., Buck, R. P. and Colmer, T. D. (2009), Effectiveness of cultural thatch-mat controls for young and mature kikuyu turfgrass, *Agronomy Journal,* vol. 101, no. 1, pp. 67-74.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

BS 7370-3:1991 (1991), *Grounds Maintenance. Recommendations for amenity and functional turf (other than sports turf).* British Standards Institute, London.

BS7755-5.4:1998 (1998), *Soil quality. Physical methods. Method by sieving and sedimentation.* British Standards Institution, London.

BS7755-5.6:1999 (1999), *Soil quality. Physical methods. Determination of dry bulk density.* British Standards Institution, London.

Canaway, P. M. (1981), Wear tolerance of turfgrass species, *Journal of the Sports Turf Research Institute,* vol. 57, pp. 65-83.

Canaway, P. M. (1985), Playing Quality, Construction and Nutrition of Sports Turf, in: Lemarie, F. (ed), *Proceedings of the Fifth International Turfgrass Research Conference,* Avignon, France, pp. 45-56.

Canaway, P. M. and Bell, M. J. (1986), An apparatus for measuring traction and friction on natural and artificial playing surfaces, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 211-214.

Caple, M. C. J., James, I. T., Bartlett, M. D. and Bartlett, D. I. (2011), Development of a simplified dynamic testing device for turfed sports surfaces, *Journal of Sports Engineering and Technology,* vol. 225.

Carre, M. J. and Haake, S. J. (2004), An examination of the Clegg impact hammer test with regard to the playing performance of synthetic sport surfaces, *Sports Engineering,* vol. 7, no. 3, pp. 121-129.

Chivers, I. H. and Aldous, D. E. (2003), Performance monitoring of grassed playing surfaces for Australian rules football, *Journal of Turf and Sports Surface Science,* vol. 79, pp. 73-80.

Clegg, B. (1976), An impact testing device for in situ base course evaluation, in: *Proceedings of the 8th ARRB Conference, vol. 8, no. 8*, Perth, Australia, pp. 1-6.

De Baets, S., Poesen, J., Gyssels, G. and Knapen, A. (2006), Effects of grass roots on the erodibility of topsoils during concentrated flow, *Geomorphology,* vol. 76, no. 1-2, pp. 54-67.

Dixon, S. J., James, I. T., Blackburn, K., Pettican, N. and Low, D. (2008), Influence of footwear and soil density on loading within the shoe and soil surface during running, *Journal of Sports Engineering and Technology,* vol. 222, pp. 1-10.

Dufour, M. J. D. and Mumford, C. (2008), GoingStick technology and electromagnetic induction scanning for naturally-turfed sports surfaces, *Sports Technology,* vol. 1, no. 2-3, pp. 125-131.

Dura, J. V., Hoyos, J. V. and Martinez, A. (1999), The effect of shock absorbing sports surfaces in jumping, *Sports Engineering,* vol. 2, no. 2, pp. 97-102.

Fleming, P., Young, C. and Dixon, N. (2004), Performance measurements on synthetic turf hockey pitches, in: Hubbard, M., Mehta, R. and Pallis, J. M. (eds.) *The Engineering of Sport 5 vol. 2,* ISEA, Sheffield, pp. 524-531.

Gibbs, R. J., Liu, C., Yang, M. H. and Wrigley, M. (2000), Effect of rootzone composition and cultivation/aeration treatment on surface characteristics of golf greens under New Zealand conditions, *Journal of Turfgrass Science,* vol. 76, pp. 37-52.

Grossi, N., Liu, C., Yang, M. H. and Wrigley, M. (2004), Tall fescue turf quality and soccer playing characteristics as affected by mowing height, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields,* ISHS, Leuven, pp. 319-322.

Guisasola, I. (2008), *Human-natural sports surface interaction* (unpublished PhD thesis), Cranfield University, Cranfield.

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010a), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010b), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Hillel, D. (1998), *Environmental Soil Physics,* Academic Press, San Diego, CA.

Issoufou, M., Zaman-Allah, M., Ferchichi, A. and Ferjani, E. (2008), Clipping effects on the growth variation, water use efficiency and photosynthetic activity in Buffel grass (Cenchrus ciliaris L.) poaceae, *Asian Journal of Plant Sciences,* vol. 7, no. 1, pp. 95-99.

James, I. T. (2011), Advancing natural turf to meet tomorrow's challenges, *Sports Engineering and Technology,* vol. 225, pp. 115-129.

James, I. T. and McLeod, A. J. (2010), The effect of maintenance on the performance of sand-filled synthetic turf surfaces, *Sports Technology,* vol. 3, no. 1, pp. 43-51.

James, S. L., Bates, B. T. and Osternig, L. R. (1978), Injuries to runners, *American Journal of Sports Medicine,* vol. 6, no. 2, pp. 40-50.

Liu, X. and Huang, B. (2002), Mowing effects on root production, growth, and mortality of creeping bentgrass, *Crop Science,* vol. 42, no. 4, pp. 1241-1250.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

McNitt, A. S., Middour, R. O. and Waddington, D. V. (1997), Development and Evaluation of a Method to Measure Traction on Turfgrass Surfaces, *Journal of Testing and Evaluation,* vol. 25, no. 1, pp. 99-107.

Mooney, S. J. and Baker, S. W. (2000), The effects of grass cutting height and pre-match rolling and watering on football pitch ground cover and playing quality, *Journal of Turfgrass Science,* vol. 76, pp. 70-77.

Murphy, J. W., Field, T. R. O. and Thomas, V. J. (1996), Racetrack traction assessment by penetrometer. Part II application of the model, *Journal of Turfgrass Management,* vol. 1, no. 4, pp. 51-62.

Naunheim, R., McGurren, M., Standeven, J., Fucetola, R., Lauryssen, C. and Deibert, E. (2002), Does the use of artificial turf contribute to head injuries?, *Journal of Trauma - Injury, Infection and Critical Care,* vol. 53, no. 4, pp. 691-694.

Newell, A. J., Hart-Woods, J. C. and Wood, A. D. (1999), The effect of three different levels of shade on the performance of three grass mixtures for use on lawn tennis courts, *Journal of Turfgrass Science,* vol. 75, pp. 82-88.

Nigg, B. M. (1990), The validity and relevance of tests used for the assessment of sports surfaces, *Medicine and science in sports and exercise,* vol. 22, no. 1, pp. 131-139.

Nigg, B. M. and Yeadon, M. R. (1987), Biomechanical aspects of playing surfaces, *Journal of sports sciences,* vol. 5, no. 2, pp. 117-145.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Orchard, J. W., Chivers, I., Aldous, D., Bennell, K. and Seward, H. (2005), Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass, *British Journal of Sports Medicine,* vol. 39, no. 10, pp. 704-709.

O'Reilly, M. P. and Brown, S. F. (1991), Cyclic loading in geotechnical engineering, in: O'Reilly, M. P. and Brown, S. F. (eds.) *Cyclic loading of soils: from theory to design,* Blackie & Son Ltd., London, pp. 1-18.

Rogers III, J. N. and Waddington, D. V. (1989), The effect of cutting height and verdure on impact absorption and traction characteristics in tall fescue turf, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 80-90.

Rogers III, J. N. and Waddington, D. V. (1990a), Effects of management practices on impact absorption and shear resistance in natural turf, in: Schmidt, R. C., Hoerner, E.F., Milner, E. M. and Morehouse, C. A. (eds), *Natural and artificial playing fields: characteristics and safety features,* ASTM, PA., pp. 136-146.

Rogers, J. N. I. and Waddington, D. V. (1990b), Portable apparatus for assessing impact characteristics of athletic field surfaces, in: Schmidt, R. C., Hoerner, E.F., Milner, E. M. and Morehouse, C. A. (eds), *Natural and artificial playing fields: characteristics and safety features,* ASTM, PA., pp. 96-110.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Spring, C. A. and Baker, S. W. (2006), Examination of a new form of fibre reinforcement including polypropylene and polyurethane fibres for winter games pitch rootzones, *Journal of Turfgrass and Sports Surface Science,* vol. 82, pp. 30-37.

Stefanyshyn, D. J. and Nigg, B. M. (2003), Energy and performance aspects in sports surfaces, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. and Dixon, S. (2007), Biomechanical response to systematic changes in impact interface cushioning properties while performing a tennis-specific movement, *Journal of Sports Sciences,* vol. 25, no. 11, pp. 1229-1239.

Stiles, V. H., Guisasola, I. N., James, I. T. and Dixon, S. J. (2011), Biomechanical response to changes in natural turf during running and turning, *Journal of Applied Biomechanics,* vol. 27, no. 1, pp. 54-63.

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British journal of sports medicine,* vol. 41, no. 9, pp. 582-587.

Tengbeh, G. T. (1993), The effect of grass roots on shear strength variations with moisture content, *Soil Technology,* vol. 6, no. 3, pp. 287-295.

Theobald, P., Whitelegg, L., Nokes, L. D. M. and Jones, M. D. (2010), The predicted risk of head injury from fall-related impacts on to third-generation artificial turf and grass soccer surfaces: A comparative biomechanical analysis, *Sports Biomechanics,* vol. 9, no. 1, pp. 29-37.

Young, C. and Fleming, P. R. (2007), A review of mechanical impact testing devices for sport surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Zebarth, B. J. and Sheard, R. W. (1985), Impact and shear resistance of turf grass racing surfaces for Thoroughbreds, *American Journal of Veterinary Research,* vol. 46, no. 4, pp. 778-784.

9. RESEARCH SYNTHESIS

9.1 INTRODUCTION

This research synthesis will draw together and present the main outcomes of the individual chapters in a wider context. Firstly, the implications of the research findings within the context of three key areas are detailed: surface testing of natural turf pitches, athlete performance and injury occurrence, and surface engineering and management. Secondly the key contributions to knowledge that the research has provided is summarised. Finally, the limitations of the research and future recommendations are presented.

9.2 IMPLICATIONS OF THE RESEARCH

9.2.1 Testing of Natural Turf Pitches

The development of the GoingStick and DST devices aids in improving surface testing of natural turf sports pitches. The DST allows the dynamic behaviour of pitches to be assessed to stresses representative of a player running on natural turf. The device can be used more easily to collect *in-situ* data than many other Category 2 type devices considered in the literature: the device and air cylinder attach onto a sack barrow, can be operated by a single operator, and can be used in inclement weather. However, as with the majority of Category 2 devices, the device is currently a one-off prototype used for research, with mass production unlikely without substantial financial investment, and infeasible due to the potential retail price of the device.

The rate at which the stress is applied by the DST device was shown to be 7 times slower than a human in Chapter 3, and this may affect the classification of surfaces as a result of the non-linear behaviour of natural turf. However, the loading rate applied by the device (up to 10.3 kN s^{-1} recorded on the soil treatments in Chapter 3) is greater than the capabilities of the 'dynamic' triaxial apparatus (6.5 kN s^{-1}), and impacts were shown to be more representative of athlete contact times than use of the CIST devices in Chapter 8. As would be expected, the strain rate of the device during impact with the surface varied as the test foot penetrated further into the surface, lending to slow quasi-static failure of the surface on mechanically weaker soils before the foot was brought to rest. This change in strain rate would also be expected of the soil under athlete impacts, meaning measurement of this behaviour by the device is important. Strain rates are required to be calculated in future biomechanical studies for further device comparison.

The DST is currently the only device that can be found in the literature replicating a specific loading component of athletes that can be used efficiently on natural turf. Similar to the AAB device, the DST device determines the absorption of impacts and does not provide an indication of the ratio of energy return that may be achieved on sports surfaces. As considered in the literature review (Chapter 2), these devices may be more applicable to assess the potential energy absorption of surfaces for athletes when contact is made with the surface accidently, i.e. where biomechanical adaptions cannot be made. The lack of biomechanical data available for these types of surface impacts means modelling devices to assess these components is currently difficult.

The GoingStick provides an efficient means to provide surface mechanical data in two orientations, and could be used to assess the penetration and shear resistance of a pitch at 15 locations within 15 minutes. This increases the possibility of it being used as a surface assessment tool by ground managers in the future. The device has already gained widespread use in the horseracing industry for this purpose as a result of the usefulness of the data produced (going index), the ease of downloading data, and ease of use by non-specialists. Therefore, transference of this technology for use on sports pitches does not require large capital investment for development and manufacturing.

The conclusions drawn from data collected with the CIST devices within this project have consequences for the future use of these devices, stemming from the measurement mechanism and the precision of measurement of the devices. The spatial dependency of data in Chapter 6 was shown to vary with drop number of the 2.25 kg CIST: drop one data was not spatially related; drop three data was spatially related. This behaviour can be explained by data of the first drop being affected by the combined effects of grass leaves, thatch, and the soil under a single impact. After two consecutive drops, flattening of grass leaves and compaction of the thatch and soil takes place. As soil gets more compacted under dynamic impacts, a change in the microstructure occurs as particles are orientated closer together and optimally orientated to increase soil stiffness and elasticity. This behaviour reduces the variation in the data for the third drop of the CIST missile and causes data to be more closely related across the pitch. For example, coefficient of variation varied from 0.16 in the first drop to 0.09 in the third drop on Pitch C in the end of season dataset.

The increase in soil stiffness after repeated drops of the CIST causes third drop data to classify surfaces as harder than the initial first drop. Twomey et al. (2011) showed that selection of first drop data on turf surfaces indicated a surface that conformed to benchmark standards, while third drop data exceeded the limits. This is a reason as to why a consensus must be made for the use of specific drop numbers in the use of the 2.25 kg CIST devices for surface benchmarking purposes worldwide. It is suggested that both first and third drop data are used: first drop data to provide insight into surface behaviour relating to single impacts on a surface; third drop data to indicate the dynamic behaviour of the soil when compacted under repeated impacts that may occur in game situations.

Variation in surface classification using the CIST devices was also shown in the grass height study (Chapter 8), where drop one of the 0.5 kg CIST showed reduced peak deceleration provided by the energy absorbing effect of the grass leaves. This effect was removed in drop three when the grass leaf was flattened after two consecutive drops. The effect of grass leaves affecting the magnitude and variance of data is a reason why the 0.5 kg missile has been less commonly used within surface testing in recent years (Baker et al., 2007). However, the impact force of the 0.5 kg missile has been shown to be similar to a ball (Fleming et al., 2004), and peak deceleration data has been correlated to ball rebound height (Bell and Holmes, 1988), indicating the device has a role to play in assessing ball-surface interaction in future surface testing. This is in comparison to the 2.25 kg CIST, which has as yet not been shown to replicate specific impacts occurring on natural turf pitches.

This research project showed that the hardness of two modern elite sand rootzone pitches exceeded benchmark limits outlined under the PQS framework for the 2.25 kg

CIST, potentially indicating that these benchmarks are obsolete for the modern pitch. Alternatively, this may also suggest that modern pitches are too hard. It is apparent from these data that the limits for surface hardness need re-evaluating, but the construction of these limits should be based on more scientific founding than simply increasing the limits based on collected data or on player perceptions. Although enforcement of benchmark limits on natural turf through regulatory standards is not currently favourable owing to the exclusion it may cause at facilities low in maintenance resources (McAuliffe, 2008), relation of these limits to specific tolerances of the human body in impact would provide more meaningful surface criteria. An approach to formulating the maximum limit for surface hardness should compare surface behaviour to head injury risk, being the only injury mechanism that currently has defined tolerance levels for the human body. The Head Injury Criterion (HIC) is used in the automotive and playground manufacturing industries to assess potential impacts occurring to the head. A HIC score of over 1000 details an impact where the risk of fatal head injury is non-zero (Shorten, 2003), and this should be regarded as the starting point for future impact assessment of natural turf surfaces relating to player safety.

The benefit of using different numbers of pitch testing locations in surface classification requires exploration. In the spatial study, 150 and 135 pitch locations were adopted. Data from these locations was used to assess the spatial dependency of the mechanical properties of the pitch using variograms. It has been shown that at least 100 data locations are required for the reliable implementation of variograms (Webster and Oliver, 1992; Webster and Oliver, 2007), indicating testing at this frequency is required for assessing the spatial structure of surface behaviour. Aside from this approach to testing, it more common to test at a much smaller number of locations on a pitch and use the data to quantify the performance of the pitch for that period in time. PQS testing designates five pitch locations where data is collected (Figure 1-1). In the development of the GoingStick (Chapter 4) and the season study (Chapter 5), 15 pitch locations were used. The rationale behind using this number of locations as opposed to five was that it provided a greater quantity of data and provision of data from more areas of the pitch than the five used within PQS testing. From the research, two specific questions can be answered relating to the number of pitch locations used in surface testing:

- How many locations are required to provide an accurate representation of how the pitch is performing for that period in time?
- What does data collected using the five PQS locations indicate about the performance of different areas of the pitch?

To investigate this, penetration and shear resistance data measured by the GoingStick in the mid-season datasets from Pitches A and C in the spatial study (Chapter 6) were used for analysis. The mean data collected from these datasets were used as a foundation to assess the accuracy of using different number of test locations, as it was considered that the greatest number of locations would provide the best indication of the performance of the pitch. The 135 locations used on Pitch A is highlighted by the black markers in Figure 9-1i; 150 locations were used on Pitch C. Three approaches to eroding this data were used: 50% of the original 150/135 data locations were selected by removing alternate horizontal rows of test locations, creating 68/75 locations on Pitches A and C respectively; the 15 pitch locations used in Chapters 4 and 5 were represented by selecting the nearest data locations from the spatial study (Figure 9-1i); the PQS locations were represented by selecting the nearest two data locations from the spatial study (Figure 9-1ii).

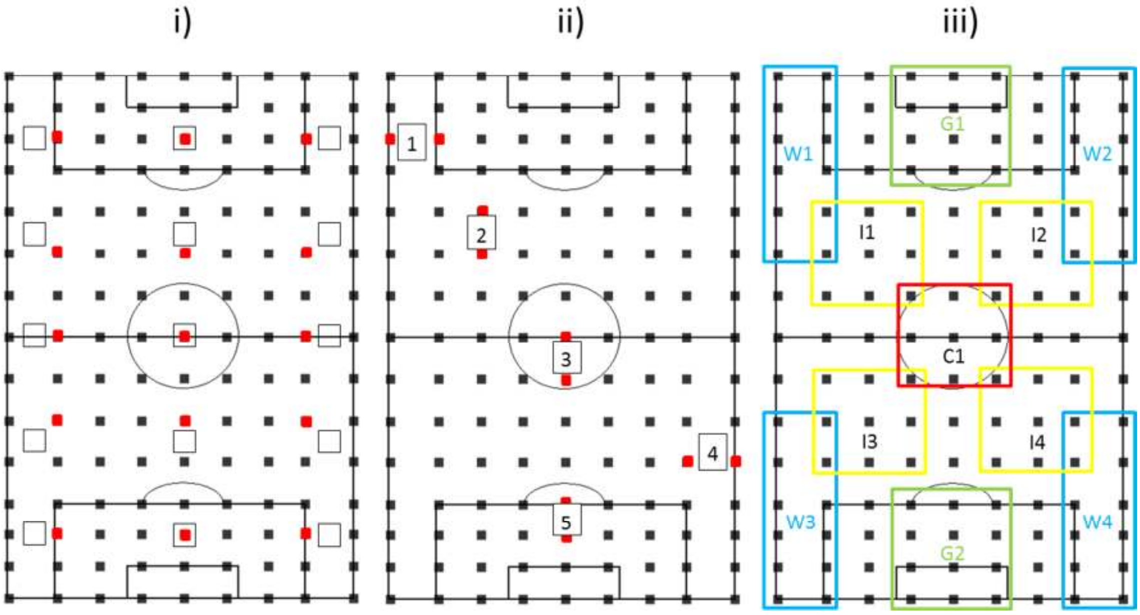

Figure 9-1 Details of data used for pitch location analysis. Solid black squares represent data locations used in the spatial study (Chapter 6) on Pitch A. i): boxes represent the 15 pitch locations used in Chapters 4 and 5, with the adjacent data points (red) used for analysis at each location; ii): Number boxes represent PQS test locations, with adjacent data points (red) used for analysis at each location; iii): Coloured boxes represent zoned areas of the pitch (W1-4; G1-2; I1-4; C1), with data points within these boxes used for analysis of each zone.

