Artificial turf systems for sport surfaces: current knowledge and research needs

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Abstract: Artificial sport surfaces, for team outdoor sports, are growing in number in many sports including soccer (association football), rugby, hockey, and football (American and Australian). The science of their behaviour has, it is argued, been under-researched in comparison to the development of artificial turf products and also the development of many of the sports with respect to athleticism and advances in equipment such as footwear. This paper reviews artificial turf design requirements and behavioural aspects to develop the science, and draws from a range of up-to-date literature to identify the key principles of behaviour and gaps in knowledge. The relationship between the material types used in the substrate support and surface system (comprising some form of shockpad and turf, the turf infilled or unfilled) behaviour is demonstrated in regard to the key performance factors of player–surface interaction – for both impact and traction. The data demonstrate the relatively complex behaviour of surface systems, and highlight the pitfalls of current simple mechanical tests in relation to human loading. Degradation and the role of maintenance to sustain long-term performance are issues also highlighted and discussed. Surface safety is discussed through a short review of studies related to injury risk, albeit most were associated with the contrast between natural turf and artificial turf; however, there is clearly more research required in injury surveillance to include aspects of objective surface measurement. This paper additionally provides the reader with a state-of-the-knowledge review of where current thinking is now, and where future research is considered to be of merit, in developing sport surface science.

Keywords: sport surfaces, artificial, injury, impact, traction, testing, measurement, durability, materials, maintenance, biomechanics, player loading, safety

1 INTRODUCTION

The general topic of sport surfaces is large, covering both indoor and outdoor surfaces for which aspects of design, materials, construction, testing, performance, and durability are all important. Indoor sports hall floors [**1**] often comprise sprung systems, and are referred to as 'area elastic' – for which the application of a point load causes deflection over a relatively large area around the point of application of the force. Outdoor surfaces are referred to as 'point' elastic with deflection local to a smaller area/or point loading. Outdoor surfaces are used for many sports, include running track, though this review paper is restricted to surfaces for the popular team sports, soccer, rugby, and hockey that rely on a rectangular 'pitch' of large dimensions for training and/or competition and have come to rely on 'artificial turf' - comprising synthetic fibres (green usually) which exhibit a look similar to natural grass. However, many behaviour principles and test methods covered here are applicable across the range of sports that also utilize artificial turf such as tennis, cricket, and rugby league.

The roles of a sport surface are essentially to provide safe provision of player interaction and/or ball interaction to an appropriate level of performance (over its design life) and be cost-effective and manageable. The importance of one particular role or the order of priorities usually depends largely upon the key stakeholder such as the funder, the owner/operator, sports governing body, or end user(s). In terms of cost and management, many facilities are of course for hire and can generate significant income revenue.

Artificial surfaces increasingly represent an effective alternative to natural turf, and permit relatively higher usage (greater durability) but require relatively higher initial capital spend [**2**]. However, their 'all weather' capability usually offers real benefit in terms of high intensity use, often suggested as up to 50 h per week, usually coupled with floodlights to extend playing hours and income. Outdoor artificial sport surfaces represent significant assets, and to ensure good value for money need to be carefully selected to suit the users, constructed to exacting standards, and then well maintained. Artificial turf was originally marketed as 'low maintenance', and poor aftercare has, in the author's opinion, affected the legacy of provision in the UK and elsewhere. The introduction of 'performance standards' specific to each sport that discriminates between competition levels has slowly educated many stakeholders into a more business-like attitude in recent years, in the author's opinion.

Notwithstanding the improvement in product guidance and specifications from policy makers (see section 2.2), there have been many significant developments in the technology applied to the manufacture and construction of surfaces, and research on the effects on human (and ball) interaction has largely lagged behind. This imbalance is, it seems, slowly changing but currently the emphasis is on elite sport performance with little aimed at the community level.

In the UK, for example, the number of artificial turf facilities has been steadily increasing, largely due to the development of products more suited to football (soccer), funding streams to promote widening participation, and the health agenda, and also the potential income benefits for community/school facilities clubs operating artificial turf facilities relative to natural turf. In addition, lower professional clubs are increasingly installing artificial turf products, primarily for business reasons.

However, from a more international perspective, the introduction of artificial turf facilities in countries with high summer temperatures, such as Australia for Aussie rules football at community level [**3**], require careful consideration. The environmental issues such as drought/water shortage provide great impetus for non-turf installations, but in contrast there is concern that artificial turf can experience elevated surface temperatures in comparison to natural turf.

Artificial turf is, it appears, under much scrutiny for aspects of its health-related implications such as player injury risk, but also its play performance to ensure that it is acceptable at all levels of sport. The current market for more artificial turf facilities and healthy industry competition has spawned a very large range of proprietary surface systems. It was estimated in 2008–9 that around 25 000 000 square metres of artificial turf carpet was produced in Europe by the main artificial carpet manufacturers, against a reported stock comprising of 15 000 soccer, more than 1000 hockey, and more than 5000 tennis facilities in Europe [**4**]. Currently, worldwide market figures are not available.

This paper presents a state-of-the-art review of both the research literature and industry perspectives describing both the types of, and behaviour of, (outdoor) artificial turf surface systems, and pertinent aspects of the regulatory framework (for soccer, rugby, and hockey) within which surfaces should/must comply. The scientific focus of the paper is intended to be international, whereas the practical aspects of design, construction, and maintenance are predominantly drawn from direct experience of UK practice and to an extent European practice.