Analysis of the mean data is presented in Table 9-1, and indicates mean values were similar across the different testing densities. Variation detected between testing densities was shown to be similar in magnitude to the standard error of the mean values, and smaller than the coefficient of variation for the most intensive values. This suggests that the use of just five data locations on natural turf pitches, as used under PQS testing, provides a precise indication of pitch behaviour in comparison to testing at 135/150 locations.

Table 9-1 Mean penetration and shear resistance measured by the GoingStick on Pitches A and C in the spatial study (mid-season dataset), using a variety of pitch data locations (outlined in Figure 9-1). CoV = coefficient of variation for the 150/135 dataset.

	Number of locations				
	150/135	**CoV.**	**75/68**	**15**	**PQS 1-5**
Pitch A					
Penetration resistance (MPa)	8.0 ± 0.1	0.17	8.0 ± 0.2	8.4 ± 0.3	8.3 ± 0.5
Shear resistance (Nm)	30.4 ± 0.3	0.13	30.4 ± 0.5	30.4 ± 0.7	29.9 ± 1.3
Pitch C					
Penetration resistance (MPa)	9.1 ± 0.1	0.13	9.1 ± 0.1	9.2 ± 0.2	9.3 ± 0.3
Shear resistance (Nm)	12.7 ± 0.2	0.19	12.6 ± 0.3	13.0 ± 0.3	13.5 ± 0.9

The positioning of the five PQS locations on a pitch were originally chosen to provide data from different areas of the pitch: wing areas (1 and 4); inside centre areas (2); the centre circle (3) and the goalmouths (5). In an early pilot study, Holmes and Bell (1986) rejected the use of 12 locations as pitch areas and regimes of wear were duplicated, with 6 locations (now 5) adopted to characterise areas of the pitch. This results in data from locations being used to characterise opposing pitch areas e.g. location 5 used to characterise both goalmouths; location 2 used to characterise all four inside centre areas. To address the second question posed, the 5 PQS locations were assessed for their viability to characterise the different areas of the pitch. Mean data was produce from 11 zones within the pitch (Figure 9-1iii), representing the centre of the pitch (C1), wings (W1-4), goalmouths (G1-2) and inside centre areas (I1-4). Mean data from the five PQS locations were compared to mean zone data in overlapping pitch locations e.g. PQS location 1 to W1; PQS 2 to I1 (Table 9-2). In addition, PQS data from each location was compared against opposing pitch location e.g. PQS location 2 to I2-4; PQS location 5 to G1 (Table 9-3).

Table 9-2 Assessment of the difference (%) in data for penetration resistance (Pen. res.) and shear resistance (Shear res.) between overlapping pitch locations using the mean PQS location data and mean zonal location data. Locations outlined in Figure 9-1.

		% Difference			
PQS Location	Zonal pitch location	Pitch A		Pitch C	
		Pen. res.	Shear res.	Pen. res.	Shear res.
1	W1	7.7%	5.6%	1.1%	2.1%
2	I1	10.0%	4.1%	4.3%	9.6%
3	C	1.0%	6.3%	4.5%	11.5%
4	W4	6.8%	3.1%	2.0%	2.6%
5	G2	12.6%	3.1%	1.0%	27.0%

Table 9-3 Assessment of the difference (%) in data for penetration resistance (Pen. res.) and shear resistance (Shear res.) between opposing pitch locations using the mean PQS location data and mean zonal pitch location data. Locations outlined in Figure 9-1.

		% Difference			
PQS Location	Zonal pitch location	Pitch A		Pitch C	
		Pen. res.	Shear res.	Pen. res.	Shear res.
Mean of 1 and 4	Mean of W2 and 3	4.2%	2.4%	2.1%	16.9%
2	I2	3.8%	1.7%	5.4%	26.7%
2	I3	21.3%	12.5%	6.5%	21.9%
2	I4	1.3%	9.8%	1.1%	6.2%
5	G1	11.6%	4.9%	10.3%	25.0%

For overlapping data (Table 9-2), the highest difference between data was 27% for shear resistance in the goalmouth. Despite this value, all other differences between data were 12.6% or lower, which was smaller than the coefficients of variation values for the respective parameter (13 - 19%; Table 9-2). This indicates that intensive sampling within areas of the pitch may not be required, as the PQS locations can provide a sufficient characterisation of areas of the pitch in which they are located. Data comparing against opposing areas of the pitch showed that six values differed by 12.5% or higher, suggesting the PQS locations can be less accurately used to extrapolate to opposing areas of the pitch.

The benefit of testing pitches with greater test locations (i.e. 75 or 150 data locations) provides a greater quantity of data, ultimately reduces the variability in the dataset. However, the time required to test at this density in comparison to lower densities is much higher (Table 9-4). Studies assessing the spatial dependency of sports pitches cannot be implemented feasibly within surface management, as three hours were required to undertake a spatial study using the DST, GoingStick, and CIST devices (Table 9-4; the CIST and GoingStick devices can be implemented simultaneously). Testing at a lower frequency reduces the time required to assess pitches, and is more feasible for grounds managers to undertake (Table 9-4). Displaying this data is important for future surface testing by researchers and grounds managers.

Table 9-4 Details of the time (in minutes) required to test pitches with four testing devices at the three testing densities used in the research project. Data are based on three replicates per location for 5 and 15 testing densities, and one replicate per location for the 135/150 testing density. * denotes this value is an estimate as this density was not undertaken in the research with this device.

	Testing density		
Device	**5 (PQS)**	**15**	**135/150**
DST	6	15	90
GoingStick	6	15	90
2.25 kg CIST	6	15	90
Studded disc apparatus	22	60	>210*

9.2.2 Athlete Performance and Injury Risk

In the season study (Chapter 5) it was shown that the sand rootzone pitches were generally more consistent in their mechanical behaviour across the season, and mean values indicated they were less deformable during impact throughout the whole season in comparison to the native soil pitches. For example, mean peak deceleration across the season was 112 g and 126 g with coefficients of variation of 6.0% and 15.8% respectively for the two sand rootzones, with mean deceleration in the range 86 - 102 g and coefficients of variation of 33.5% – 44.0% for the four native soil pitches. The reduced surface deformation of sand rootzone surfaces during impact has been shown to be as a result of increased intrinsic stiffness and shear strength within sand soils compared to clay-dominated soils in laboratory experiments (Guisasola et al., 2010b). The effect of playing on more temporally consistent surfaces may be beneficial to players in terms of a more predictable surface to run on and predictable ball bounce and roll, allowing particular performance skills to be undertaken throughout the year i.e. fast passing and off-the-ball movements.

Playing on sand surfaces that are less deformable under impact may increase the efficiency and speed achievable for players when running - less work is done on the surface as a result of reduced deformation during contact. This reduces the energy expenditure of players in performing these movements (McMahon and Greene 1978; Lejeune et al. 1998). This greater efficiency in athletic movement would not only benefit players, but would provide greater entertainment to spectators watching a faster game – Norton et al. (2001) have shown that rugby game speeds are faster on harder surfaces. Injuries in rugby union have increased since the sport turned professional in 1995 (Garraway et al. 2000). Although a number of factors have contributed to this increase (increased exposure time, intensity of training, and player fitness), the developments in surface engineering and management may be an overlooked factor. The development of the professional game has meant that elite level games are played more frequently on sand rootzone surfaces, often through ground-sharing schemes with football teams. The hardness of these modern surfaces have increased, which has been mirrored by the increases in player fitness and player mass (Quarrie and Hopkins 2007;

Stiles et al. 2009). These two components may contribute to injuries through generation of greater forces within impacts between players and the surface (Norton et al. 2001).

It was shown that the quasi-static mechanical behaviour and resistance to dynamic deformation of native clay-dominated soil pitches generally reduced in the mid-season winter period (November to mid-March) in the season study (Chapter 5). The increased deformation of native soil pitches during impact within the winter months may be accompanied by increased energy expenditure and muscle fatigue in players (Lejeune et al., 1998; Millet et al., 2006), although the extension of impact forces over longer ground contact time may reduce the occurrence of injuries associated with large impact forces and rates of loading i.e. impact and overuse injuries (James et al., 1978; Grimston et al., 1991; Butler et al., 2003). This variation in surface behaviour between sand and native soil pitches defines the hypothetical trade-off evident between athlete performance and the reduction of injuries, as both are not considered to be positively correlated past a certain point (Kolitzus, 1984).

Coaches and physiotherapists should be wary of the extent of temporal variation in mechanical behaviour that occurred on the pitches with greatest proportions of clay in their surface layer (0-50 mm): greater resistance to deformation shown in the early and end periods of the season. Harder surfaces in the former period have been considered to contribute to an early season bias of injury (Orchard, 2002), and player's training should be tailored around activities that place players at a lower risk of injury in these periods. This may include training on more compliant surfaces, undertaking fewer activities that involve athlete collisions, or reducing training loads. The latter has been shown to be successful in reducing the incidence of injuries in rugby union pre-season preparations, as well as increasing the fitness (maximum aerobic power) of the players (Gabbett, 2004).

Switching between pitches of different mechanical behaviour may be detrimental for players in terms of predicting ball behaviour, provide variation in injury risk, and difficulty in implementing skills and techniques learnt on a particular surface. Variations in pitches were shown between match and training pitches at Club A in the season study, and it is hypothesised that this is not an uncommon occurrence in professional sport. Sports clubs would benefit from installing the same construction profiles on both training and match pitches to solve this issue, although finances may restrict this. Failing this, coaches should aim to familiarise players with different surfaces by performing low intensity drills prior to activities of high intensity.

The spatially random variation in mechanical behaviour found on the pitches in Chapter 6 is a result of the non-homogenous and anisotropic nature of soil (Emori and Schuring, 1966). Considering the extent of this random variation, two locations 7.5 m apart on Pitch B in the mid-season dataset were shown to exhibit shear resistance of 19.8 Nm and 47 Nm, an increase of 137% over this short distance. This behaviour may affect athletic performance and injury risk on these surfaces. An unexpected reduction in shear resistance whilst running may cause players to slip or fall as a result of reduced traction. Alternatively an unexpected increase in traction when performing rotational movements may increase the risk of foot-locking injuries to joints. Athletes have been shown to produce biomechanical adaptations in running style when encountering surfaces of different stiffness (Dixon et al., 1999; Kerdok et al., 2002), yet these adaptions cannot be performed without feedback from the surface from at least one footstrike, which may be enough exposure to cause injury. Variation in natural turf surface condition for horses during locomotion has been cited as an injury risk as a result of enforced biomechanical adaptions (Stover, 2003), and this may be a mechanism in athlete injury occurrence. In the Stiles et al. (2011) study, despite a sand turf surface measuring lower hardness in CIST tests than a clay loam surface, it was shown to produce a greater rate of loading to athletes when running on it. Biomechanical adaptions were not evident between the two surfaces in the study, indicating that variation in athlete performance and injury may be more subtle, and not shown by a pronounced variation in biomechanics.

9.2.3 Surface Engineering and Management

Two common sand rootzone constructions, Fibresand and Desso GrassMaster, were assessed for their mechanical behaviour within the season study (Chapter 5). Direct comparisons between surface types could not be made because of variations in the timing and testing frequencies, and the potential variability in surface management and climatic conditions. Fibresand improves the strength of sand rootzones by mixing loose fibres into the sand before the rootzone is installed; the Desso system stitches longer vertical fibres to a depth of 200 mm. A difference in shearing failure was noted between the surface types when testing the horizontal shear resistance with the GoingStick. This behaviour was also noted within pilot studies in the season prior to that assessed in the study. The soil in the Fibresand pitch horizontally heaved more than the soil in the Desso pitch and produced larger divots of turf. This behaviour is believed to be as a result of the longer Desso strands confining the soil horizontally and preventing some horizontal movement, meaning a smaller amount of turf is divoted on the surface. Controlled experiments are required to test this hypothesis.

The range in surface mechanical behaviour exhibited on clay-dominated soil pitches poses problems to grounds managers trying to provide consistent and durable surfaces. As has been considered in earlier literature, the data presented in the season study showed that moisture content of the soil was shown to greatly influence mechanical behaviour. Preventing the soil becoming excessively hard during dry periods can be resolved by the application of irrigation, although facilities with clay-dominated pitches rarely possess the means to apply large quantities of water to the surface uniformly. This was encountered at some of the pitches in the season study. The soil losing strength during periods of heavy rainfall and low ET is also a problem. Drainage designs such as sand slitting or mole ploughing that increase surface infiltration and hydraulic conductivity are options available to sports clubs at relatively low cost in comparison to full-size pitch construction (James et al., 2007). However, the costs of these works and additional maintenance are still beyond the financial resources of many amateur and community facilities. In this instance, a major threat to surface provision is the forced cancellation of matches due to waterlogging. Adoption of synthetic surfaces is an option for heavily used clay soil pitches (Stiles et al. 2009), but these surfaces also require substantial initial construction costs. Often, amateur and community level sports facilities are left with little option but to withstand the variations in mechanical behaviour that can occur on pitches.

Topdressing of natural turf pitches (applying sand to the surface) is an established maintenance practice, undertaken to increase surface evenness and the infiltration of water into surfaces. Over a number of years, surface layers of pitches become higher in sand content than the underlying native soil. This was found on some of the native soil pitches in the season study (A-TP, C-MP and C-TP), and on Pitch B in the spatial study. Although water infiltration is increased on these sand-ameliorated pitches, hydraulic conductivity does not increase owing to the high clay contents of the deeper soil layers, causing the profile to become saturated in periods of heavy rain. Evidence presented in Chapters 5 and 6 showed that the application of this sand does little to improve the temporal or spatial consistency of mechanical behaviour, with the surfaces behaving similarly to pitches where no sand is applied.

The importance of the grass roots in increasing surface strength on pitches was highlighted in this research project. An inadequate root system (not quantified) was believed to contribute to the low shear resistance of the B-MP in the start and winter periods of the season in the season study. Measurements of shear resistance with the GoingStick, when correlated with PQS limits for the studded disc apparatus, were shown to fall below the minimum benchmark limit for shear resistance on a number of occasions across the season on this pitch. It was also found in Chapter 8 that under repeated impacts from the 2.25 kg CIST, the presence of grass leaves reinforced the soil and prevented plastic deformation occurring. Considering this finding, a loss of grass cover on pitches would result in surface degradation under repeated impacts, resulting in soil compaction. These two components highlight that maintenance operations should be directed towards providing conditions that allow for healthy grass growth and recovery to increase the durability of the surface.

Grass leaves are maintained longer on rugby pitches than football pitches due to specific demands on the surface that are not as prevalent on football pitches. Grass leaves are maintained at heights of 18-25 mm on football surfaces, which is believed to optimise ball bounce and roll; heights of around 50 mm are used for rugby, where ball bounce is less important than the absorption of impacts (Baker and Canaway, 1991; McClements and Baker, 1994; Mooney and Baker, 2000). In Chapter 8, it was shown that grass leaf height in the range of 25 – 50 mm does not contribute to surface impact absorption on natural turf to athlete-specific high energy impacts (measured with the DST), as long as a root network is present. The practice of maintaining grass heights at 50 mm for rugby to increase energy absorption of surfaces is therefore not due to the effects of the leaves, but most likely due to a combination of secondary effects provided by maintaining longer grass leaf heights i.e. the increase in root length/density and thatch production (Liu and Huang, 2002; Issoufou et al., 2008). This notion is supported by the work shown in the dynamic triaxial experiments, showing that plastic deformation was increased and stiffness reduced in the sand soil by the inclusion of roots in the soil. This behaviour would aid in dissipating energy during surface impacts occurring from players, and may be an important mechanism to reduce the magnitude of peak forces returned by sand rootzone surfaces.

The typical increase in root length/density provided by grass plants when maintained at longer grass lengths is particularly important on rugby surfaces. Larger horizontal forces can be applied to the surface during games of rugby than in football, such as those that can occur in scrums and rucks, highlighting the requirement for high horizontal shear resistance of these surfaces. This component is a reason as to why grass leaves are maintained at heights of around 150 mm on horse racing surfaces (Zebarth and Sheard, 1985), where impact absorption and shear resistance are particularly important for the safety of the horses, who apply high impact and horizontal shear forces to the turf. Ball roll is not a critical playing quality on rugby surfaces, so management of grass leaves at a longer height (50 mm), which would reduce ball roll distances, does not affect surface playability in the same manner as it would on football pitches.

The use of objective measures (testing devices) to assess pitch performance, with maintenance operations tailored around results, is not a common practice in the management of natural turf pitches. Most grounds managers base their maintenance schedules on previous experience and knowledge. The lack of the former approach is partially down to the lack of efficient testing devices. Moreover, benchmark testing frameworks provide target ranges for surface quality, but do not provide an indication of how to manage pitches to achieve these targets. The development of a simple to use and efficient testing device such as the GoingStick provides an important first step in developing a decision-support framework for the precision management of natural turf pitches (Mumford, 2006; Carrow et al., 2010).

9.3 KEY CONTRIBUTIONS TO KNOWLEDGE

An overall contribution to knowledge that this research project has provided is advancement in the understanding and testing of natural turf surfaces. The development of both the GoingStick and the DST devices undertaken in this research provide significant contributions to the testing of natural turf sports pitches. Both devices successfully met criteria outlined in the Literature Review (Chapter 2): a Category 1 testing device that improves the efficiency of testing surfaces (Bartlett et al., 2009); a Category 2 impact device for use on natural turf, able to measure large surface deformations and suitable for testing *in-situ*. GoingStick technology was transferred from implementation on horseracing surfaces, and through the development of a specific sports pitch calibration, was shown to successfully measure the temporal range of mechanical behaviour that occurred on a sports pitch across a season. Initial data were also linearly correlated to the CIST (r^2 = 0.75) and studded disc apparatus (r^2 = 0.88), showing a potential to assess GoingStick data to established PQS standards. For the latter, correlation was attributed to similar strain rates. Impacts of the DST device were compared against those of athletes in a prior biomechanical study, replicating the vertical stress of an athlete impacting the surface during running at 3.83 m s^{-1}. Although the device is a simplification of the interaction occurring between athletes and the surface, it was shown to more closely represent the contact times of athletes when running than the CIST devices. The device was successfully implemented *in-situ*, collecting 117 datasets on six pitches across one season of sport.

Comprehensive studies assessing the mechanical behaviour of natural turf pitches over a season of sport is lacking since early work was performed with the PQS framework in the 1980s and 1990s. A season study (Chapter 5) undertaken within this project provides important data for characterising modern surfaces, and allowed comparison of a range of surface constructions and soil textures. The results indicated that the benchmark ranges for impact hardness under the PQS framework may be obsolete for modern sand rootzone surfaces, as data consistently exceeded preferred limits of hardness. The reduced energy absorbing behaviour of sand rootzone surfaces to athlete impacts, previously identified in biomechanical and laboratory experiments (Guisasola et al., 2010a; Stiles et al., 2011), was confirmed with *in-situ* data from the DST. The study also showed that the presence of a sand rootzone surface does not automatically equate to more temporally consistent playing surface, with quasi-static measures of mechanical behaviour measured with the GoingStick shown to vary in similar magnitude to native soil pitches on one of the sand rootzone surfaces.

The finding that natural turf pitches can exhibit spatially random mechanical behaviour is a significant contribution to knowledge that has not been shown before. Mechanical behaviour of surfaces was previously thought to vary spatially in a diamond pattern (Holmes and Bell, 1986), although this assumption may be based more on the cosmetic damage to the grass plant or soil surface. The use of variograms to assess the spatial structure of natural turf pitches has only been found in one previous study in the literature (Miller, 2004). The evaluation of the methodology presented in Chapter 6 also provides a testing protocol for future use of these methods on turf pitches.

Analysis undertaken within this chapter (9), highlights that collecting data at as little as 5 locations, as used under the PQS framework, is sufficient to characterise the behaviour of a pitch for a particular period in time. It was shown from two datasets that using a higher density of test locations provided similar mean data but would be less time efficient. The PQS test locations were also shown to provide a good representation of the performance of the particular pitch zone in which they were located, although data was less accurately extrapolated to characterise opposing pitch areas. These findings are important for future surface assessment by both researchers and grounds managers.

The effect of grass roots and leaves on the dynamic behaviour of soil and natural turf was successfully separated within the research project. This approach has not been undertaken previously, as a popular approach to quantifying the effects of grass leaves on natural turf behaviour is to assess impact hardness of surfaces of different grass heights (Zebarth and Sheard, 1985; Mooney and Baker, 2000; Grossi et al., 2004). This approach does not take into account the effects of varying root density that can occur when grass is maintained at different heights of cut. This issue was resolved by normalising the root system in the assessment of grass leaf height in a controlled soil bin experiment, and removing grass leaves from soil samples for use in the triaxial apparatus. Use of this equipment to assess the dynamic behaviour of soil with roots is novel in its application, with previous studies assessing soils with roots to quasi-static compression stresses only (Pu et al., 2009; Guisasola et al., 2010b). Results of the study indicated the dynamic behaviour of soil with roots is complex, with the micromechanical interactions between roots and soil particles differing with the mineralogy of the soil.

9.4 RESEACH LIMITATIONS AND FUTURE RECOMMENDATIONS

Further device development is required of the GoingStick in order for it to be broadly accepted as a surface assessment tool. This includes collection of data across a greater number of playing seasons and pitches, representing a wide range of surface constructions, soil textures, intensities of use, management resources, and climatic conditions. The many contributory factors that affect mechanical behaviour means that data collected in the study cannot be extrapolated to characterise all surfaces. The number of pitches assessed in the season and spatial studies were limited to six and three respectively, due to a single person collecting data and single devices available for use. Expanding the number of pitches where data is collected in the future would allow further analysis of the relationships between the device and the studded disc apparatus, particularly on sand rootzone surfaces. The studded disc apparatus was not implemented within the season study as a result of the restricted time available to test the pitches, and the demands of testing with three other testing devices (GoingStick, CIST, and DST). Future research will aim to incorporate the GoingStick within a decision support framework for the objective management of natural turf surfaces.

The sports pitches assessed in the season and spatial studies were subjected to intensities of wear that were within the maximum weekly usage levels for their construction type, as outlined by Baker and Gibbs (1989) – up to ten hours for sand rootzone pitches and up to four hours for an undrained clay soil pitch. Surfaces that are subjected to intensities of wear which exceed these guidelines are required to be quantified for their temporal and spatial variation. These pitches are typically evident at amateur and community level facilities. Clay soils receiving higher intensities of wear may exhibit spatial dependency in mechanical behaviour over a short range, as opposed to the random variation shown in this research.

Comparison between types of sand rootzone constructions has not been found in the literature. Within the season study, direct comparisons could not be made between the Fibresand and Desso construction systems. Despite this, it was hypothesised that the different shear failure noted on the Desso system (less horizontal heave; smaller divots) may be a result of the increased stability of the fibres in the rootzone. Controlled experiments are required to test this hypothesis, ideally through the construction of test plots submitted to artificial wear.

Historical studies assessing injury trends to natural turf soil texture or surface constructions are lacking, with researchers preferring to assess differences in trends between natural and synthetic surfaces in epidemiology studies (Fuller et al., 2007; Meyers, 2010). Within these studies, surfaces are rarely characterised, in terms of soil texture/surface construction and surface mechanical behaviour. Instead, the surfaces are often generically categorised as 'grass' or 'natural turf'. As has been shown, the temporal variation in mechanical behaviour of natural turf can be large, meaning that any conclusions between surface types drawn within these studies are limited and dependent upon surface behaviour on that day. Comprehensive characterisation of natural turf pitches used in epidemiological or biomechanical studies is required, and this may be achieved with the use of efficient testing devices such as the GoingStick or CIST. This approach has only been undertaken in a limited number of studies (Orchard, 2001; Takemura et al., 2007). Undertaking this integrated approach may help to understand the specific mechanisms involved in injury occurrence and biomechanical adaptations.

The DST device is currently a prototype. This restricts the quantity of data that can be collected from this type of device on natural turf. The device was considered to apply stresses seven times slower than athletes when running (Chapter 3), limited by the speed and magnitude of pressure through the pneumatic system and current form of the device. With increased investment and development, aspects of the device can be improved to increase its biomechanical validity: replication of a greater quantity of sports movements by increasing the applied pressure; increasing the loading rate; developing more biofidelic test feet, limbs, joints and articulation; allowing impacts to be applied at a range of angles more representative of athlete running or landing; consideration of energy return from turf surfaces. The requirement of a compressed air cylinder during operation of the device means that cylinder refills and suitable storage is required. This may restrict the use of the device outside of facilities such as universities, and suggests avenues should be explored to apply the pressure differently i.e. hydraulically (Carré et al., 2007).

The triaxial apparatus was shown to successfully quantify the dynamic behaviour of soils with roots. The number of treatments (four) was limited by the time-consuming nature of the testing procedure and the time required in developing suitable test conditions; more treatments were originally planned for the study, representing a wider range of soil physical conditions. Future testing of soil with roots samples should be more efficient in the future, now that a suitable methodology for testing these types of samples has been established. Variations in the loading, confining, and soil physical conditions should be explored. The confinement of the roots into narrow diameter (68mm) tubes was also considered to restrict the extrapolation of data to *in-situ* situations, as both horizontal and vertical root fibres combine to absorb the applied stress (Wu et al., 1988; Graf et al., 2009; Zhang et al., 2010). The addition of roots within the soil also compromises the homogenous and isotropic assumption of triaxial loading by providing planes of failure in particular orientations. Irrespective of these limitations of the methodology, the method that was developed and equipment used provides an opportunity to quantify the effect of roots on dynamic soil behaviour in greater detail than other equipment such as the shear box.

The surface area (1.75 m^2) of the controlled test plots used in the grass leaf height experiment (Chapter 8) was limited by the size of the soil bins that were available for use in the study. These bins were built and used in a previous research project (James and Shipton, 2011), and were used for the current experiment because of their availability and ease of packing. With the method used and the size of the surface area of turf available, it was possible that data from the devices (CISTs, GoingStick, and DST) may have been affected by soil disturbance from previous tests. Measures were made to minimise these affects by randomly mapping the location of the tests in the plots, ensuring the whole available surface area was implemented. Ideally for experiments such as these, larger test plots are constructed to maximise surface area (Barton et al., 2009), but financial and time restrictions meant this approach was not feasible. The morphology of the grass plants at the 25 mm and <1 mm treatments were that of a 50 mm plant reduced to lower heights of cut: shoot numbers per area are typically higher for lower heights of cut on turf when maintained continuously at these heights (Grossi et al., 2004). This is a limitation of the study, but was a consequence of normalising the root structure across treatments.

9.5 ADDITIONAL PUBLICATIONS

Additional to the six research chapters submitted as papers to peer-reviewed journals (statuses outlined in Table 1-1), the following publications have been formulated from this research project:

- Caple, M. C. J., Bartlett, M. D. James, I. T. Characterising winter games pitches for player-surface interaction. Presented at BSSS Young Scientists' Meeting, Reading, 31st March – 1st April 2009.
- Caple, M. C. J., James, I. T. Bartlett, M. D. and Bartlett, D. I. Development of a Simplified Dynamic Testing Device for Turfed Sports Surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.
- James, I. T. and Caple, M. C. J. Understanding the dynamic response of sports fields. Presented at The 8th SportSURF Workshop, Sheffield, 15th June 2011.

9.6 REFERENCES

Baker, S. W. and Canaway, P. M. (1991), The Cost-Effectiveness of Different Construction Methods for Association Football Pitches, II, Ground Cover, Playing Quality and Cost Implications, *Journal of the Sports Turf Research Institute,* vol. 67, pp. 53-65.

Baker, S. W. and Gibbs, R. J. (1989), Levels of use and the playing quality of winter games pitches of different construction types: Case studies at Nottingham and Warrington, *Journal of the Sports Turf Research Institute,* vol. 65, pp. 9-33.

Baker, S. W., Wheater, J. A. and Spring, C. A. (2007), Performance requirements for surface hardness of winter games pitches, *Journal of Turfgrass and Sports Surface Science,* vol. 83, pp. 83-89.

Bartlett, M. D., James, I. T., Ford, M. and Jennings-Temple, M. (2009), Testing natural turf sports surfaces: The value of performance quality standards, *Journal of Sports Engineering and Technology,* vol. 223, no. 1, pp. 21-29.

Barton, L., Wan, G. G. Y., Buck, R. P. and Colmer, T. D. (2009), Effectiveness of cultural thatch-mat controls for young and mature kikuyu turfgrass, *Agronomy Journal,* vol. 101, no. 1, pp. 67-74.

Bell, M. and Holmes, G. (1988), The playing quality of association football pitches, *Journal of the Sports Turf Research Institute,* vol. 61, pp. 19-47.

Butler, R. J., Crowell III, H. P. and Davis, I. M. (2003), Lower extremity stiffness: Implications for performance and injury, *Clinical Biomechanics,* vol. 18, no. 6, pp. 511-517.

Carré, M. J., Kirk, R. F. and Haake, S. J. (2007), Developing relevant tests for traction of studded footwear on surfaces, in: *Proceedings of the First International Conference of the SportSURF Network: Science, Technology and Research into Sport Surfaces,* 17-18 September 2007, Loughborough.

Carrow, R. N., Krum, J. M., Flitcroft, I. and van Cline (2010), Precision turfgrass management: Challenges and field applications for mapping turfgrass soil and stress, *Precision Agriculture,* vol. 11, no. 2, pp. 115-134.

Dixon, S. J., Batt, M. E. and Collop, A. C. (1999), Artificial playing surfaces research: A review of medical, engineering and biomechanical aspects, *International Journal of Sports Medicine,* vol. 20, no. 4, pp. 209-218.

Emori, R. and Schuring, D. (1966), Static and dynamic penetration tests of soil, *Journal of Terramechanics,* vol. 3, no. 1, pp. 23-30.

Fleming, P., Young, C. and Dixon, N. (2004), Performance measurements on synthetic turf hockey pitches, in: Hubbard, M., Mehta, R. and Pallis, J. M. (eds.) *The Engineering of Sport 5 vol. 2,* ISEA, Sheffield, pp. 524-531.

Fuller, C. W., Dick, R. W., Corlette, J. and Schmalz, R. (2007), Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: Match injuries, *British Journal of Sports Medicine,* vol. 41, no. 1, pp. 20-26.

Gabbett, T. J. (2004), Reductions in pre-season training loads reduce training injury rates in rugby league players *British Journal of Sports Medicine,* vol. 38, no. 6, pp. 743-749.

Garraway, W. M, Lee, A. J., Hutton, S. J., Russell, E. B. A. W., and Macleod, D. A. D. (2000), Impact of professionalism on injuries in rugby union, *British Journal of Sports Medicine*, vol. 34, pp. 348-351.

Graf, F., Frei, M. and Böll, A. (2009), Effects of vegetation on the angle of internal friction of a moraine, *Forest Snow and Landscape Research,* vol. 82, no. 1, pp. 61-77.

Grimston, S. K., Engsberg, J. R., Kloiber, R. and Hanley, D. A. (1991), Bone mass, external loads, and stress fractures in female runners, *International Journal of Sports Biomechanics,* vol. 7, no. 3, pp. 293-302.

Grossi, N., Liu, C., Yang, M. H. and Wrigley, M. (2004), Tall fescue turf quality and soccer playing characteristics as affected by mowing height, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields*, ISHS, Leuven, pp. 319-322.

Guisasola, I., James, I., Stiles, V. and Dixon, S. (2010a), Dynamic behaviour of soils used for natural turf sports surfaces, *Sports Engineering,* vol. 12, no. 3, pp. 111-122.

Guisasola, I., James, I., Llewellyn, C., Stiles, V. and Dixon, S. (2010b), Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction, *Sports Engineering,* vol. 12, no. 2, pp. 99-109.

Holmes, G. and Bell, M. J. (1986), A pilot study of the playing quality of football pitches, *Journal of the Sports Turf Research Institute,* vol. 62, pp. 74-91.

Issoufou, M., Zaman-Allah, M., Ferchichi, A. and Ferjani, E. (2008), Clipping effects on the growth variation, water use efficiency and photosynthetic activity in Buffel grass (Cenchrus ciliaris L.) poaceae, *Asian Journal of Plant Sciences,* vol. 7, no. 1, pp. 95-99.

James, I. T., Blackburn, D. W. K. and Godwin, R. J. (2007), Mole drainage as an alternative to sand slitting in natural turf sports surfaces on clays, *Soil Use and Management,* vol. 23, no. 1, pp. 28-35.

James I.T., and Shipton P.M.R. (2011), Quantifying compaction under rollers using marker tracing image analysis, *Soil and Tillage Research,* (in review).

James, S. L., Bates, B. T. and Osternig, L. R. (1978), Injuries to runners, *American Journal of Sports Medicine,* vol. 6, no. 2, pp. 40-50.

Kerdok, A. E., Biewener, A. A., McMahon, T. A., Weyand, P. G. and Herr, H. M. (2002), Energetics and mechanics of human running on surfaces of different stiffnesses, *Journal of applied physiology,* vol. 92, no. 2, pp. 469-478.

Kolitzus, H. J. (1984), Functional standards for playing surfaces, in: Frederick, E. C., (ed), *Sport Shoes and Playing Surfaces, Biomechanical properties,* Human kinetics publishers Inc, Champaign, IL, pp. 98-118.

Lejeune, T. M., Willems, P. A. and Heglund, N. C. (1998), Mechanics and energetics of human locomotion on sand, *The Journal of Experimental Biology,* vol. 201, pp. 2071-2080.

Liu, X. and Huang, B. (2002), Mowing effects on root production, growth, and mortality of creeping bentgrass, *Crop Science,* vol. 42, no. 4, pp. 1241-1250.

McAuliffe, K. W. (2008), The role of performance testing and standards in the sports turf industry: a case study approach, in: Stiel, J. C., Han, L. and Li, D. (eds.), *Proceedings of the Second International Conference on Turfgrass Management for Sports Fields,* ISHS, Leuven, pp. 391-398.

McClements, I. and Baker, S. W. (1994), The playing quality of rugby pitches, *Journal of the Sports Turf Research Institute,* vol. 70, pp. 29-43.

McMahon, T. A. and Greene, P. R. (1978), Fast running tracks, *Scientific American,* vol. 239, no. 6, pp. 112-121.

Meyers, M. C. (2010), Incidence, mechanisms, and severity of game-related college football injuries on FieldTurf versus natural grass: a 3-year prospective study, *The American Journal of Sports Medicine,* vol. 38, no. 4, pp. 687-697.

Miller, G. L. (2004), Analysis of Soccer Field Hardness, in: Nektarios, P. A. (ed.), *Proceedings of the first international conference on turfgrass science and management for sports fields,* ISHS, Leuven, pp. 287-294.

Millet, G., Perrey, S., Divert, C. and Foissac, M. (2006), The role of engineering in fatigue reduction during human locomotion, *Sports Engineering,* vol. 9, pp. 209-220.

Mooney, S. J. and Baker, S. W. (2000), The effects of grass cutting height and pre-match rolling and watering on football pitch ground cover and playing quality, *Journal Turfgrass Science,* vol. 76, pp. 70-77.

Mumford, C. (2006), *The optimisation of going management on UK racecourses using controlled water applications* (unpublished EngD thesis), Cranfield University, Cranfield.

Norton, K., Schwerdt, S. and Lange, K. (2001), Evidence for the aetiology of injuries in Australian football, *British Journal of Sports Medicine,* vol. 35, no. 6, pp. 418-423.

Orchard, J. (2001), The AFL penetrometer study: Work in progress, *Journal of Science and Medicine in Sport,* vol. 4, no. 2, pp. 220-232.

Orchard, J. (2002), Is there a relationship between ground and climatic conditions and injuries in football?, *Sports Medicine,* vol. 32, no. 7, pp. 419-432.

Pu, Y., Zhihai, X., Xiasong, H., Guorong, L., Haili, Z., Xiaoqin, M. and Zhangzhi, C. (2009), Limit load of soil-root composites, *Computers, Materials and Continua,* vol. 10, no. 2, pp. 117-137.

Quarrie, K. L. and Hopkins, W. G. (2007), Changes in player characteristics and match activities in Bledisloe rugby union from 1972 to 2004, *Journal of Sports Sciences,* vol. 25, no. 8, pp. 895-903.

Shorten, M. R. (2003), Sports surfaces and the risk of traumatic brain injury, in: *Proceedings of the International Association for Sports Surface Sciences 3rd Symposium on Sports Surfaces,* August 2003, Calgary.

Stiles, V. H., Guisasola, I. N., James, I. T. and Dixon, S. J. (2011), Biomechanical response to changes in natural turf during running and turning, *Journal of Applied Biomechanics,* vol. 27, no. 1, pp. 54-63.

Stiles, V. H., James, I. T., Dixon, S. J. and Guisasola, I. N. (2009), Natural turf surfaces: The case for continued research, *Sports Medicine,* vol. 39, no. 1, pp. 65-84.

Stover, S. M. (2003), The epidemiology of thoroughbred racehorse injuries, *Clinical Techniques in Equine Practice,* vol. 2, no. 4, pp. 312-322.

Takemura, M., Schneiders, A. G., Bell, M. L. and Milburn, P. D. (2007), Association of ground hardness with injuries in rugby union, *British Journal of Sports Medicine,* vol. 41, no. 9, pp. 582-587.

Twomey, D. M., Otaga, L. and Saunders, N. (2011), Challenges in the development of standards for synthetic turf for Australian football and cricket, *Journal of Sports Engineering and Technology,* vol. 225, pp. 93-101.

Webster, R. and Oliver, M. A. (1992), Sample adequately to estimate variograms of soil properties, *Journal of Soil Science,* vol. 43, no. 1, pp. 177-192.

Webster, R. and Oliver, M. A. (2007), *Geostatistics for Environmental Scientists,* Second ed, John Wiley & Sons Ltd, Chichester, England.

Wu, T. H., McOmber, R. M., Erb, R. T. and Beal, P. E. (1988), Study of soil-root interaction, *Journal of Geotechnical Engineering,* vol. 114, pp. 1351-1375.

Zebarth, B. J. and Sheard, R. W. (1985), Impact and shear resistance of turf grass racing surfaces for Thoroughbreds, *American Journal of Veterinary Research,* vol. 46, no. 4, pp. 778-784.

Zhang, C., Chen, L., Liu, Y., Ji, X., and Liu, X. (2010), Triaxial compression test of soil-root composites to evaluate influence of roots on soil shear strength, *Ecological Engineering,* vol. 36, no. 1, pp. 19-26.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The aim of the research study was to advance the understanding of surface mechanical behaviour of natural turf sports surfaces, through *in-situ* and laboratory experiments, and via the development of new testing devices. Six key objectives were outlined in Chapter 1, and the conclusions are aligned with these objectives:

1. Two existing test devices, The DST device and the GoingStick, were adapted for implementation on natural turf sports pitches.
    a. Impacts of the DST device replicated the magnitude of impact stress from a biomechanical study of players running on natural turf. Developmental experiments showed that the device was sensitive to changes in soil condition, successfully identifying differences ($P<0.05$) between 4 prepared soil treatments. The device was also successfully implemented on *in-situ* surfaces within a season study, owed in part to the portability of the device.
    b. By developing and implementing a new sports pitch calibration for the GoingStick, the device successfully measured the full range of surface mechanical behaviour exhibited across a sports season on three pitches. Data from the device were linearly correlated to the established PQS devices: the CIST ($r^2 = 0.75$) and the studded disc apparatus ($r^2 = 0.88$), allowing future assessment of data to established PQS benchmarks. The correlation with the latter was considered to be as a result of similar strain rates applied (48 and 49 degrees per second).

2. The DST device was used to quantify the dynamic behaviour of six *in-situ* sports pitches to athlete-specific impact stresses over a season of sport. Sand rootzone pitches showed smaller mean values, and smaller variation in impact absorption throughout the season compared to native soils containing greater proportions of clay. The greater consistency in impact behaviour provided by the sand pitches were considered beneficial for athletes in terms of more consistent, predictable surfaces that tend towards more efficient movements, although the effect of playing on

surfaces with lower impact absorption may contribute to specific impact or overuse injuries (not tested).