2 ARTIFICIAL SURFACES – TYPES AND REQUIREMENTS

To those outside of the surfaces industry, including researchers, the vast range of products marketed and the large array of terms used (often incorrectly applied in the author's opinion) can be confusing. In addition, several terms are used interchangeably to mean artificial turf, such as: synthetic turf; synthetic fibres; synthetic carpet; artificial grass; plastic grass; and football turf, in marketing literature and the popular press.

The artificial grass carpet is made from yarn which may be either woven (produced on a loom similar to cloth) or tufted (injected and looped into a backing material using a machine that is like a large sewing machine and cut so that each loop forms two strands). Once woven or tufted the individual strands of yarn are then termed fibres, and also referred to collectively as the carpet 'pile'. Usually some form of adhesive is used to reduce the problem of fibres being pulled out of the carpet backing. Another different form of producing an artificial turf carpet is termed 'needle punching', in which the yarn is punched into a centre fabric to produce a more felt-like mix of fibres with more random vertical, horizontal, and angled orientations.

Furthermore, the terms relating to the 'generation' of artificial turf products is also confusing – and is further clarified below.

2.1 Surface systems and classification

There exist many documents that describe artificial turf systems in relation to specific sport provision including a range of specifications and standards. In the UK, the term 'synthetic turf pitches' was and still is common in British Standards [**5**] and industry guidance [**6**], though recent guidance from Sport England [**7**] on selecting surfaces uses the term 'artificial grass pitch'. However, 'artificial surface' was also used in the early British Standards and the latest European Standard [**8**] uses the term 'synthetic turf surface' to mean a sports surface comprised a carpet of tufted, knitted, or woven construction whose pile is designed to replicate the appearance of natural grass. FIFA's documentation [**9**] now refers to artificial turf as 'football turf'.

The artificial turf market has changed considerably since the early days of the first installation for American Football in the Astrodome, Houston, Texas, in the 1960s. The products have been developed largely by manufacturers with sufficient resources and vision such that, despite the very negative publicity surrounding its introduction into English professional football in the 1980s, today, sports such as hockey, rugby, soccer, tennis, and cricket utilize artificial grass for training and/or competition – up to international level.

The first generation of products was developed in the 1960s and comprised a dense artificial turf carpet, usually with nylon fibres (good for durability) and was unfilled (also termed non-filled). These systems were relatively hard in terms of impact absorption, and were abrasive to skin contact from sliding. Carpets typically comprised 10–12 mm length fibres, woven or tufted into the carpet, and anecdotally these systems were observed to develop very high traction. The earlier systems used no shockpad underneath the carpet and a high ball bounce in football was one consequence, though an integral shockpad (part of the carpet backing) was common in later developments. Water was added to the surface by hockey to help reduce ball speed and skin abrasion effects (note: in 1974 this system was used for hockey for the first time at the Olympics). Hockey still uses a form of this simple system today, though currently with more shockpad and softer fibres. It was a general finding, unsurprisingly, that these hard abrasive early surfaces carried a greater risk of injury relative to today's available systems [**10**].

The second generation of products were developed and introduced in the 1970s, and is often termed sand-filled carpets. Typically, it comprised 20–25 mm length fibres of either monofilament or fibrillated polyethylene, a softer yarn than nylon, with wider spaced tufts of fibres saving costs and used to accommodate the sand infill. This system is in wide use today, and is very popular at clubs for community multi-use facilities. Denser tuft spacing with a smaller quantity of sand has been subsequently developed and termed 'sand-dressed'. The sand infill provides weight and stability to the lighter (less dense) carpet, and it also helps control play performance aspects such as underfoot traction and ball bounce. Sand-filled systems proliferated throughout Europe, and are used for hockey (it is a cheaper than denser non-filled watered systems) and also for tennis. The 'astro-turf boot', as it was often termed, was introduced for these surfaces specifically comprising multiple short dimples on the base to provide better shoe–surface interaction. The term astro-turf™ was a trade name and is sometimes incorrectly used today to mean many forms of artificial carpet.

The third generation (3G) of products were developed in the late 1990s, and were specifically aimed at better simulation of natural turf and to permit the use of normal studded (cleated) soccer boots. FieldTurf, now FieldTurf Tarkett, a division of Tarkett Inc., based in Calhoun, Georgia, USA is the company credited with inventing this product. The 3G systems typically comprise a relatively long fibre in the carpet, 40–65 mm is a typical range, using monofilament or fibrillated fibres with a relatively low tuft density (large space between tufts). They are termed 'filled' surfaces [**8**], and relatively large quantities of infill are required in comparison to first or second generation products, with usually a sand layer at the base (for stability) and crumbed rubber/elastomeric particles (can be a recycled tyre source) to aid the play performance and comfort. The infill is installed to a depth of typically two-thirds of the pile height, and may comprise some 120 tonnes of recycled rubber for a full-sized soccer pitch. The free-standing length of fibre showing above the infill (sometimes referred to as 'pole' length) is important for aspects of surface friction such as ball roll. These 3G surfaces have proliferated in association football (soccer) and more recently also in rugby union. There exist detailed performance standards from the IRB [**11**] and FIFA [**9**] following their own research and monitoring programmes into play performance, testing, and injury, discussed further in sections 2.2 and 3, respectively.

The term fourth generation is also now in use in the industry, though its meaning is less well defined and may be used inconsistently as there is little precedence from implemented systems. Some would suggest that this new generation describes a surface system with a reduced need for infill (and its associated maintenance) and that the carpet may comprise fibres that both maintain their resilience performance but are also durable, a difficult behaviour to achieve with thermoplastics. The products currently being marketed as fourth generation usually include a mix of fibre types in the carpet that are shaped during extrusion (into fibres with a stiffened profile or are composite fibres) and may then also be textured (curled) to improve resilience. A mix of fibre lengths and relatively close tuft spacing also seem to be a feature.