3. The mechanical behaviour of six *in-situ* sports pitches were quantified across a season of sport, studying the effect of time, soil texture and water content.
    a. Additional to the behaviour outlined in Conclusion 2, the sand rootzone surfaces were shown to exhibit harder ($P<0.05$) surfaces (measured with the 2.25 kg CIST) in the winter period (November to mid-March) compared to native soil pitches containing greater proportions of clay. The effect of harder surfaces within this period of the season is again considered beneficial for players to perform specific game tactics i.e. short fast passing, but may place the player at greater risk of injuries within this period.
    b. It was shown that sand rootzones can exhibit temporal variation in quasi-static mechanical behaviour similar to native soil pitches, depending on aspects such as the ratio of grass cover, maintenance operations undertaken, soil water content, climatic conditions, and construction method. This highlights that the adoption of sand rootzone surfaces does not automatically equate to more temporally-consistent playing surfaces.
    c. Soil water content is key in the mechanical behaviour of surfaces. The mechanical properties of clay-dominated pitches were linearly correlated ($P<0.05$) to soil water content owing to cohesion and plasticity being dependent upon soil water content. No relationship was evident on a sand rootzone pitch within a soil water content range of 14.5% - 20.9%. The physical properties of the sand soils (hydraulic conductivity, water release characteristics) and the application of irrigation means these rootzones are managed within a narrow range which increases shear strength as a result of tension provided by the soil water.
    d. The sand rootzone surfaces were shown to behave similarly ($P<0.05$) in dynamic impact testing (DST and CIST), but differently when stressed quasi-statically in the horizontal direction with the GoingStick. This highlights the difference between confined compression and unconfined shear resistance of natural turf. The reduction in the latter when an

    established grass root system is not present highlights the importance of synthetic fibers on cohesionless sand soils used as sports pitch rootzones.

   e. Variation in surface mechanical behaviour of a training pitch was shown to be greater across a season than a match pitch at one of the sports clubs. This was caused by a variation in soil texture and surface construction of the surfaces (native clay loam; sand rootzone). Similar soil textures and management regimes of a training and match pitch at another sports club produced mechanical behaviour that was similar throughout the season. It is hypothesised that a large number of professional teams train and play on surfaces varying in soil texture and construction, and switching between surfaces of different mechanical behaviour may be detrimental for players in terms of predicting ball behaviour, variations in injury potential, and the difficulty in implementing specific skills and techniques learnt on a particular surface.
   f. All data collected with the CIST on the sand rootzone surfaces exceeded preferred values under the PQS framework, indicating these ranges may be obsolete for the modern elite natural turf pitch, or that surfaces are too hard. New benchmark limits should be proposed by focussing on player safety, such as correlating surface behaviour to injury tolerances of the human body i.e. the HIC.

4. The spatial variation in mechanical behaviour of three natural turf sports pitches (sand rootzone; sand ameliorated; clay loam) was assessed at three periods of the season (beginning, mid, and end).
   a. Pure nugget variograms produced for soil water content, penetration resistance, shear resistance, and impact absorption in all the datasets indicated data was not spatially dependent, and that surfaces exhibited random variation in their mechanical behaviour. This was attributed to the non-homogenous and anisotropic nature of soil, and should be considered further for its effect on player performance and injury.
   b. Surface hardness data from the third drop of the 2.25 kg CIST was spatially dependent in all datasets, fitting a spherical variogram model. This

behaviour was attributed to the first two drops of the device conditioning the surface (flattening the grass leaves and compacting the thatch and soil), producing a stiffer surface which caused third drop data to have less variance and be related.

   c. Measured spatial variation within the pitches was similar in magnitude to temporal variation detected across the three periods of the season. Both temporal and spatial variation in the datasets was generally smaller on the sand rootzone pitch in comparison to the sand ameliorated and clay loam soil pitches. This is due to: shear strength having a greater reliance on soil water content on clay-dominated soils, which varied temporally; clay-dominated soils being more susceptible to plastic failure under the concentrated effects of wear from play; the uniformity in the construction of sand rootzone surfaces increasing their spatial consistency.
   d. The methodology was considered robust for future implementation on sports pitches, although the time required in undertaking these studies (3 hours) means they are not feasible as a surface management tool.

5. The effect of grass leaves and roots on the dynamic behaviour of soil and natural turf surfaces was assessed in two separate studies.
   a. The effect of roots on the dynamic behaviour of soils in dynamic triaxial loading was considered to be dependent upon the micro-mechanical interactions between roots and soil particles: a reduction in soil stiffness and increase in plastic deformation in a sand soil with roots treatment was attributed to the compressible nature of the roots reducing the frictional properties of the soil; independence of soil behaviour to roots in a clay loam soil was attributed to the greater adherence of roots to soil particles owing to the cohesive properties of clay soils. The increased compressibility of sand soils with roots may be an important mechanism in reducing the magnitude of peak forces returned to players when impacting the surface.
   b. Grass leaves were shown to absorb some impact energy of the first drop of the 0.5 kg CIST, reducing ($P<0.05$) impact hardness values in comparison to surfaces without leaves. This effect is removed when the grass leaf is

flattened under repeated impacts. The energy-absorbing properties of grass leaves were not significant ($P<0.05$) for the higher energy impacts of the 2.25 kg CIST, although the leaves were found to reinforce the soil and prevent plastic deformation occurring under repeated drops, evident when the grass leaves were removed. Independence of DST data to grass leaf heights suggests grass leaves may not affect the impact absorption athletes experience during contact with the surface, providing the root network of the soil is present.

6. Data from the various testing devices (DST device, GoingStick, CIST, studded disc apparatus) implemented in the study were evaluated to increase understanding of natural turf stress-strain behaviour, and to inform on the use of the devices in future surface testing.
    a. Despite the variation in the strain rates and function of the devices, penetration resistance measured with the GoingStick and peak deceleration measured with the CIST were shown to be significantly ($P<0.05$) linearly correlated in Chapters 4 and 5 ($r^2 = 0.75$; $r = 0.58 – 0.96$), meaning that data collected with the GoingStick can be used to assess surfaces to established PQS benchmarks.
    b. The 0.5 kg CIST should be used to assess the behaviour of surfaces to ball impacts, as loading conditions have been shown to be similar. The 2.25 kg CIST should be regarded as providing a generic indicator of impact behaviour, as it has not as yet been shown to replicate specific impacts occurring on sports surfaces.
    c. Selection of various CIST drop numbers (1-3) was shown to vary surface characterisation in the spatial study (Chapter 6) and in the grass height study (Chapter 8), highlighting the effect of stress history on surface classification. Future implementation of the device should aim to use both the first and third drops of the device, to provide details on single drops on the surface and the behaviour of the soil under repeated impacts that may occur in game situations.

d. Aside from the relationship between displacement evident in Chapter 8 (r = 0.96), the correlation between data produced by the DST and the 2.25 kg CIST was inconsistent (r = -0.31 - -0.77). This is attributed to the variation in ground contact times of the different impact devices (120 ms and 8.2 ms) and strain rates (300 mm s^{-1} and 1557 mm s^{-1}). This emphasises the importance of replicating the loading conditions of specific impacts when assessing surfaces i.e. impacts from players running, head impacts, ball impacts, rather than providing generic readings of impact behaviour on natural turf.

e. Category 1 type devices should not be used to assess whether surfaces are safe for use as they do not replicate the loading or boundary conditions of athletes, and are not as yet correlated to injury data or defined tolerances of the human body.

f. Using the five PQS pitch locations was shown to be adequate to provide an indicator of surface performance for a given period in time, as mean values were similar to data from 135/150 pitch locations, and is much more time efficient. Data from the PQS locations were shown to adequately characterise the behaviour of the zone of the pitch in which they were situated, but were less reliable when extrapolating to characterise opposing pitch areas.

10.2 FUTURE RESEARCH RECOMMENDATIONS

1. Collect a greater quantity of data with the GoingStick testing device on a range of natural turf pitches and surface conditions, to further validate the device as a surface assessment tool.
2. Incorporate the GoingStick device within a decision support framework for the maintenance of natural turf.
3. Assess the temporal and spatial variation in mechanical behaviour of a wider range of natural turf pitches, particularly those subjected to high intensities of sporting wear.
4. Perform controlled experiments to compare the mechanical behaviour of different sand rootzone constructions i.e. Desso Grassmaster and Fibresand.

5. Use surface assessment devices to objectively quantify the mechanical behaviour of natural turf pitches within integrated injury epidemiological studies. Soil textures and surface constructions are also required to be quantified within this type of studies.
6. Undertake further development of the DST device to increase the biomechanical validity of impacts produced by the device.
7. Quantify the effect of grass roots on a range of soil physical conditions using the dynamic triaxial apparatus.

11. APPENDICES

11.1 DEVELIOPMENT AND CALIBRATION OF THE DST DEVICE

11.1.1 Original Spike Going Meter Program

```
LIST
  10 REM--Program to control data collection from the spike going meter
  20 REM     SPIKE7_9.TTB  15-10-2009
  30 REM--Version to measure and send raw data to pc.  Includes theta probe
  31 REM  Calibrations 1mm = 631  1N = 44  1g = 832  11840 = 0.9v  energy 17668
  40 REM  Includes acceleration measurement chan(1),@3,Force chan(2),@1 Distance chan3,@2
  50 RATE 16
  60 K=0 : GOSUB 3000 : GOSUB 3000 : REM---Assemble channel control routine
  65 PRINT"  Sports surface tester SPIKE7_9.TTB  15-10-2009"
  70 @(37)=20480 : @(38)=&H4000 : @(9)=&H720E : PSET(1) : Z=20481 : H=0
  80 REM--Setup ADLOOP control block
 110 @(32)=0 : @(33)=0 : @(34)=0 : @(35)=3 : @(36)=0 : @(1)=0 : @(2)=0 : @(3)=0 : @(39)=3
 120 REM--Check for start switch pressed.
 130 IF PIN(0)=0 RTIME : M=? : SLEEP 0 : GOTO 130
 140 SLEEP 10                 :REM--Avoid contact bounce
 150 IF PIN(0)=1 GOTO 150       :REM--Wait until switch is released
 160 RTIME
 170 IF(?-M) > 200 GOSUB 7000    :REM--Go to output dialogue when pressed for more than 2 seconds
 180 IF M<0 GOTO 110           :REM--Restart the measurement routine
 190 REM--Switch pressed so start measurement sequence
 200 H=H+1                   :REM--Increment the measurement counter
 210 STORE Z,"**"
 220 STORE Z,#2,H,?(2),?(1),?(0),?(3),?(4)             :REM--Store '**',Measurement No.,second,hour,minute,day,month
 230 PCLR(2)                 :REM--Switch off the ready lamp
```

```
 240 REM--Measure the theta probe sequence
 250 GOSUB 4010                :REM--Read theta probe and the GPS receiver
 252 STORE Z,#2,A,B,C            :REM--A = Theta probe a/d (CHAN(4))  B = Northings C = Eastings
 254 IF PIN(0)=0 PSET(2):SLEEP 100: PCLR(2): SLEEP 100:GOTO 254
 258 SLEEP 10 : PCLR(2)
 259 IF PIN(0)=1 GOTO 259       :REM--Push the button to fire the spike.
 260 L=0 : W=0 : T=0
 270 FOR I=1 TO 20 : T=T+CHAN(2) : L=L+CHAN(1) : W=W+CHAN(3) : NEXT I
 280 L=L/20 : W=W/20 : T=T/20   :REM--Calculate the starting values
 290 STORE Z,#2,L,W,T            :REM--Store starting values Force(L),Distance(W) and Acceleration(T)
 300 ADLOOP
 310 PCLR(1)                  :REM--Load spike
 320 C=0                    :REM--Initialise the end of penetration test
 330 GOSUB 1000                :REM--Test for end of penetration
 340 PSET(1)                  :REM--Switch to unloading
 350 C=0                    :REM--Initialise the end of extraction test
 360 GOSUB 2000                :REM--Test for end of extraction
 370 @(32)=0                  :REM--Stop ADLOOP
 380 GOSUB 6000                :REM--Process loading phase
 390 STORE Z,#2,F/27764,(X*1000)/1183,D/631,E/44,G/832
 410 PRINT "Test No. ",H," Speed mm/s ",(X*1000)/1183," Dist. mm ",D/631," Max force N ",E/44," Max Acc'n g ",G/832
 420 REM--End of measurement loop
 430 PSET(2)                  :REM--Switch on the ready lamp
 440 GOTO 110
1000 B=@(2)                   :REM--Get current value of distance
1010 IF B>(W-300) C=0 :GOTO 1000 :REM--Loop until distance starts to increase
1020 C=C+1
1030 IF C < 2 GOTO 1000
1032 Y = @(34)                 :REM--Save the buffer pointer to start of loading
```

```
1035 C=0
1040 A=B
1050 B=@(2)                    :REM--Get current distance
1060 IF (A-B)>200 A=B : C=0 : GOTO 1050 :REM--Check that the spike is moving
1070 C=C+1
1080 IF C>2 N=@(34) : RETURN     :REM--Save the buffer pointer to end of loading
1090 GOTO 1050
2000 B=@(2)                    :REM--Get the current distance value
2004 IF (W-B)>1500 C=0 : GOTO 2000
2020 C=C+1
2030 IF C>1 RETURN
2050 GOTO 2000
3000 X=&H4000
3010 ASM X, LDD &H7196; LDX &H71F6; STD 0,X; LDAA &H718F; STAA &H717F; DECA ; BEQ K; STAA &H718F; LDAA &H71F7; ADDA #4; STAA &H71F7; RTI
3020 K=X
3030 ASM X, LDAA #3; STAA &H718F; LDD #&H720E; STD &H71F6; RTI
3040 RETURN
4000 REM--Theta probe control sequence
4010 A=0
4020 FOR I=1 TO 20 : A = A + CHAN(4) : NEXT I
4030 A = A/20
4040 REM--Get the gps data
4050 B = 0 : C = 0
4070 RETURN
5000 A=GET(Y,#2)
5020 IF (A%256&&HF)<>3 GOTO 5000
5090 B=A : A=GET(Y,#2): U=GET(Y,#2) :REM--Channel 1 read first
5095 REM--- PRINT"A=  ",A,"  B=  ",B," U= ",U
5100 RETURN
```

```
6000 D=65000 : E=0 : F=0 : J=0 : G=0 : X=0 : REM-- Set distance, maxforce, energy, time, Acceleration, distance step
6020 GOSUB 5000 : REM--Read first set of values
6070 V=32704 : REM--Set reference value for distance to ground level
6080 O=B : P=A : REM--Set starting values
6090 B=GET(Y,#2) : U=GET(Y,#2) : A=GET(Y,#2) : REM--Read next set of values
6094 REM--- PRINT"  ",(A-L)/44,"  ",(V-B)/631,"  ",(U-T)/832
6096 STORE Z,#2,A,B,U
6098 PRINT A," ",B," ",U
6100 IF B<D D=B    : REM--Save maximum distance
6110 IF A>E E=A    : REM--Save maximum force
6115 IF U>G G=U    : REM--Save maximum acceleration
6120 Q=O-B         : REM--Distance increment
6130 R=((A+P)/2)-L : REM--Mean force acting
6140 S=Q*R         : REM--Energy in dt
6150 F=F+S         : REM--Sum energy
6155 IF X<Q X=Q    : REM--Save maximum velocity
6160 IF Q>631 J=J+1 : REM--Increment time counter when the spike is moving
6170 IF Y<N GOTO 6080 : REM--Check for end of loading
6172 D=V-D : REM--Calculate penetration
6174 E=E-L : REM--Calculate maximum force (in)
6176 G=G-T : REM--Calculate peak acceleration
6178 STORE Z,#2,-1,-1,-1
6179 PRINT -1," ",-1," ",-1
6180 RETURN
7000 M=-1
7005 SLEEP 100
7010 PRINT"Set the clock"
7015 IF ?(5) = 80 GOSUB 8000:RETURN: REM--Set the time if year is 0
7020 U=20481
7025 W = GET(U)
```

```
7030 IF W = 42 GOSUB 9000 : GOSUB 10000 : GOTO 7070 :REM--Read back the header for the test
7040 GOTO 7025: REM--Search for "*"
7070 IF U<Z GOTO 7025
7080 RETURN
8000 INPUT 'The Year is (0 - 99) '?(5)
8010 INPUT 'The Month is (1 - 12) '?(4)
8020 INPUT 'The day is (1 - 31) '?(3)
8030 INPUT 'The hour is (0 - 23) '?(2)
8040 INPUT 'The minute is (0 - 59) '?(1)
8050 INPUT 'The second is (0 - 59) '?(0)
8060 STIME
8070 RETURN
9000 U=U+3
9010 PRINT"Test number ",#2,GET(U,#2)
9020 PRINT GET(U,#2),":",GET(U,#2),":",GET(U,#2),"  ",GET(U,#2),"/",GET(U,#2)
9025 PRINT #8,GET(U,#2),GET(U,#2),GET(U,#2)
9030 PRINT #8,GET(U,#2),GET(U,#2),GET(U,#2)
9040 RETURN
10000 W = GET(U,#2): PRINT #8,W; : W=GET(U,#2) : PRINT #8,W; : W=GET(U,#2) : PRINT #8,W
10010 IF W = 65535 GOTO 10030
10015 SLEEP 0 : SLEEP 25
10020 GOTO 10000
10030 PRINT"Energy mJ ",#6,GET(U,#2)," Speed mm/s ",GET(U,#2)," Distance mm ",GET(U,#2)," Max force N ",GET(U,#2)," Max acceleration g ",GET(U,#2)
10035 SLEEP 20
10040 RETURN

OK
>
```

11.1.2 Initial Calibration Experiments of the DST Device

Early calibration experiments were performed with the DST device to understand the physics of the device impacts and the range of loading forces that were achievable. Free body diagrams of the different stages of DST impact are presented in Figure 11-1. During operation of the DST device, the force of the compressed air system is provided to the moving part of the DST, which includes the test foot, the moving part of the ram, and the moving rails attached to the test foot platform (Figure 11-1 a). The physics of the DST are different to that of a falling object impacting the surface in that the test foot is being driven into the surface by the pneumatic system. When the button of the DST is pressed, the pressure in the pneumatic system is applied to these moving parts (mass = 1.07 kg) to create an applied force (F_{app}) and the test foot accelerates from rest towards the surface (Figure 11-1 b). Within this stage of movement, gravity (F_{grav}) is also relevant to the downward movement of the device, while the forces acting in the opposite direction are friction on the moving rails (F_{frict}) and air resistance (F_{air}), but both are considered to have negligible affects. During the impact and penetration stage (Figure 11-1 c), the forces applied by the pneumatic system and gravity are still present, while opposing forces applied to the test foot include the ground reaction force (F_{grf}) and friction forces from the moving rails and metal-soil friction. In this stage the forces applied by gravity and the pneumatic system are greater than the opposing forces, resulting in the test foot moving downwards into the soil, although the test foot is decelerating as the ground reaction force increases. As indicated in Figure 3-1, the reaction mass of the device impact is provided by the operator. When the test foot is brought to rest (velocity = 0), the ground reaction force is equal to the force applied by the pneumatic system (Figure 11-1 d), which is present until the foot is retracted and the pressure released.

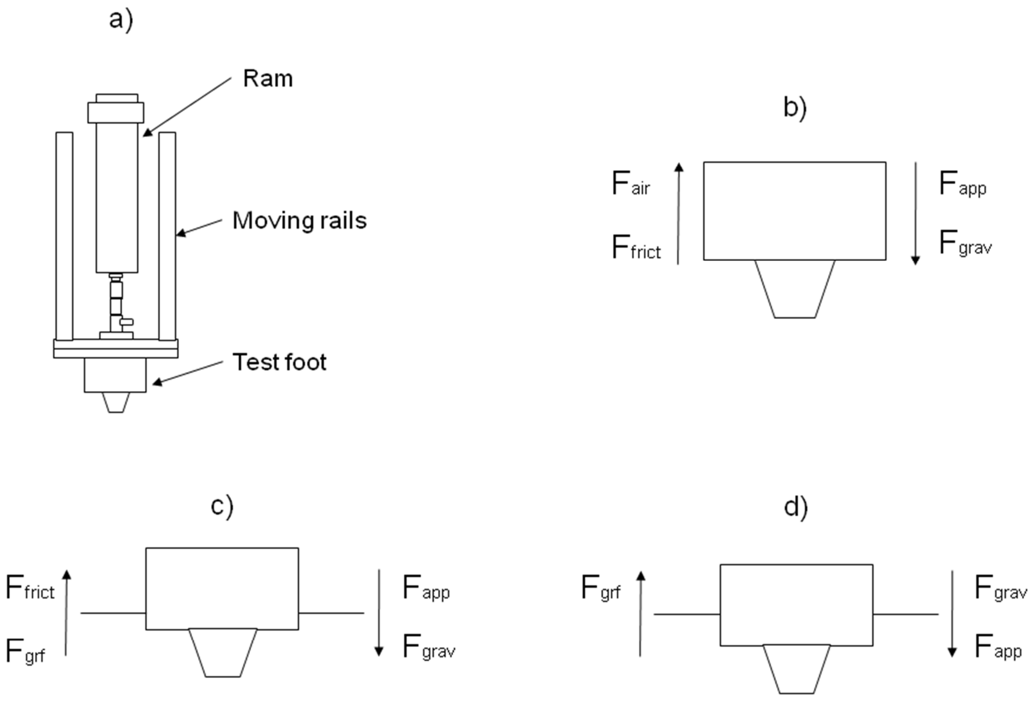

Figure 11-1 a) Schematic diagram of the moving part of the DST device (adapted from Figure 3-3; free-body diagrams of the forces acting on the DST test foot during: b) movement towards surface, c) during impact and penetration into the surface, d) when test foot is brought to rest.

Calibration of the DST force transducer was undertaken by statically loading the device with a range of loads. The linear correlation presented in Figure 11-2 indicates the precision of the transducer (Figure 11-2).

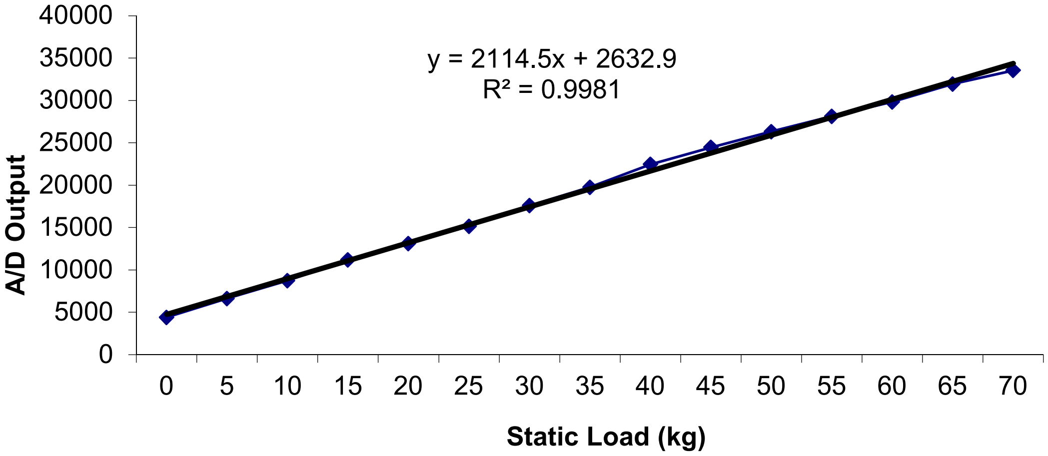

Figure 11-2 Mean A/D output values produced when the DST test foot was loaded with a range of static loads.

Measurements were taken with the DST device from *in-situ* turf surfaces and a 300 mm x 300 mm x 15 mm thick piece of styrene butadiene rubber (SBR) shockpad (as used in the construction of synthetic turf surfaces). At this stage in the development process, a MatLab script was written to enable loading graphs of the different parameters to be plotted. An example of these sets of figures is shown in Figure 11-3 for an *in-situ* turf surface at a regulator pressure of 0.6 MPa. The force-time and force-depth graphs indicate that as the test foot is fired towards the surface, acceleration of the test foot occurs (indicated as a reduction in force) prior to impact with the surface. As the stud impacts and penetrates into the soil (at a depth of 35 mm), the force acting on the foot increases, and continues to increase as the test foot comes in contact with the soil at 50 mm depth. These two occurrences are highlighted with dashed lines in Figure 11-3. These initial data highlighted that the majority of force applied to the test foot from the surface occurs within the first 0.1 s of impact as the test foot decelerates quickly. After this point the rate of deceleration decreases as a result of the mechanical behaviour of the soil (strain rate dependency), which is discussed in greater detail in Chapter 3. The final value of force (ground reaction) acting on the test foot when the device is brought to rest is used as an indicator as the initial impacting force of the device (assuming Newton's laws of motion).

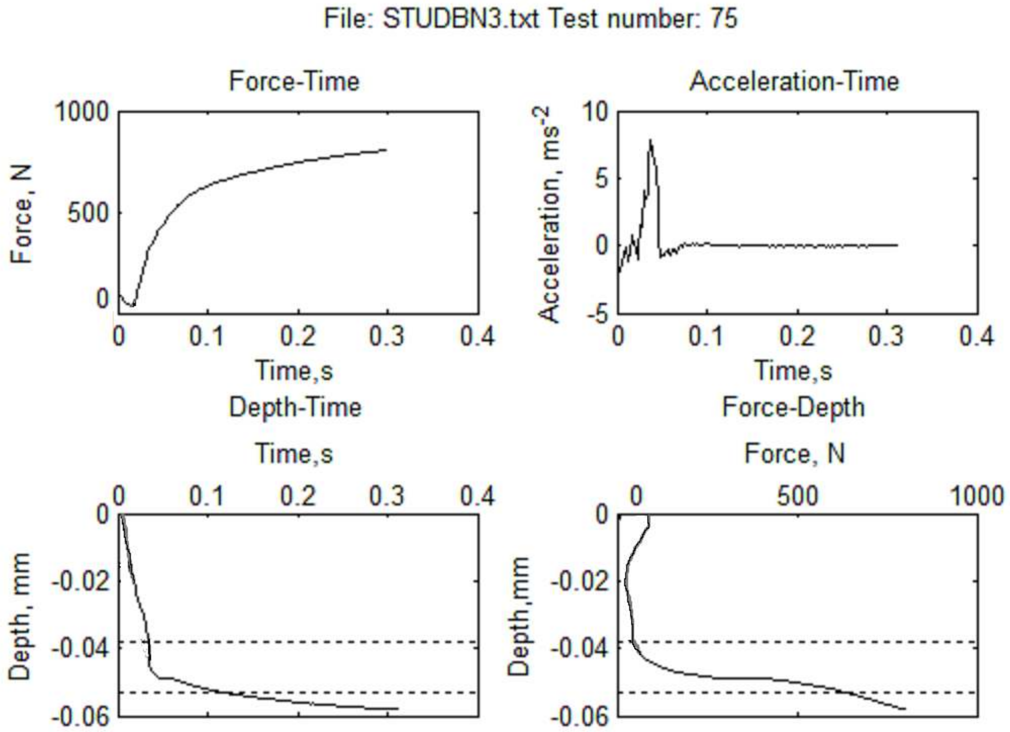

Figure 11-3 An example of the loading graphs produced from initial experiments with the DST on an *in-situ* turf surface. Dashed lines indicate the depths at which the stud (35 mm) and test foot (50 mm) initially impact the soil.

During the experiments, it was apparent that a reference surface for benchmarking loading conditions of the DST was required. It was decided that the rubber shockpad over concrete would be adequate for this purpose as a result of the uniformity of surface behaviour and portability of the piece of material for future use. As part of the calibration experiments, a dataset was collected from the rubber shockpad at a range of operating pressures to understand the range of impacting forces and velocities produced by the device (Table 11-1). It was found that the force applied by the device at 0.6 MPa pressure was nearest to the force values (0.74 kN) required to meet the desired stress value calculated from the biomechanical data (discussed in Chapter 3). It was also found that the device behaved most reliably at this force, indicated by the lowest standard error values. Reliability of impacts at 0.7 MPa was reduced as the force applied sometimes caused the device to tilt off the ground as a result of the force being greater than the static reaction mass force provided by the user and device. This restricted the use of higher forces by the DST in its current form.

Table 11-1 Mean (± standard error) impacting force of the DST device on the rubber shockpad at a range of operating pressures (n = 20 for each operating pressure).

Operating pressure	**Force (N)**	**Impact velocity (m s^{-1})**
2	262 ± 19	1.10 ± 0.01
3	415 ± 43	1.19 ± 0.03
4	540 ± 27	1.20 ± 0.02
5	667 ± 32	1.27 ± 0.03
6	785 ± 12	1.33 ± 0.01
7	829 ± 56	1.34 ± 0.03

The cylindrical studded test foot designed for the device is shown in Figure 11-4. The sack barrow used to transport the DST device and cylinder is shown in Figure 11-5.

Figure 11-4 Close-up of the studded test foot of the DST device, dimensions 41 mm diameter, 38 mm height, 1320 mm^2 surface area.

Figure 11-5 The DST device and compressed air cylinder being transported on a sack barrow for use on *in-situ* surfaces.

11.2 DEVELOPMENT AND CALIBRATON OF THE GOINGSTICK DEVICE

The relationship between force and penetration values measured by the GoingStick for the original horseracing calibration (H1) is presented in Figure 11-6. The relationship between torque and shear values measured by the GoingStick for this calibration is presented in Figure 11-7. Red values on the calibration curves (e.g. GS pen values 1-3 on Figure 11-7) did not exhibit the same linear behaviour as the higher values. However, values this small were not recorded on the sports pitches within the project, meaning a regression equation was not required. As indicated in Chapter 4, the measurable range of the H1 calibration did not allow the full range of mechanical behaviour on *in-situ* surfaces to be measured. An updated calibration (H2) was developed by technicians at TurfTrax Ltd, with the relationships indicated in Figures 11-8 and 11-9. To increase the force and torque values able to be achieved by this new calibration, the resolution of the lower values (0-2 Figure 11-8 and 0-3 Figure 11-9; red values) was reduced. This calibration was also insufficient to measure the range of mechanical behaviour on *in-situ* natural turf pitches.

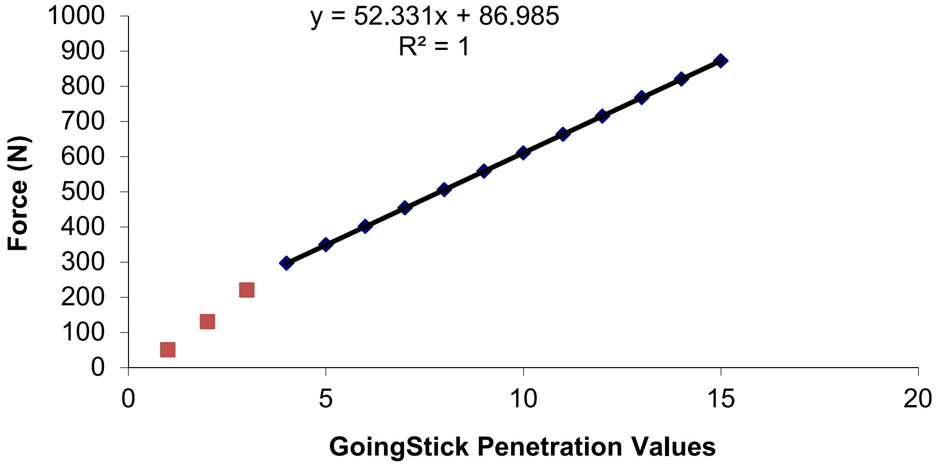

Figure 11-6 Linear regression analysis of force and GoingStick penetration values for the H1 calibration.

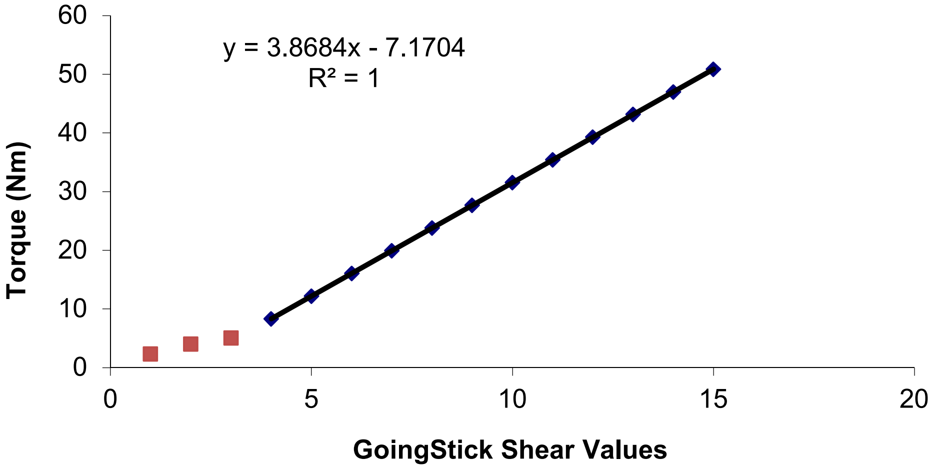

Figure 11-7 Linear regression analysis of torque and GoingStick shear values for the H1 calibration

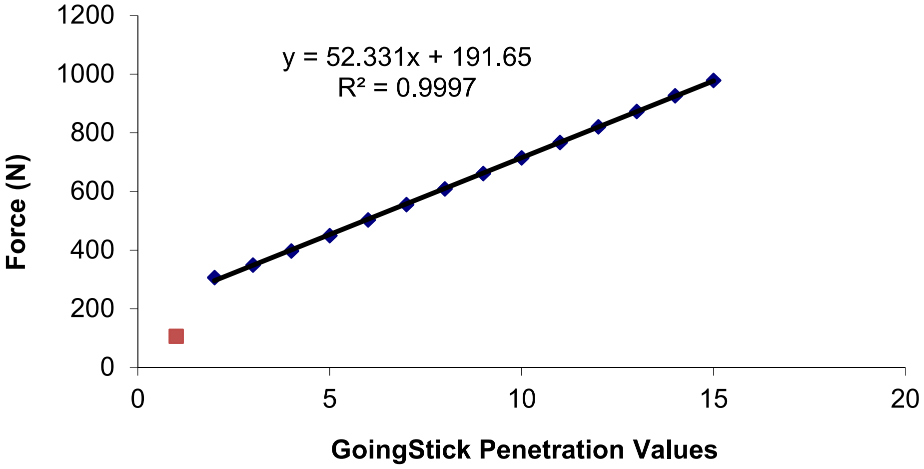

Figure 11-8 Linear regression analysis of force and GoingStick penetration values for the H2 calibration.

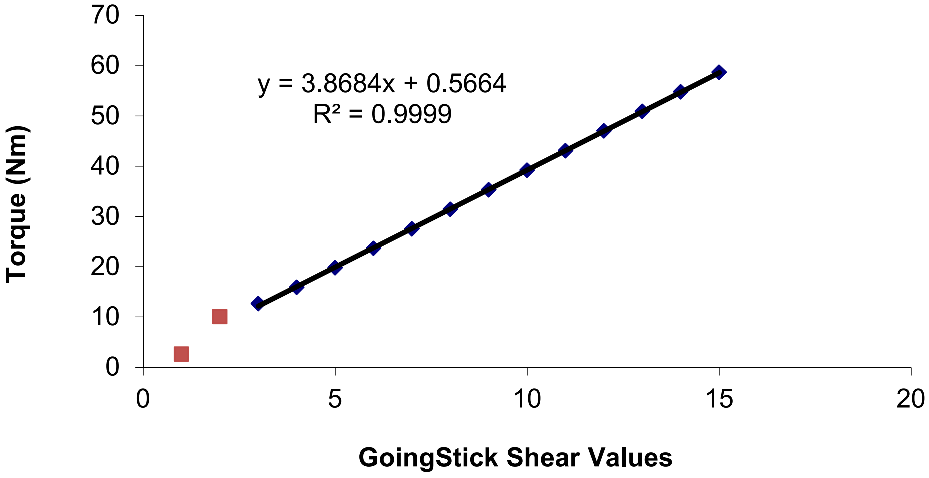

Figure 11-9 Linear regression analysis of torque and GoingStick shear values for the H2 calibration

A third calibration (SP1) was developed by TurfTrax, which allowed penetration and shear values that were 33% greater than the standard horse racing calibration (H1) to be measured (Figures 11-10 and 11-11). The data presented in Chapter 4 indicated that this calibration was suitable for use on the surfaces, successfully measuring the range of mechanical behaviour of three pitches across a season. However, the increase in measurable range provided by this calibration meant that some resolution was lost: numerical values were separated by intervals of around 53 N (penetration) and 4 Nm (shear) for the H1 and H2 calibrations, while these intervals were around 69 N and 5 Nm for the SP1 calibration.

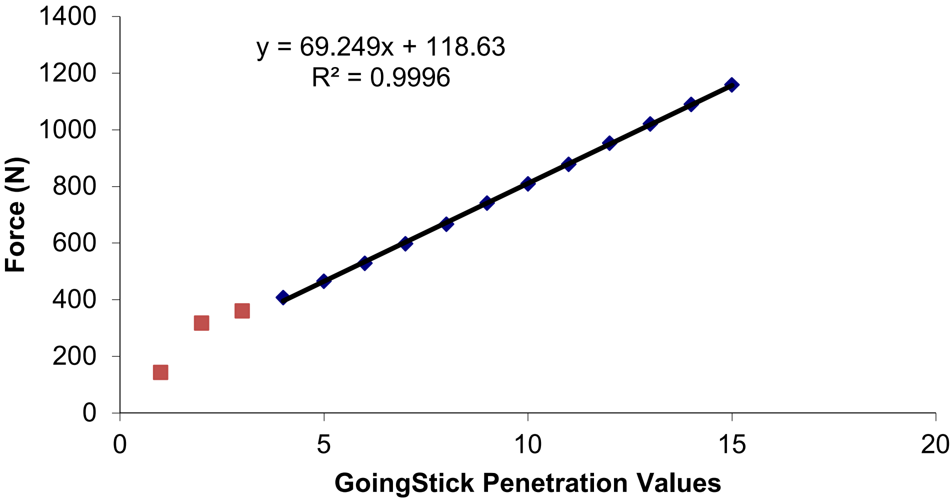

Figure 11-10 Linear regression analysis of force and GoingStick penetration values for the SP1 calibration.

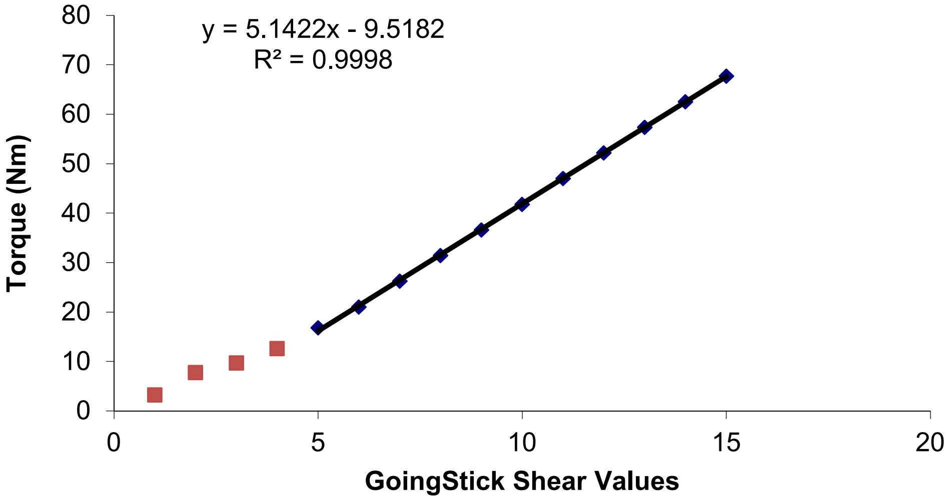

Figure 11-11 Linear regression analysis of torque and GoingStick shear values for the SP1 calibration

11.3 SOIL TEXTURE OF SURFACES USED IN CHAPTER 4

Figure 11-12 illustrates the soil textures of the three football pitches (A, B, C) and the soil bin soil within the soil UK soil texture triangle. The three sports pitches tested were regarded to represent the range of soil textures that are evident in football and rugby pitches within the UK: pitches typically range from engineered sand rootzones (Pitch A) to native ‘heavy’ clay dominated soils that drain poorly (Pitch C). Between these two soil textures a range of intermediate surface constructions are evident, often consisting of sand ameliorated surface layers overlying native soil (as evident on Pitch B).