Recent technological developments in artificial surface systems include innovations to the three key components that make up the surface 'system': the shockpad; carpet; and infill. Shockpads have been developed and improved with regard to *in situ* products mixed and laid on site (also known as wetpour), prefabricated products including tiles (interlocking like a jigsaw) or rolls, and in some cases are designed into the aggregate base beneath the surface system. In some cases the shockpad may be excluded if the design of carpet/infill together with the underlying base provides enough shock absorption. Carpets, and specifically developments in the fibres that are woven or, more commonly today are tufted into a carpet product, have been developed to meet different sport's requirements and many advances have focused on the compromise between friction properties, and durability, softer fibres are favoured by the players but they wear out quickly or flatten. Carpets with a range of fibre lengths, number of fibres per tuft, shape, texture, and tuft spacing are available. Fibres that absorb and radiate less heat to users are also being developed into carpets for hotter climates. Infill developments have tended toward alternatives to recycled rubber crumb (shredding truck/car tyres) with other types of 'waste' products or bespoke new products from virgin material emerging on the market. This includes coloured infills used for aesthetic purposes, and also to overcome some limitations of (black) recycled rubber such as their odour and high heat absorption. Many claims are made in marketing information regarding infill qualities but little published research is currently available on their behaviour or assessment in any detail [**12**].

A typical cross-section of an artificial pitch design is shown in Fig. 1. This shows the sub-layers that form the pitch foundation, with concomitant requirements for stability, load bearing (relatively light from the users but the designer must consider maintenance plant and other applications such as for emergency vehicles or other uses of the facility such as public events), frost resistance, planarity, and through drainage (in most cases the surface systems are designed as porous). The requirements for the thickness of the sub-base is based upon the strength of the subgrade (natural soil), and for the asphalt is based on required planarity usually with a minimum buildable thickness of 40 mm. The design life of the foundation should be at least 25 years. The expected life of the surface system is expected to depend on intensity of use, and to some extent the maintenance regime, but is typically 5–10 years for a 3G system and perhaps 15 years for a second generation system – though no authoritative data exists. The shockpad (when separate) should be designed to last two carpet lifetimes. Product quality and installation quality are also expected to affect longevity.

In the UK a recent publication by Sport England about surface selection, aimed at educating clubs [**7**], has attempted to establish a set of clearer guidelines for discriminating between water-type (water-based) systems aimed at high level hockey; sand type (sand-filled and sand-dressed) aimed at hockey primarily; and rubber crumb type: long-pile 3G 65 mm (with shockpad) aimed at rugby; 55–60 mm (with or without shockpad) aimed at football; and short pile $<$40 mm (also considered acceptable for some levels of hockey). This publication, produced in conjunction with the national sports governing bodies, was in response to increasing confusion of users/clubs/schools on how to select an appropriate surface for their needs. The issue as to whether hockey can be played to an appropriate skill level on short-pile 3G systems in the UK, installed for soccer as the primary sport but that have passed FIH performance testing, has raised the very real problem of player feedback not seeming to agree with the suite of compliance testing specified in the relevant sport's performance standards (see section 4.3).

In spite of the increasing number of documents available it is a challenging task to objectively compare between the many surface systems available, or contrast cost versus product 'value'. It is only since 2006, in the UK, that audits of the stock of sport facilities has been made public by the database

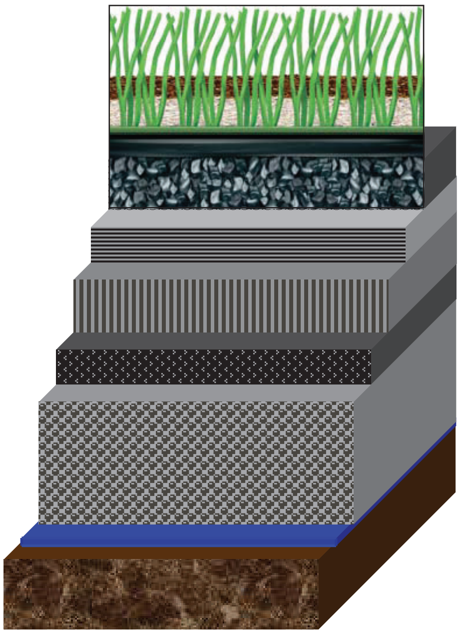

Fig. 1 Cross-section of typical construction profile for a typical long-pile infilled (3G) pitch designed for soccer and/or rugby, showing layers and typical thickness

'Active Places' [**13**]. However, enhanced sport standards [**9**, **11**] and codes of practice for construction [**6**] and aftercare, and dissemination of research into practice [**14**] has, in the author's opinion, led to improvements in the quality of sports surface provision in the last 10 years, in the UK at least.

2.2 Performance requirements

The sports governing bodies set out their own methodologies for performance compliance of newly installed artificial turf pitches (ATPs). These in general follow a similar framework, however, comprising the following steps for approval for high level competition play performance.

Step 1: accreditation of manufacturer's products for use in the specific sport. This is based on the complete 'system', from a series of laboratory tests (most are to BSEN standards) with set limits for compliance stated in the performance standard for the sport. This allows the product vendor to show that a system has been approved by that sport for a specific level of competition, or for multi-use.