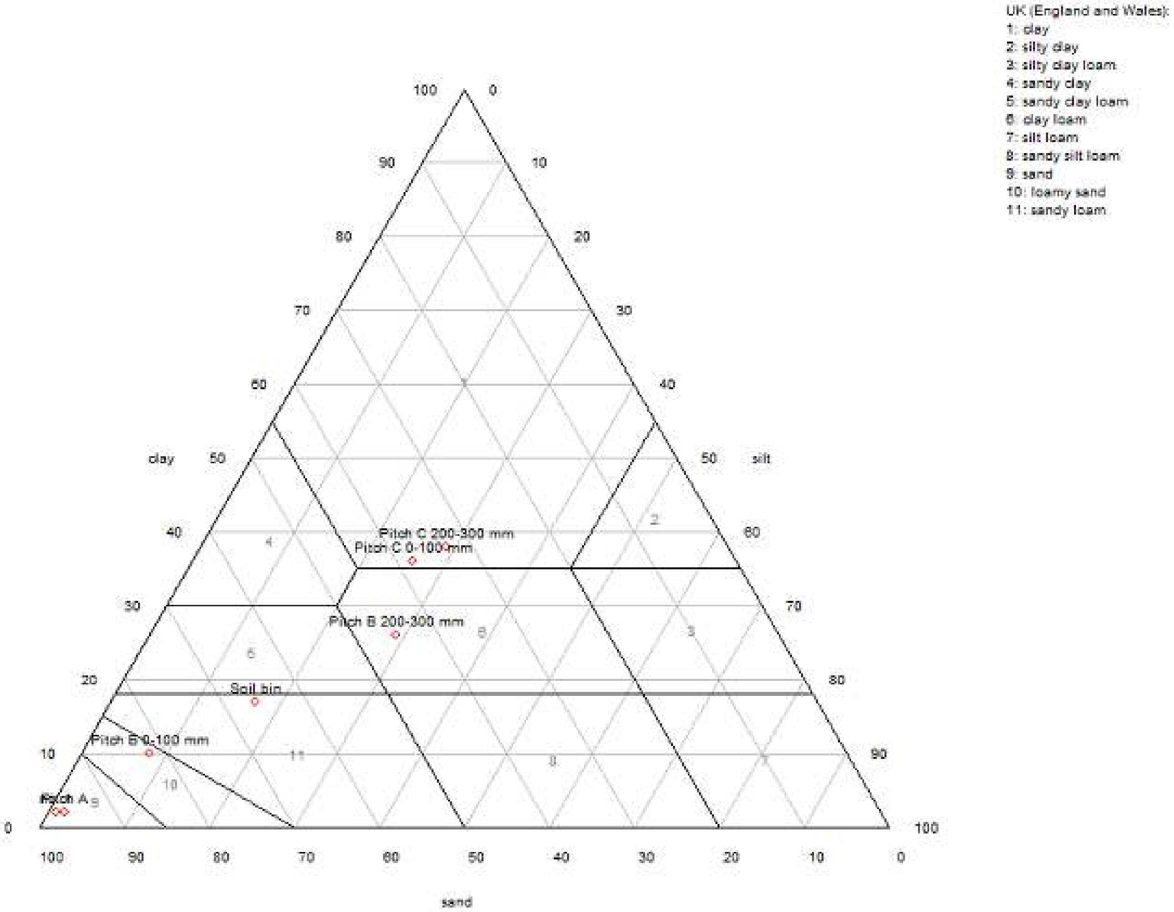

Figure 11-12 Soil texture of the three pitches (A, B, and C) at two soil depths (0-50 mm and 200-300 mm) and the soil bin soil used in Chapter 4.

11.4 CALCULATING STRAIN RATE OF THE GOINGSTICK AND STUDDED DISC APPARATUS

The rate at which stress is applied by the GoingStick and studded disc apparatus devices is not defined in the literature. Experiments were undertaken to calculate these rates by filming the devices being used on natural turf and recording the time taken to perform the movement. Figure 11-13 shows screenshots of the penetration and shear components of the GoingStick being analysed. For the GoingStick penetration component, the time taken to insert the tine to the full 100 mm was recorded and strain rate was indicated in mm s^{-1}. For the shear component of the GoingStick and the studded disc apparatus, the time taken to reach 45 degrees of rotation (GoingStick pulled back; studded disc rotated) was recorded and strain rate presented in terms of degrees per second. The movement of the devices was kept constant during operation, and 10 replicates were performed with each device to calculate a mean value. It must be noted that data are reliant upon the rate of movement applied by the operator – these data are accurate for the rate that was used in collecting the data in this project. Results are presented in Table 11-2, alongside data for strain rate of the DST device and CIST devices as calculated within Chapters 3 and 8.

Figure 11-12 Screenshots of videos of the Goingstick shear (left) and penetration (right) movements being analysed.

Table 11-2 Strain rates applied by the various devices used within this research project.

Device/Movement	Strain rate
GoingStick penetration	140 mm s^{-1}
GoingStick shear	48 degrees per second
Studded disc apparatus	49 degrees per second
2.25 kg CIST	up to 1557 mm s^{-1}
0.5 kg CIST	up to 1867 mm s-1
DST device	up to 300 mm s-1

11.5 CHARACTERISATION OF PITCHES USED IN CHAPTER 5

The soil textures of the pitches used in Chapter 5 are indicated in a soil texture triangle (Figure 11-14). As is highlighted by this figure, a wide range of soil textures were represented by the selection of pitches used within this season study. Some pitches used within this study are the same as those used in Chapter 4 (Using the GoingStick to assess pitch quality): Pitch A-MP is the same as Pitch A; Pitch C-MP is the same as Pitch B; Pitch D-MP is the same as Pitch C. It is considered that these soil textures provide a good representation of the typical soil used for natural turf pitches in the UK.

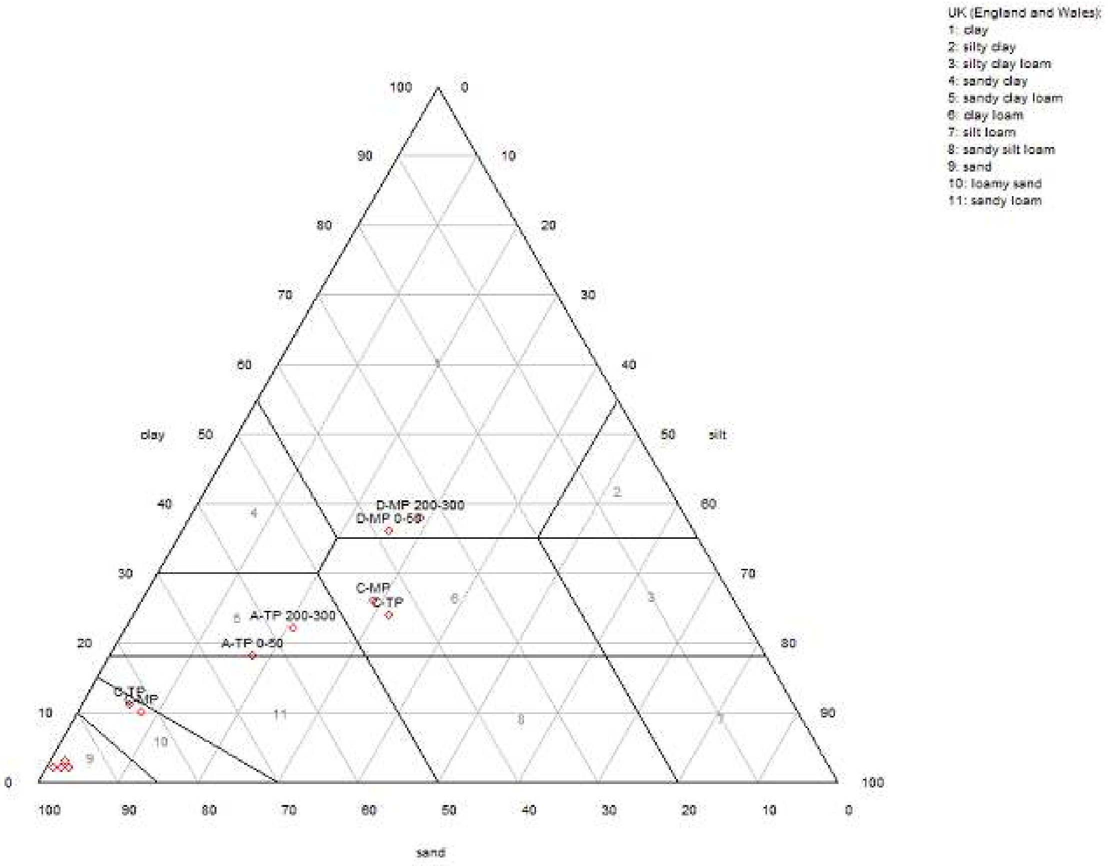

Figure 11-13 Soil texture of the six pitches used for data collection in Chapter 5 at two soil depths (0-50 mm and 200-300 mm). C-MP and C-TP soils located in the clay loam classification (6) refer to the 200-300 mm profile depth; C-MP and C-TP soils located in the loamy sand classification (10) refer to the 0-50 mm profile depth, and highlight the sand layering within these surfaces. The soils located within the sand classification (9) refer to the 0-50 mm and 200-300 mm profile depths within pitches A-MP and B-MP.

11.6 SPATIAL STUDY VARIOGRAMS

The following pages contain all of the variogram models for the data collected in the spatial study (Chapter 6). As indicated within the methodology, models were fitting using the smallest sum of square errors, calculated by VESPER software.

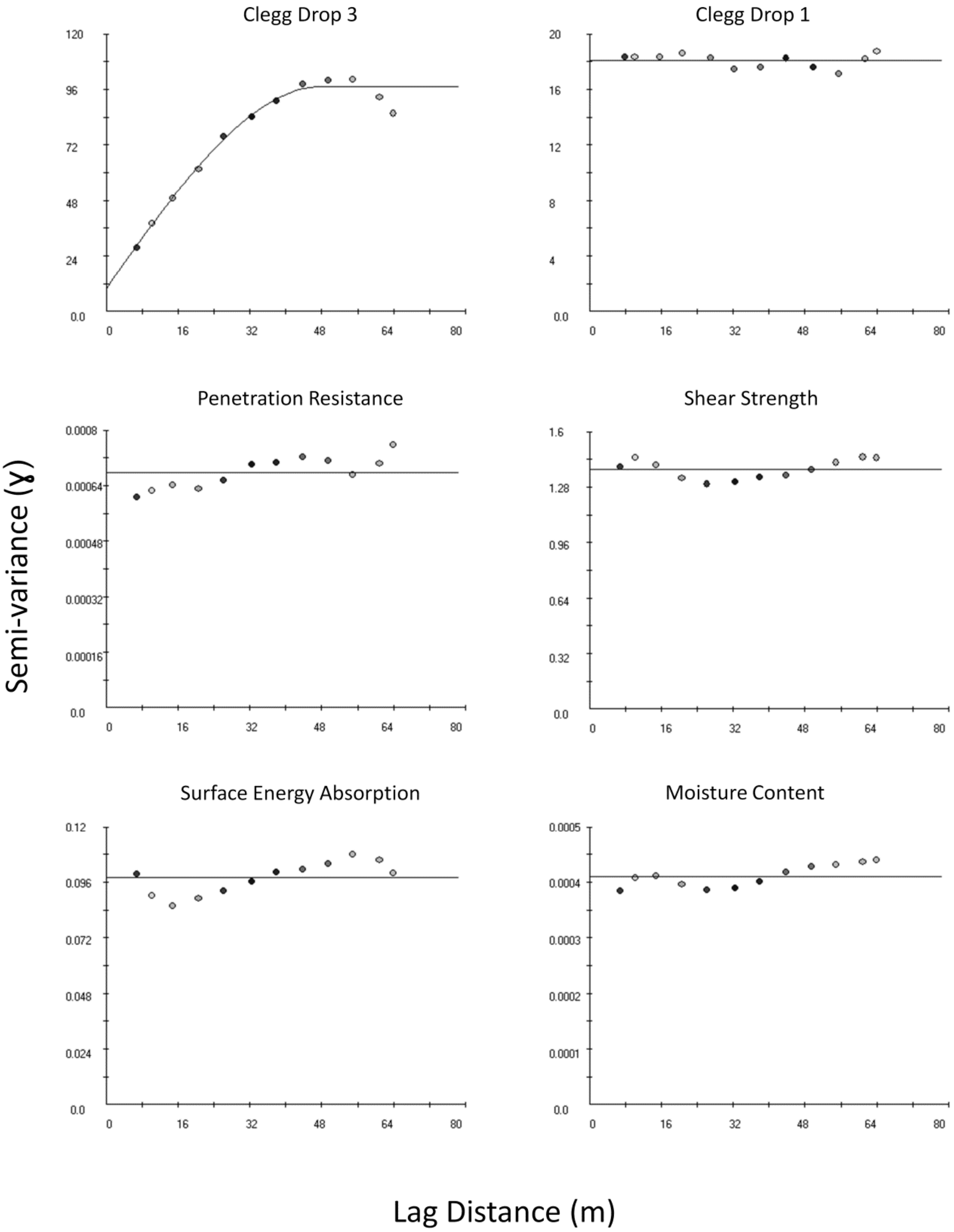

Figure 11-14 Variogram models of the mechanical parameters and soil moisture content from dataset 1 on Pitch A, calculated in VESPER software and fitted using the smallest sum of square error.

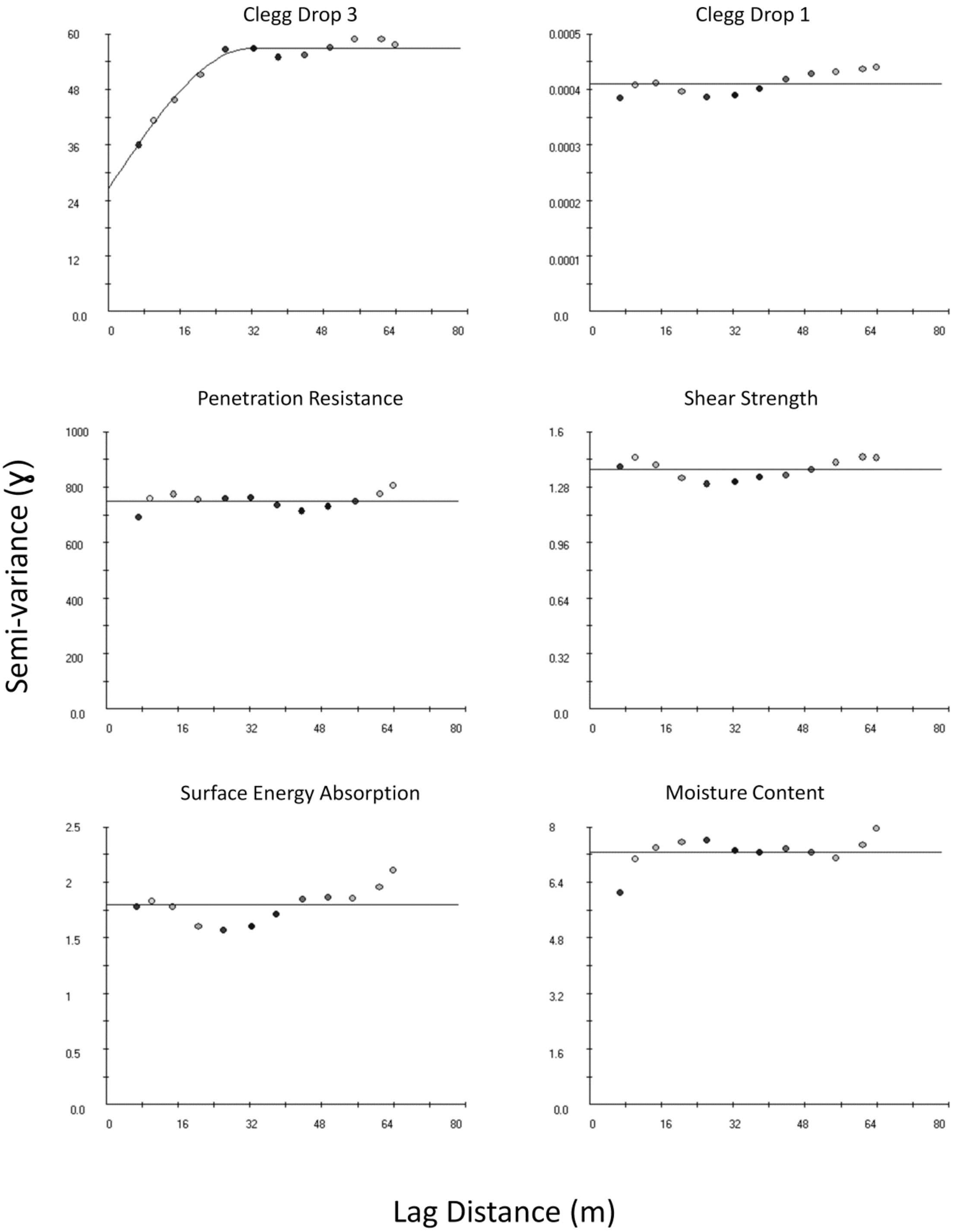

Figure 11-15 Variogram models of the mechanical parameters and soil moisture content from dataset 2 on Pitch A, calculated in VESPER software and fitted using the smallest sum of square error.

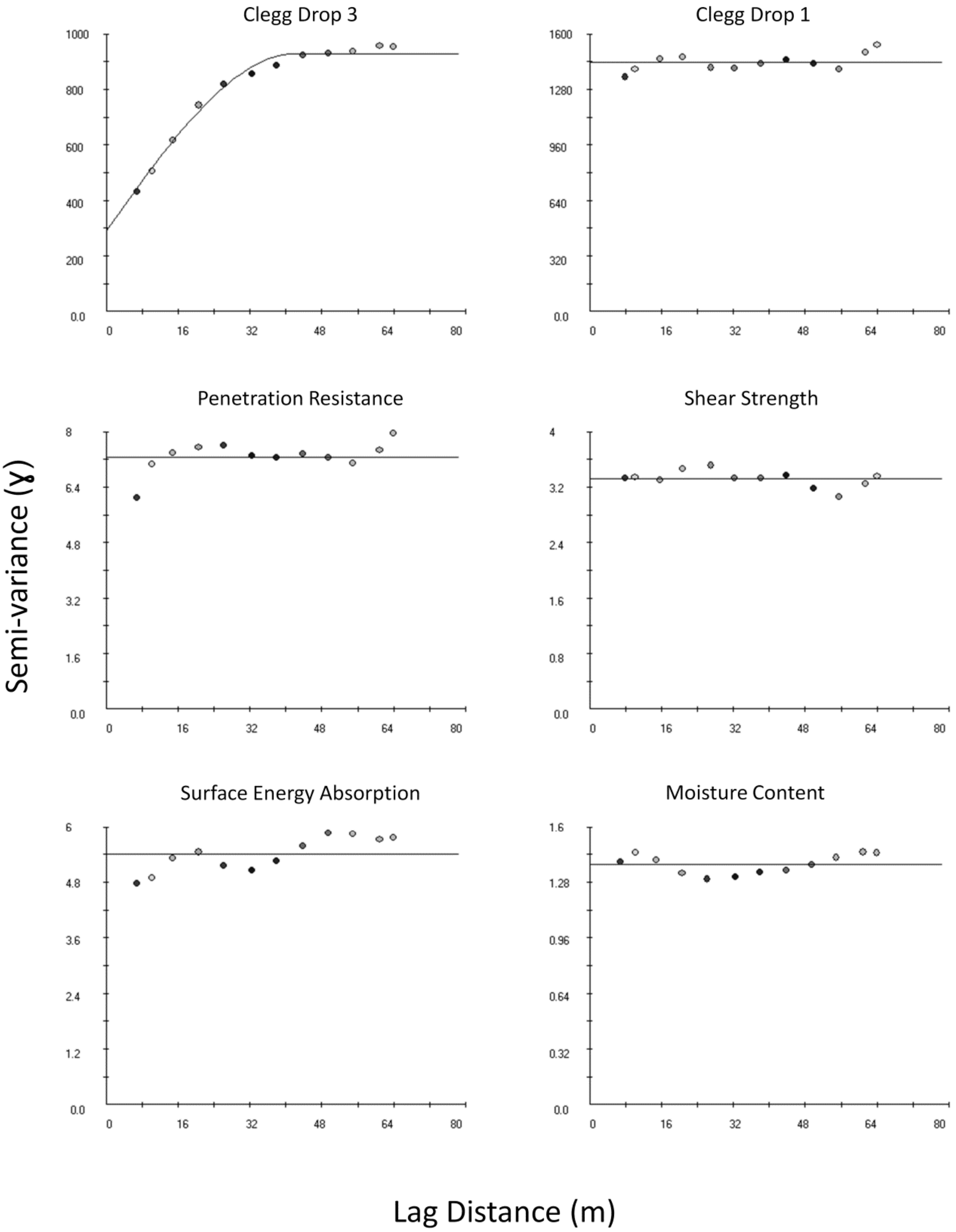

Figure 11-16 Variogram models of the mechanical parameters and soil moisture content from dataset 3 on Pitch A, calculated in VESPER software and fitted using the smallest sum of square error.