Step 2: accreditation of a constructed pitch. This is based upon a series of field tests (many are to BSEN standards) required to meet the compliance targets. This shows field compliance with the system approved in the laboratory in step 1 and acceptable quality of installation (e.g. for FIFA 1 or 2 star approval in their 'quality concept' [**9**]).

Step 3: Long-term performance. This requires pitch retesting at intervals, testing as per step 2, to demonstrate ongoing quality at the specific level for which it was originally designed. The frequency of retesting is dictated by the play level 'rating' of the pitch.

Note: all accredited testing has to be carried out by certified and approved testing laboratories.

The development of performance-related standards and specification for test methods in the UK dates back to the introduction of the British Standard 7044 'Artificial Sport Surfaces' [**5**], which superseded previous Sports Council guidance, and has been updated and superseded by the European harmonization of many standards in 2007. Multi-use facilities, also termed multi-use games areas.

Offer a cost-effective solution for schools and other facilities with a wide range of sporting demands. While a multi-sports area is often seen as a 'safe option', it should be recognized that there will almost always be a need for compromise, primarily in terms of the performance of the playing surface, as no one surface is suitable for all types of sport [**8**].

Furthermore, compromises on the player–surface interactions are considered more difficult if players are to be protected from an increased risk of injury. For example, reducing the shock absorption level to increase the ball rebound for tennis might result in a greater number of injuries to football players who will fall onto the surface more frequently than

Table 1 Summary table of performance specifications for soccer, rugby union, hockey, and multi-use

	Sport and level of competition				
Player-surface tests	Units	FIFA 1 Star	FIFA 2 Star	FIH (Global)	IRB
Force reduction[1]	%	55–70	60–70	40–65	60–75
Multi-use		55–80		35–54	61–80
Vertical deformation[2]	mm	4–9	4–8	N/A	4–10
HIC-critical drop height[3]	m	—	—	N/A	>1.0 (>1.3)
Rotational resistance[4]	Nm	25–50	30–45	N/A	30–50
Multi-use		25–50			25–50
Slip resistance[5] (pendulum test)		—	—	0.6–1.0	0.6–1.0
Linear friction- stud deceleration value (modified pendulum test with studs)	g	3.0–6.0	3.0–5.5		
Ball–surface tests					
Ball rebound resilience (from set drop height)	m	0.6–1.0	0.6–0.85	0.1–0.4	0.6–1.0
Multi-use		0.61–1.14		0–0.5	0.61–1.14
Ball roll (simple ramp)	m	4–10	4–8	9–15	—
Multi-use		5–10		5–15	
Angled ball behaviour (change in velocity)	%	45–70 dry 45–80 wet	45–60 dry 45–80 wet	N/A	50–70

Note that space does not permit full explanations of the test methods or test philosophy. In general all the sports have used test results from 'high quality' natural turf as the gold standard to help set the acceptability test limits (with the exception of hockey). Key points (1–5) made about the tests in Table 1 can be found within the text.

tennis players. It is suggested that, as a general rule [**8**], the characteristics of the surface should be designed to satisfy the priority sport of a facility.

The test techniques previously referred to in the 'approval' process steps are largely aimed at 'performance' in relation to player–surface and ball–surface behaviour, and Table 1 summarizes the required target values for several tests used for soccer [**9**], rugby [**11**], hockey [**15**], and also multi-use [**8**] to provide a comparison. In addition to those shown, a number of test methods exist for durability of systems in relation to environmental factors and also resistance to mechanical wear – which require climate cabinets and simulated footfall machines. In addition, in brief, physical assessment of artificial turf carpets includes measurement of: mass per unit area; tufts per unit area; pile weight; tuft withdrawal force; pile length above backing; fibre Identification, to show product compliance. Tests also exist for shockpads such as: mass/area; thickness; compressibility; and tensile strength. Infill-related tests for sand include: shape; size range; and bulk density; and for rubber infill the size range.

1. The per cent force reduction (also often termed shock absorbency) represents the test result peak vertical impact force when compared between the sport surface and concrete, a larger percentage meaning 'softer' underfoot (see section 4.1 for further details).
2. Vertical deformation is measured from a similar impact test to that used in the per cent force reduction, but which measures the maximum surface deformation under the impact loading.
3. HIC is the 'head injury criterion', also interpreted as 'critical drop height' – interpreted from analysis of an accelerometer attached to a (5.5 kg) metal hemispherical missile dropped from increasing height. It aims to help provide protection against concussions and serious head injury. Rugby guidance stipulates a shockpad to pass this test.
4. Rotational traction – a simple studded disc is rotated on the surface until the maximum resistance torque is measured. Too low a torque is said to represent too slippery, and too high represents the possibility of 'foot lock' and ankle injuries (see section 4.2 for more details)
5. The pendulum test measures the energy lost through surface friction from contact of the test foot swung from a set height. It was developed from skid resistance testing of road surfaces. For infilled 3G surfaces a studded foot is used and the peak deceleration on contact is also recorded. The mass of the swinging arm and studded test foot is specified as 2 kg in mass.

There are many potential challenges for approximating a human athlete's surface interaction with simple mechanical tests such as these, discussed further in section 4.