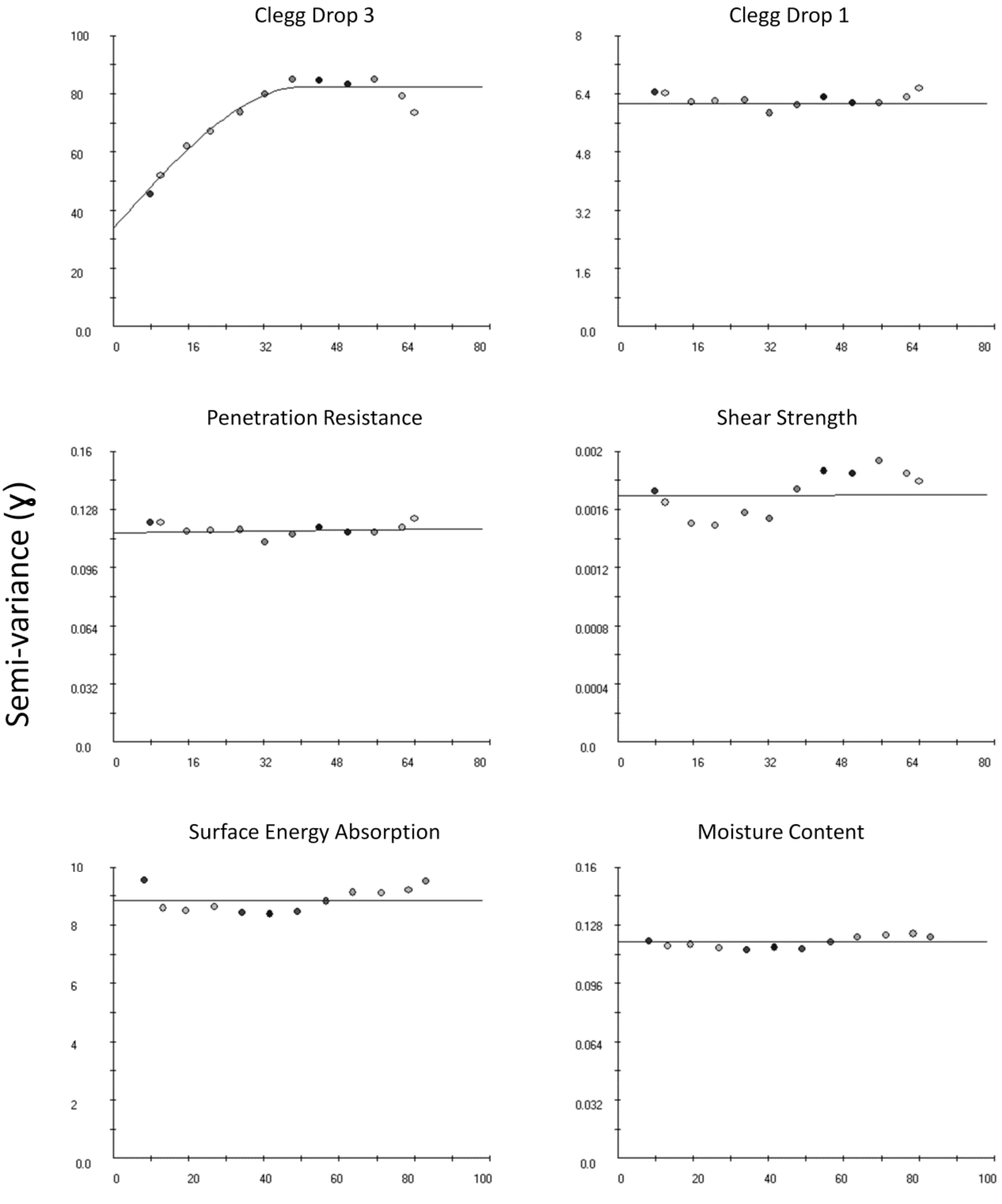

Figure 11-17 Variogram models of the mechanical parameters and soil moisture content from dataset 1 on Pitch B, calculated in VESPER software and fitted using the smallest sum of square error.

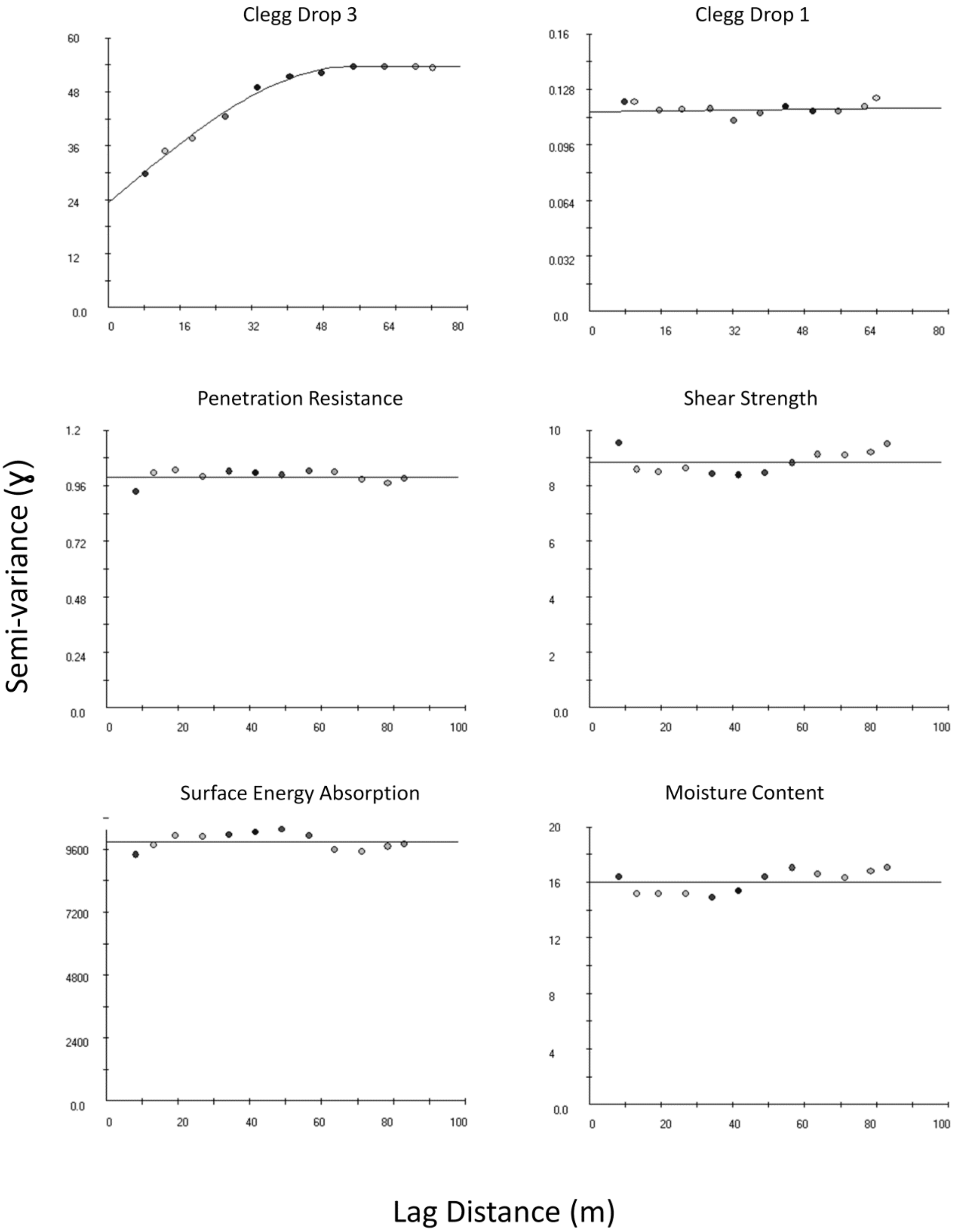

Figure 11-18 Variogram models of the mechanical parameters and soil moisture content from dataset 2 on Pitch B, calculated in VESPER software and fitted using the smallest sum of square error.

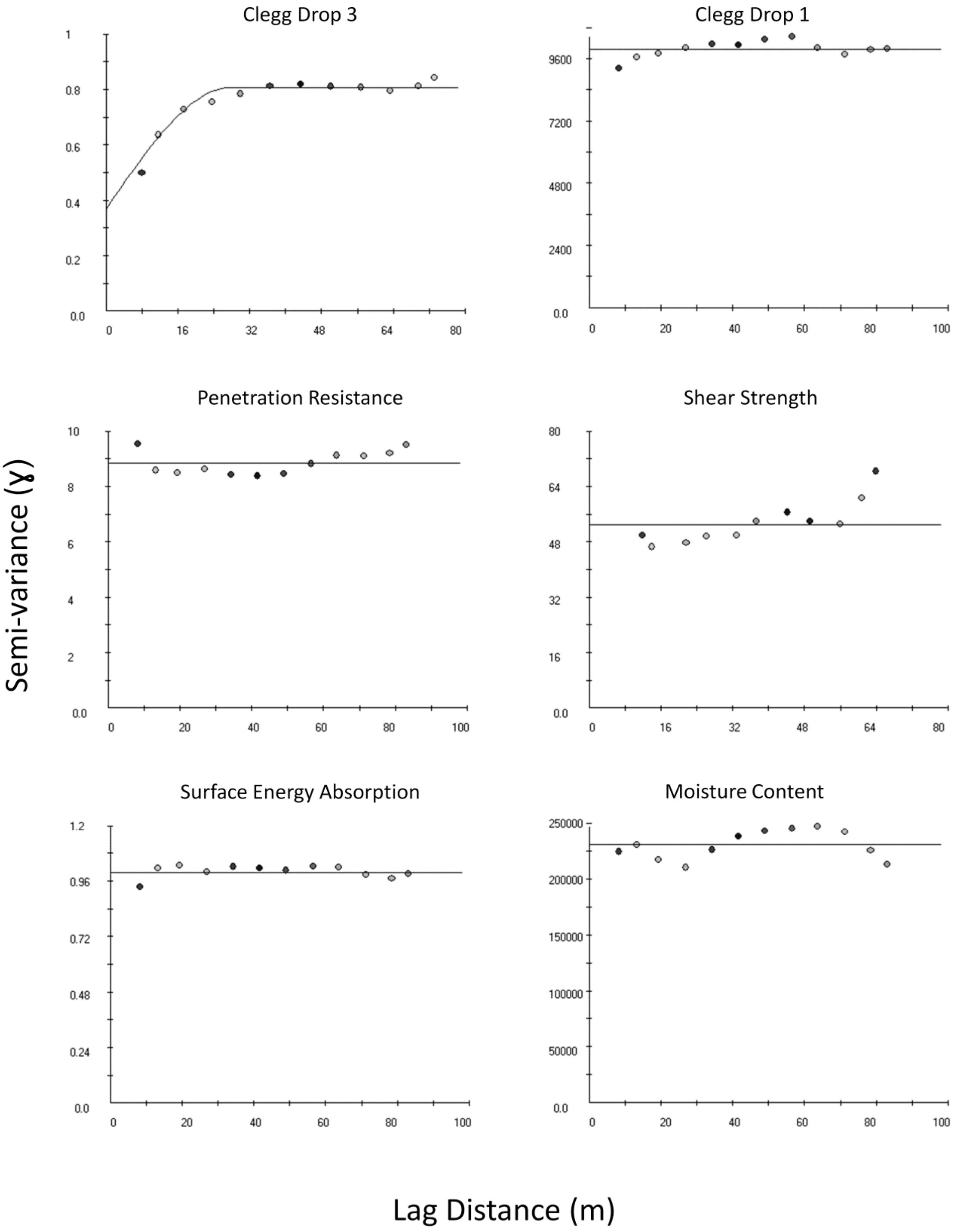

Figure 11-20 Variogram models of the mechanical parameters and soil moisture content from dataset 3 on Pitch B, calculated in VESPER software and fitted using the smallest sum of square error.

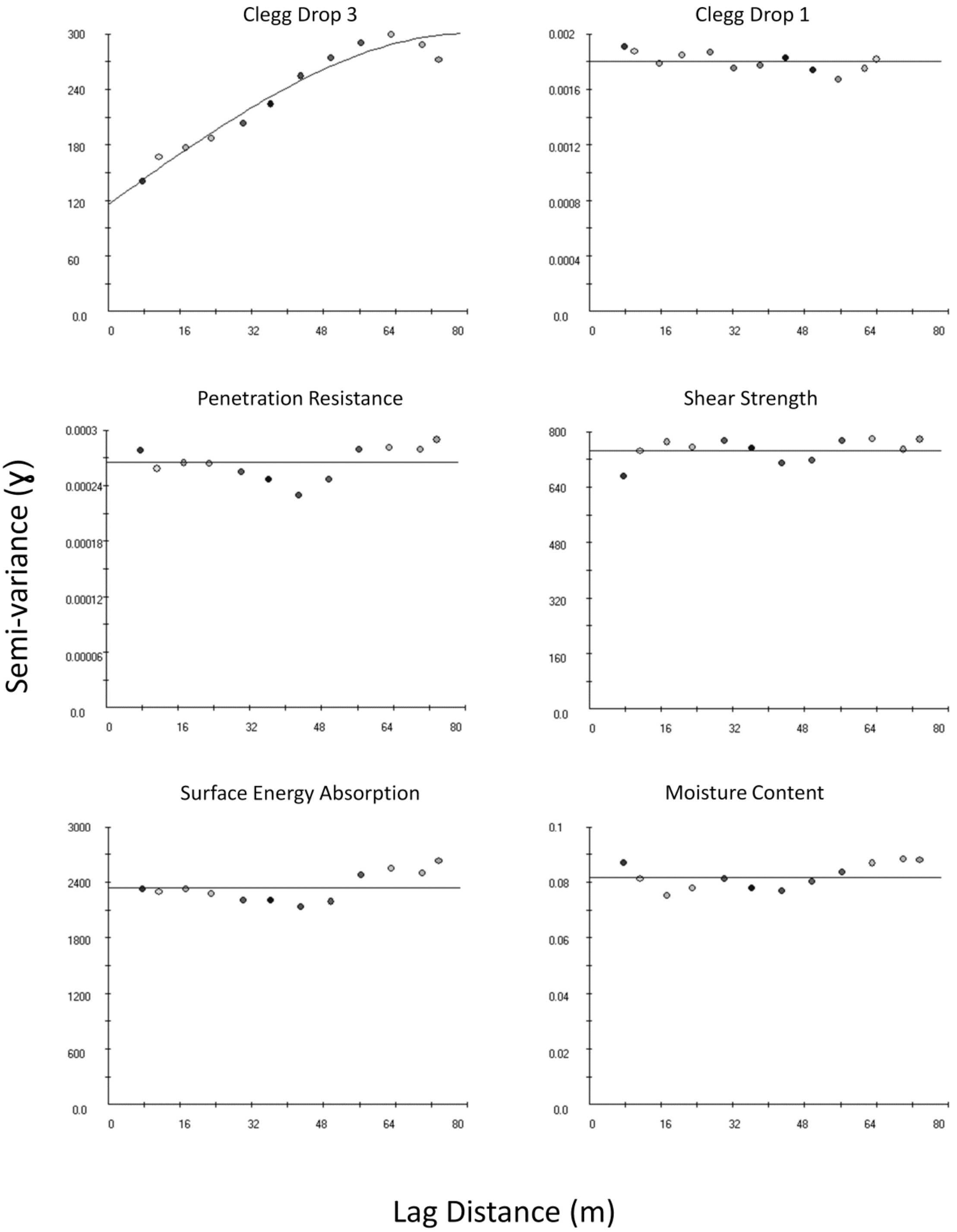

Figure 11-19 Variogram models of the mechanical parameters and soil moisture content from dataset 1 on Pitch C, calculated in VESPER software and fitted using the smallest sum of square error.

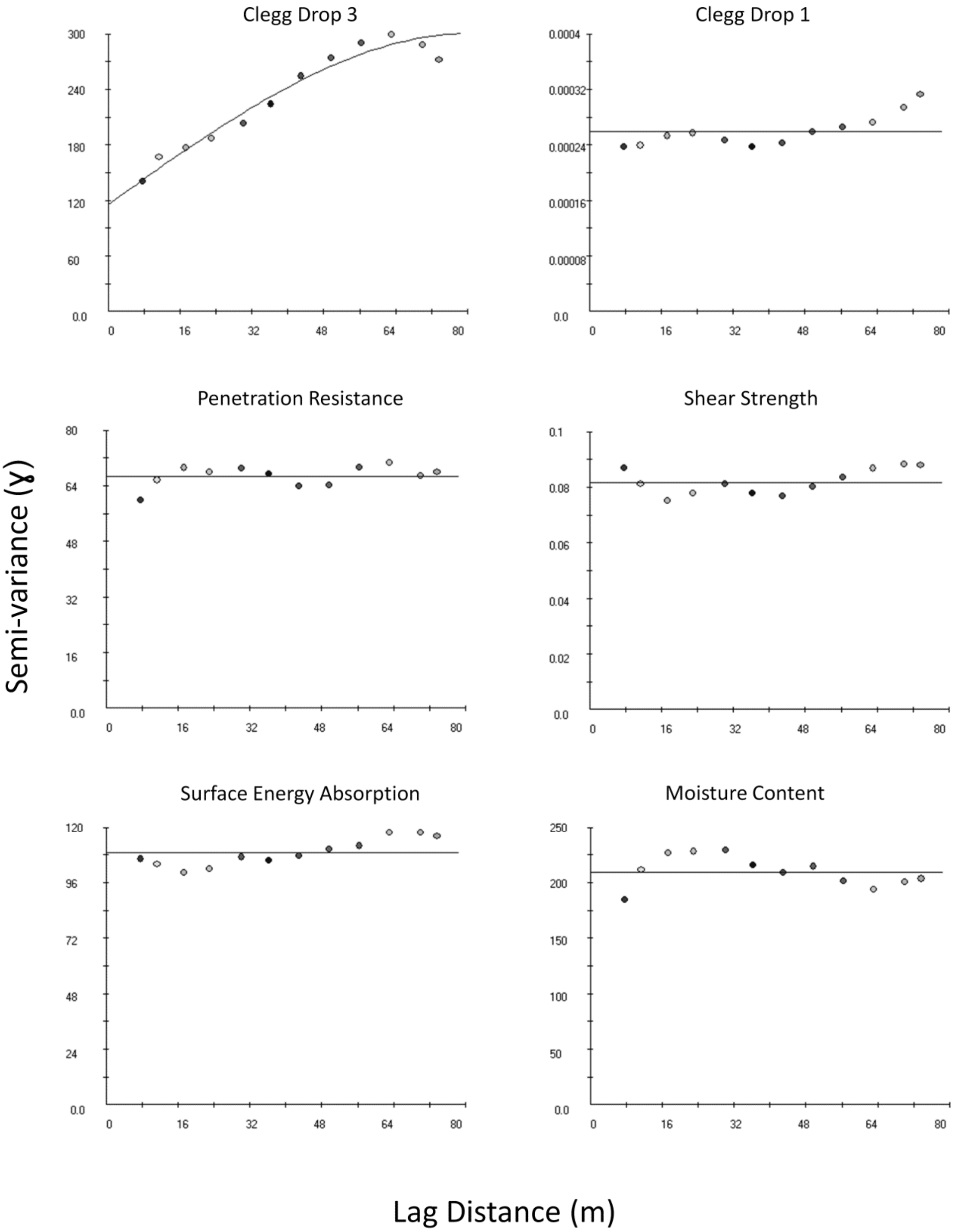

Figure 11-20 Variogram models of the mechanical parameters and soil moisture content from dataset 2 on Pitch C, calculated in VESPER software and fitted using the smallest sum of square error.