2.3 Durability

The long-term degradation/wear and resulting performance behaviour of artificial turf has not been well documented to date. A few studies have collected data in the UK that demonstrate the changes

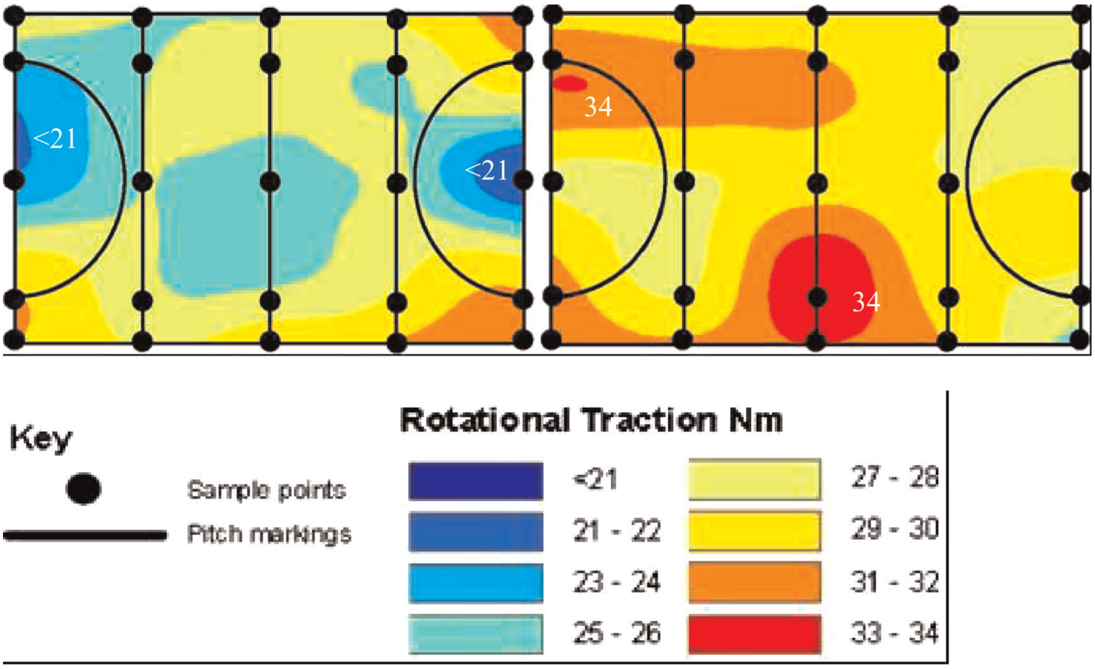

Fig. 2 Hockey pitch rotational traction variability (note the 25 test positions shown as large dots are not equally spaced) for two pitches in the UK with the same construction specification. See section 2.3 for further details of the analysis. The left-hand pitch (Cannock) is several years older than the one on the right (Highfields), and gave much lower traction readings (some sport values are shown) in general and supported by obvious visual signs of wear such as fibre shortening and loss (adapted from [**16**])

in performance over a significant time period, for hockey [**16**], and regarding maintenance [**17–19**]. There are also industry guides [**6**] that present what is considered 'best practice' for maintenance but are largely based on qualitative measures of observed behaviour.

Recent studies of note have contributed increased understanding of the effects of contamination on the performance of sand-based systems [**17**], the use of simple tests to evaluate changes in performance [**18**], and the 'wear' across elite hockey surfaces over several years [**16**, **20**]. Figure 2 shows the results from rotational traction testing on hockey water-based fields [**16**]. The figure shows interpretation of the data from 25 spot test positions (and each values is the mean of five tests at that position) after processing with an interpolation function in the ArcGIS software [**16**] that smoothes the transition between spot values using a simple weighting for each neighbouring value dependent on its distance. The figure is intended not for detailed interpretation but to illustrate the spatial variation of tractions across a pitch to show high and low traction regions, and to compare between two pitches of the same construction specification and with exactly the same artificial turf carpet product. The older carpet (by several years) showed lower peak traction results, corroborated by visual observation of more excessive pile wear.

The results of a project in Holland which monitored 50 long-pile 3G soccer fields to FIFA test standards for the period 2001/02–2008, and which also summarized the hours of use and maintenance regimes have been recently presented [**21**]. In general, these findings showed that the pitches had become harder (average of a 10 per cent drop in force reduction, a 19 per cent change from the original state) and had become less compressible (an average deformation reduction of 5 mm, a 45 per cent change from the original state). The data also showed increased ball roll (average change of 3.5 m, a 35 per cent change from the original state) and increased ball rebound (average increase of 0.15 m, a 17 per cent change from the original state). However, for rotational traction (test 4 in Table 1) the field values remained very similar over the period – perhaps surprisingly in light of the other changing data. It was concluded in the study that there was a (weak) trend of higher use and lower levels of maintenance leading to poorer performance (i.e. failures to comply with the target values in Table 1) across a range of the play-performance-related tests. It was pointed out in the study that during the period of this programme of testing the performance limits in the standards for soccer had changed [**9**] and to an extent so had the surface product designs to meet newer more stringent criteria. This data represents a unique study in the literature but it is unfortunately limited due to non-inclusion of other possibly influential data (which was not collected) such as temperature and moisture state of the surfaces at the time of testing. Furthermore, for the standard FIFA testing six positions are selected from specific sub-areas of a pitch and clearly more test positions would be beneficial to substantiate the extent of changes as would relocating on the same test position for each revisit.

The degradation mechanism(s) of artificial turf wear and the effectiveness of maintenance practice are currently poorly understood and under-researched.

3 SPORT SURFACES AND INJURY RISK

The subject of injury risk is broad and very complex, particularly if the full range of risk factors is considered and a full review of the details of the many epidemiological studies in team sports – even with the specific focus here on sport surfaces. However, this section is offered as a brief overview of some pertinent studies and findings that are considered useful to inform the debate on surface design and testing in relation to aspects of player performance and injury risk.

There have been many major studies on injury incidence, some in reports by government-related bodies such as the European Union (EU), that have analysed the data acquired from the EU injury database for example. In a 2007 EU report [**22**] soccer was stated as responsible for most injuries comprising 36 per cent of the 2 500 000 sport-related injuries reported, and hockey sixth comprising 5 per cent. A study in Australia reported that soccer was responsible for 8 per cent of the total injuries recorded, and rugby and hockey were found to be responsible for 8 and 3 per cent, respectively [**23**]. An added complexity for reviewing past injury studies is that the classification and categorization of injuries and injury types are not comparable between studies reported from around the world. In response to this, a consensus statement was developed in 2006 [**24**] on injury definitions and data collection procedures for studies in soccer, and subsequently for rugby union in 2007 [**25**]. The definition of injury therein includes any physical complaint sustained by a player that results from a match or training, and the analysis and reporting method promotes the expression of injuries per 1000 hours of exposure (typically) – leading to a much better determination of risk and risk management strategies. This specific development in harmonizing data collection has been pivotal and underpinned the recent work of FIFA and the IRB in their research into injury risk of artificial turf in comparison to natural turf. Two studies [**26**, **27**] concluded that injuries on natural and artificial turf, for both genders, was more than seven times higher in a match situation than during a training situation based on the incidence per 1000 playing hours. During the FIFA 2002 and 2006 World Cups the injury incidence [**28**, **29**] in the matches was recorded as extremely high at 81 and 69 per 1000 playing hours, and was compared to a maximum of 28 per 1000 hours in other comparable studies. The increase was attributed to the high value and high intensity of these tournaments, and also relatively short rest periods between matches.

However, against the context of these findings of a relatively high risk of injury at the elite level of professional soccer the question of what changes in injury statistics or patterns is less clear for the surface as a factor, or as a consequence of change in surface from natural to artificial, or from training on artificial and playing on natural, or from varying properties across pitches. There has been concern of a perceived higher risk of injuries on artificial turf in comparison to natural turf for many years, and to some extent this still exists in contemporary media coverage. However, some relatively recent robust injury studies have concluded that there is no difference in risk between natural and artificial surfaces in soccer [**30**]. In a study by Meyers and Barnhill [**31**] on American football they claimed that natural and artificial turf gave similar risk for injuries, but that there were significant differences between the types the injuries. Fuller *et al.* [**27**] looked at the risk factors and showed that player-to-player contact was the highest cause of a risk of injury. Although studies by FIFA have shown very similar statistics regarding in-game activities (passes, tackles, etc.), an increased risk of sliding burns on artificial turf was highlighted in a study by Ekstrand *et al.* [**30**]. FIFA have since added a simulated 'skin abrasion' mechanical test requirement to their suite of tests [**9**] for a product to pass and acquire a FIFA star rating.

However, there remains a lack of detail in nearly all injury studies regarding the properties of the surfaces utilized and very little research to date into natural turf behaviour and injury risk. In a study by Orchard *et al.* [**32**] on the risk of anterior cruciate ligament (ACL) injuries in Australian rules football (AFL), they showed differences in injury risk for different species of natural grass (the species is usually chosen to suit the specific growing related climate of the region). Similarly, it is suggested here, that might not differences in pile length and tufting density combined with the type and amount of infill that is used across the range of artificial turf systems be considered to have similar possibilities for affecting the risk of injury to users on artificial turf surfaces? However, previous injury studies have not provided real detail on the surface systems encountered in the studies.

In addition to the better injury study design and reporting overcoming issues of comparing injury datasets, clearly there have also been major changes in many sports relating to the physical conditioning of the athletes, the footwear used, and to an extent the rules or the nature of the game. The evolution of surfaces and their behaviour is another extrinsic factor and is complex.

To date it is not yet clear what affect a change of surface can have on the nature of the athlete–surface interaction, and hence loading on the body, and hence injuries that can be directly attributed to the user's interaction with the surface. One recently reported study has highlighted some problems and limitations of using objective (simple) mechanical tests within an epidemiological study seeking to determine the effect of the surface state [**33**]. In this work by Twomey and colleagues in Australia, detailed ground testing was carried out at the natural turf venues of 41 AFL games, and tests included measures of hardness and peak rotational traction. Of the 130 injuries recorded 12 were considered as likely to be related to ground conditions, and 29 possibly related. However, for those injury events classed as 'likely', the mechanical measurements showed no unacceptably hard (or strong) ground, and six of these 12 injuries were on grounds with very low traction data – as opposed to the usual hypothesis of high traction creating greater risk. In general, the injuries observed in this study occurred on surfaces that were assessed to be in the 'acceptable' range for both hardness and traction. Larger prospective studies such as this are very rare in the research literature and from findings such as these the merits of including the current range of industry standard portable mechanical tests can be questioned, specifically as to whether they are in fact the right tests to use in relation to injury risk studies. It is apparent that these industry tests currently used to 'certificate' pitches to International Governing Body (IGB) standards may not be suited to injury studies if they do not simulate athlete movement and loading (see section 4).