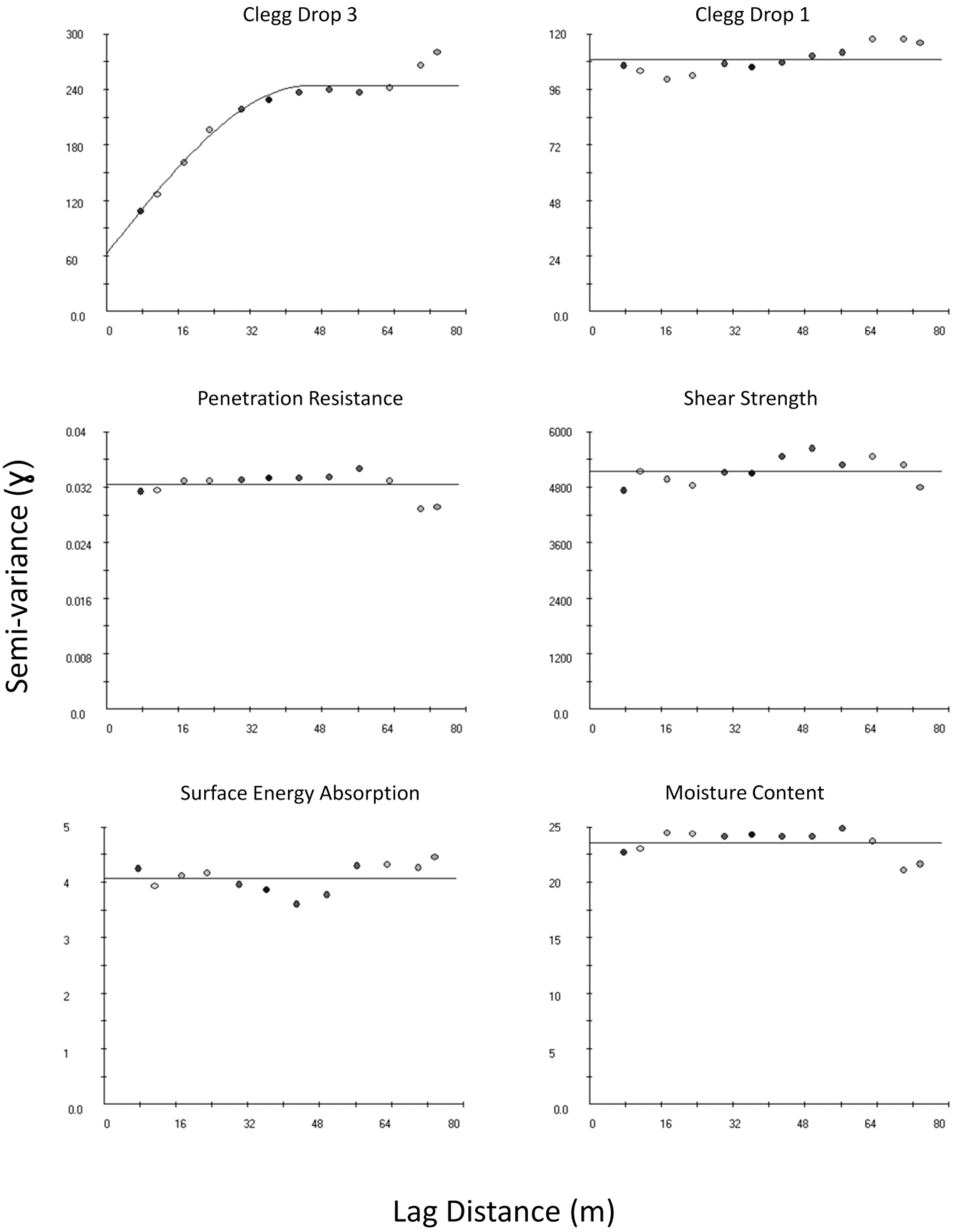

Figure 11-21 Variogram models of the mechanical parameters and soil moisture content from dataset 3 on Pitch C, calculated in VESPER software and fitted using the smallest sum of square error.

11.7 PICTURES OF CHAPTER 7 METHODOLOGY

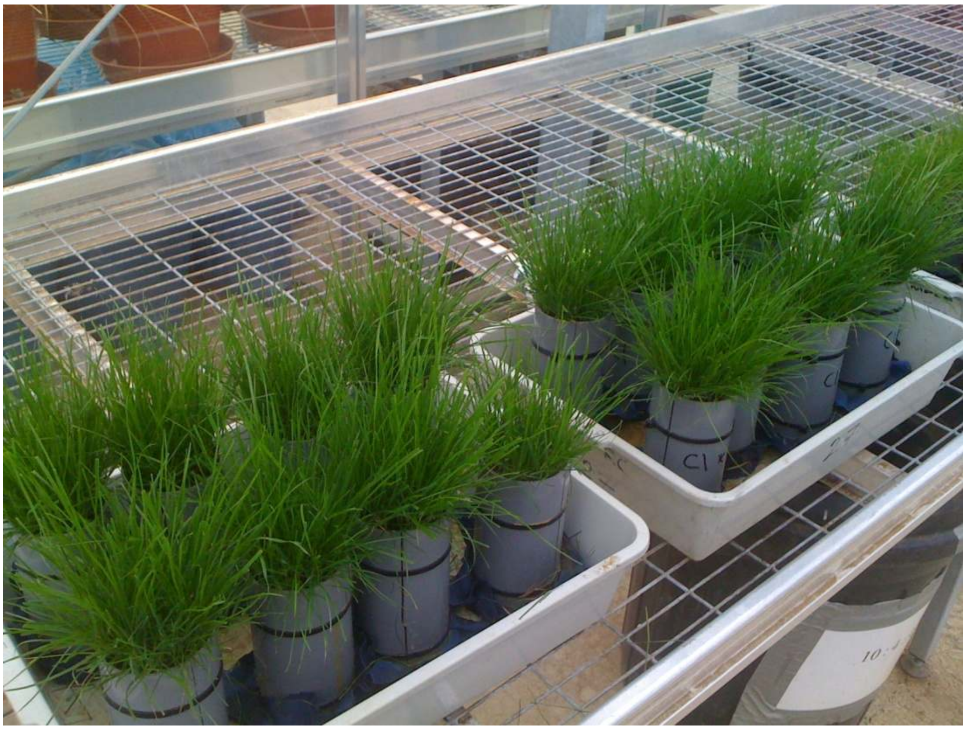

Figure 11-22 The grass rooted samples growing within the PVC tubes in the glasshouse.

Figure 11-23 Left: a rooted sand soil sample with grass leaves removed; right: a rooted sand soil sample within the rubber membrane prior to testing.

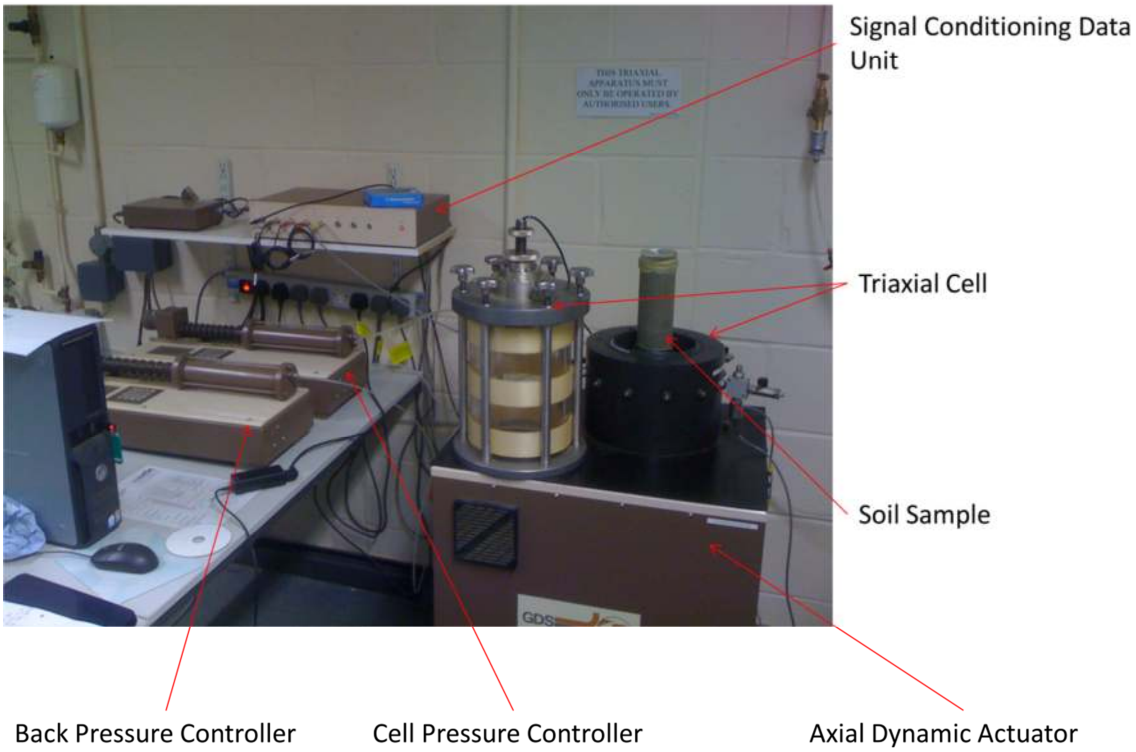

Figure 11-24 Outline of the main components of the Triaxial Apparatus.

11.8 METHOD OF FILTERING THE RAW CIST SIGNALS

A raw data plot of the CIST acceleration signal is shown in Figure 11-27. The baseline indicates when the impact missile was stationary at the specified distance above the ground (0.45 and 0.55 m). The missile was then dropped onto the surface, with contact indicated by the large increase in deceleration as the missile is brought to rest, up to a point of maximum deceleration. It can be seen that there was noise present on the signal baseline prior to and post impact with the surface. This may be a result of the quality of the cable used on the device. Manual post-hoc processing was required on these signals as the impact occurred at a similar frequency as the noise on the signal (around 0.01 s, highlighted in Figure 11-28). This restricted the use of automatic filters.

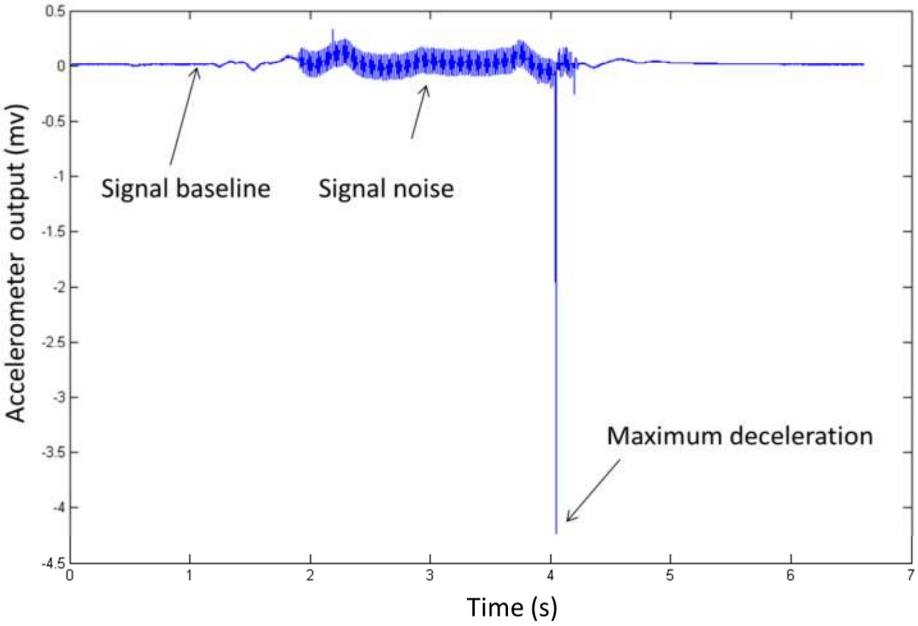

Figure 11-25 A raw data plot of the acceleration signal from the 0.5 kg CIST device, with signal baseline, noise and point of maximum deceleration indicated.

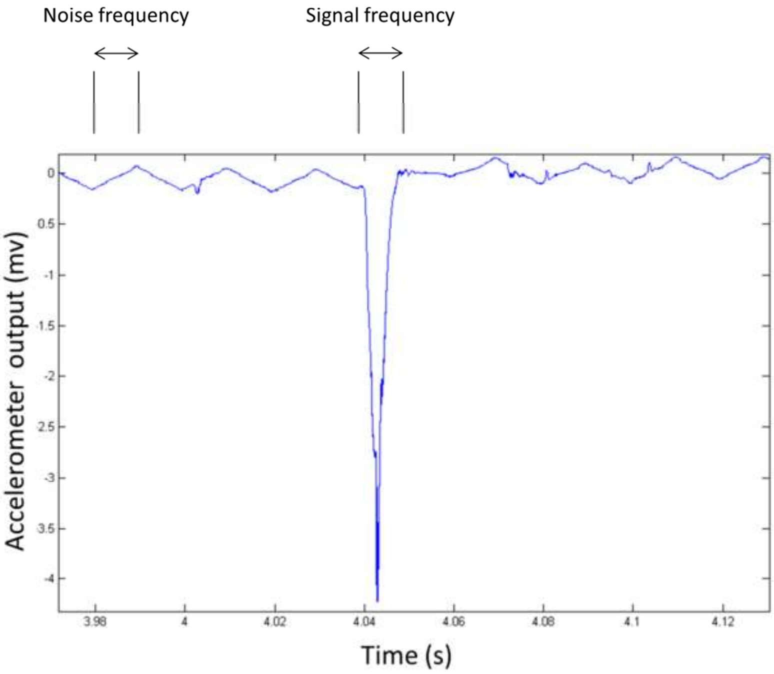

Figure 11-26 A close-up of the raw acceleration data from the impact shown in Figure 11-27. Annotations above the figure indicates that the noise occurred at a similar frequency to the actual data, restricting the use of automatic filters.

The noise present on the acceleration signal meant that a robust method of determining the start and end point of the impact from a designated datum was required. This was performed by calculating the maximum acceleration within a window of 1000 data points positioned 4000 data points prior and post impact. These maximum acceleration values are indicated by the dashed line in Figure 11-29. The impact was determined as starting and ending when the acceleration signal passed through these maximum values of acceleration. Capturing the data by this method meant that there was a potential error of 7.4 % and 5.8 % in the 0.5 kg and 2.25 kg CIST devices (the ratio of the magnitude of the noise to the magnitude of the actual impact). As considered in Chapter 8, no obvious elastic behaviour was evident in the raw acceleration signals, and would have been indicated by a spike in acceleration after impact. However, capturing the data by the method used meant that any elastic behaviour would not have been able to be measured.

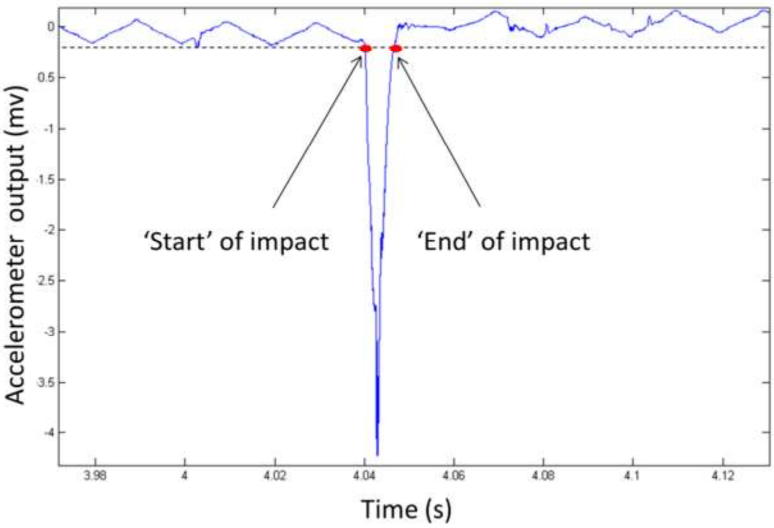

Figure 11-27 Illustration of designating the start and end points of the impact in the raw acceleration signal (red dots). The dashed line illustrates the maximum value of deceleration that was determined within a 1000 data point window positioned 4000 data points prior to and post impact.

Figure 11-30 illustrates the variation in parameter data that occurred when the 95% assumption of velocity was altered to 100% and 90% assumptions. The 95% value was decided upon as it yielded velocity values similar to that of Carré and Haake (2004).

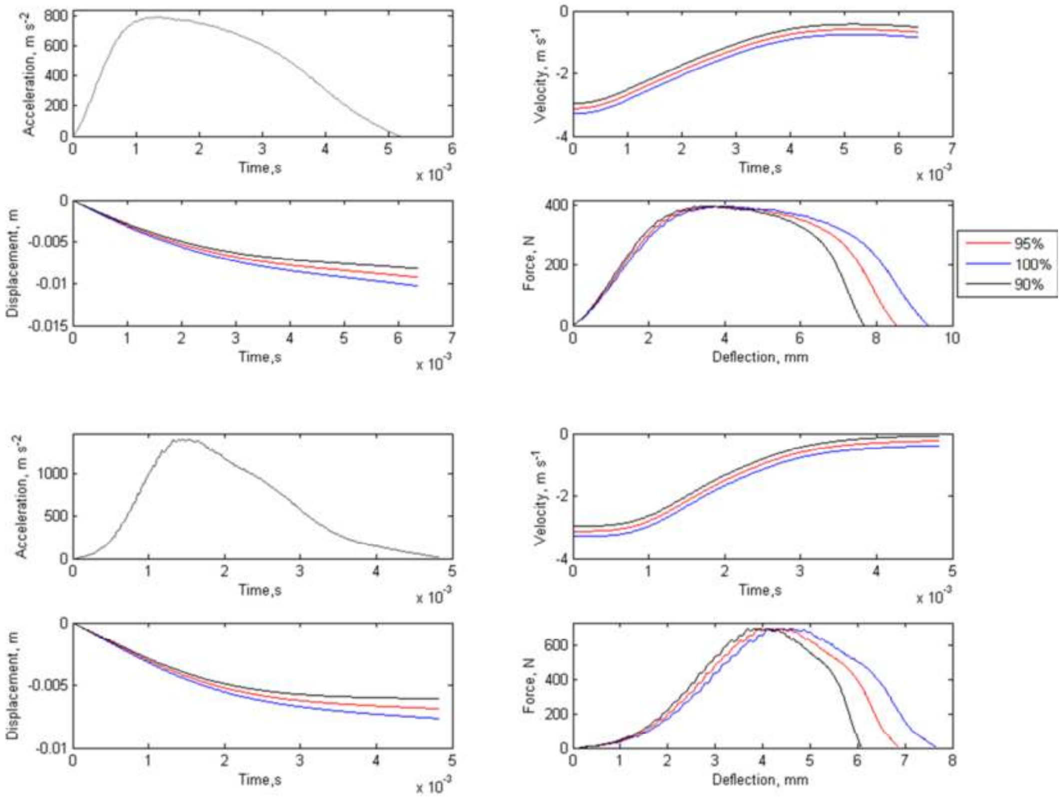

Figure 11-30 Illustration of the variation in impact parameters that can occur when the assumed impact velocity of the CIST is altered between 95%, 100%, and 90%. Top: a 0.5 kg missile on the clay loam surface; bottom: a 0.5 kg missile on the sand surface.