In addition to damage to muscle and bone, a more recently identified concern for human health issues is that of chemical 'contamination' produced from the materials used in the manufacture and construction of artificial turf and also biological contamination from bacteria that may grow more prevalently in the conducive environment of an artificial pitch. Recycled rubber infill (from tyres) has in some countries been under intense scrutiny and been restricted in its use, though the increasing volume of recent related literature suggests a very low risk to human heath from contact or inhalation. *Staphylococcus aureus* bacteria (SAB) is a pathogenic bacterium, termed MRSA [**34**] for strains resistant to methicillin-type antibiotics, and although harmless and prevalent on human skin can access the internal body through cuts and grazes and cause infections that generally take longer to treat and can be severe if untreated. In a recent study a survey of 20 infilled synthetic turf fields, along with two natural turfgrass fields, was conducted [**35**] to determine microbial population and presence of SAB. SAB colonies were not found to be present on any field; however, SAB colonies were found on other tested surfaces such as balls and other accessory equipment. It was concluded in this study that concerns that infilled synthetic turf harbours and provides a breeding ground for SAB is unfounded and unwarranted. However, in addition to this one notable study there are many discussion items and magazine articles in the media, particularly in the USA, relating to both an increase in MRSA in athletes (not necessarily focused on sport surfaces, skin-to-skin contact is a high risk factor). Furthermore, it appears maintenance companies are offering services to regularly treat sport fields with disinfectants to reduce the perceived risk of infection.

It can be concluded that sport surfaces remain a likely and plausible risk factor in sports injury aetiology, albeit perhaps one amongst many other confounding factors, and are perceived as a risk factor by users – especially in the UK for professional soccer players for example [**36**] on natural turf. The user perception of risk relating to the surface they play on is an interesting issue, although little researched it appears. The latest artificial surface products are still relatively new, and older professional players and coaches within the sport of soccer in particular remember the poor quality first generation products that were trialled in the UK in the 1980s and were soon deemed unplayable and banned at the professional level. It is the author's opinion, based on experience, that many users and coaches lack detailed knowledge of the artificial turf systems they play or train on and have had little or no education regarding footwear selection. Clearly, there is also uncertainty as to how to best measure the parameters that describe surface performance in a way that is most relevant to the user regarding their performance and safety and this is discussed in the next section.

4 MEASURING SURFACE BEHAVIOUR

There exists a need to scientifically evaluate the suitability of the specific play-performance tests, introduced in section 2.2, that are utilized in current practice for surface system assessment and approval. Table 1 sets out many of the test requirements, grouped into player–surface interaction and ball–surface interaction, the latter considered no further in any detail in this paper but is clearly very important to the surface users (see section 4.3). In regard to player–surface interaction, the suite of tests currently utilized are aimed at impact behaviour (vertical forces), and foot–surface traction–slip behaviour (horizontal forces).

Impact behaviour and traction behaviour have received the most attention in past research across all sports in general, largely from researchers in biomechanical and engineering disciplines. Impact behaviour in relation to head injury has received considerable attention for sports such as American football and AFL, and more recently in guidance for rugby union (see Table 1 for limits). However, space does not permit further consideration of head impacts in this paper. The focus of the following sections will be on the response of the whole surface system to loading of different magnitudes and different rates of loading and the relevance and interpretation of the available impact tests will be discussed.

Recent research work at Loughborough [**20**, **37**, **38**] has aimed to contribute to the knowledge base of sport surface science, specifically with regard to better describing artificial surface system composition to explain the behaviour under load, and much of the work in this section is drawn from this recent doctoral work.

4.1 Impact response

The interaction of a user with the surface in terms of an impact can take many forms; however, the current testing standards specify tests regarding 'foot contact' and 'head contact'. The industry measurement standard for (simple) foot–surface contact is based on a portable device known as the 'artificial athlete' (AA), mechanical test. The AA measures the peak impact force from a controlled energy spring damped impact, from which force reduction is determined, and the device is adapted by changing the spring (to lower stiffness) to measure the surface's vertical deformation under impact (see Table 1 for limits). Figure 3 shows the AA, in picture and schematic form. The AA test has remained the 'gold' standard test across many sports, and was originally devised for athletic track testing to represent the heel impact of a heel–toe running action and measure cushioning behaviour of a surface as shown in Fig. 4, in simple form. The AA load cell measures the peak impact force (the mechanism involves a 20 kg weight dropped 55 mm onto a sprung bearing plate of 70 mm diameter) and compares this peak value to a reference force representing a rigid surface, and from this determines the 'force reduction' value (in per cent) for the surface under test. Three repeat drops are normally done at each test location. Recent technological developments have introduced the advanced AA which uses an accelerometer (instead of the load cell used in the AA), and by manipulation of the impact data also reports both a peak surface deformation and the 'energy restitution' for each impact – currently a draft European standard. The energy restitution of a surface is currently a topic of interesting debate on whether the surface recovery is a factor in player fatigue and how best to measure it. Figure 5 shows a graph of force reduction for two hockey short-pile carpets, with a range of thickness of shockpad beneath, and demonstrates the large range of force reduction measurement that can be achieved, and in comparison to the limits set out in the FIH requirements (also see Table 1).

Research into human–surface interaction loading has demonstrated that the athlete adapts to the surface at, or soon after, first contact on a change of surface properties [**39**, **40**] by changing leg stiffness through flexion/extension. This observation of human behaviour on surfaces leads to the question as to whether a fixed energy impact device, that produces very different peak reaction forces on the range of different surfaces, is the best method to represent the real human interaction condition. However, the AA force reduction scale is useful to rank 'hardness' across a range of surfaces. When one considers the effect of the (vertical) impact force applied to the materials under test and their likely response, particularly those strain hardening (see Fig. 6) elastomeric materials such as rubber particulate and foams (used widely in sport surfacing products), the stiffness response is clearly dependent on the initial state and also the load

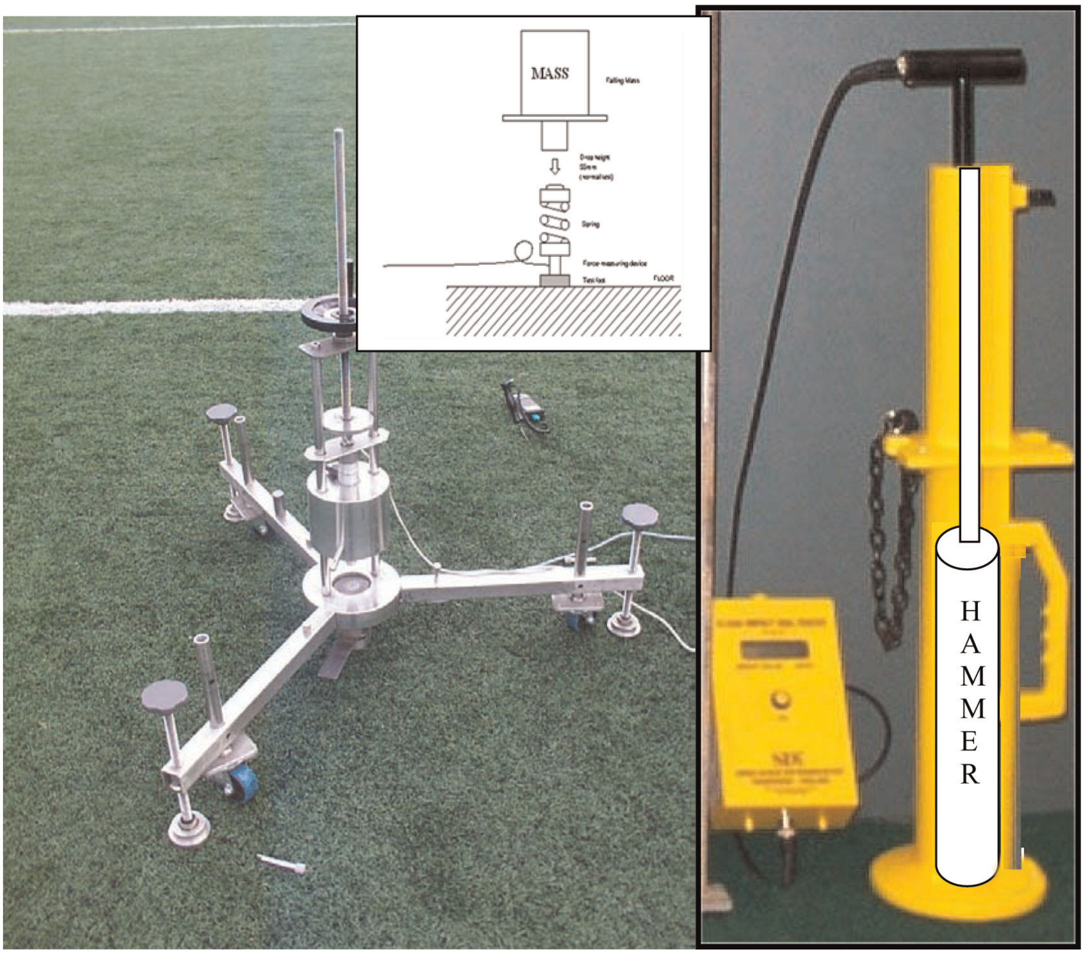

Fig. 3 Impact test apparatus. Left is the AA, showing the 10 kg drop mass and the test foot visible beneath the frame, the schematic drawing shows the impact mechanism. Right is the 2.25 kg Clegg hammer (not to scale) showing the guide tube and readout – the overlaid drawing shows the drop mass connected to the handle

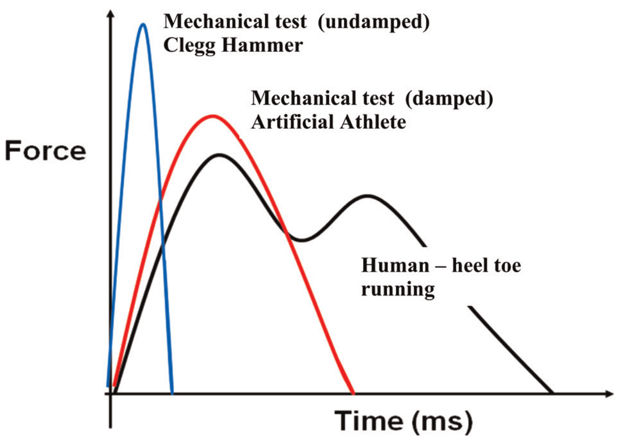

Fig. 4 Comparison of the relative impact loading from a human runner and two mechanical impact testers, the AA and Clegg hammer (see also Fig. 3)

path length (i.e. applied load magnitude). As a consequence, there is a need to carefully set the mechanical test load magnitude (and contact area) to produce the most appropriate material response in relation to the expected response under an athlete's loading. Furthermore, the hysteresis behaviour of the materials under test, i.e. energy loss through deformation, is a function of the strain levels induced and hence the load/area magnitudes applied. As a result, the application of inappropriate loads in mechanical testing will lead to incorrect material responses for deformation and strain, energy loss, and energy return in relation to what may be expected for the human loading. The multilayer (and thin layer) construction of most modern sport surface systems leads to further exacerbation of these challenges of interpreting impact test data, as the impact response will depend on the stress and strain distribution in possibly all of the layers. The shockpad beneath the carpet, in long pile filled (3G) systems for example, has been show to have a very large affect on force reduction measurements [**20**].

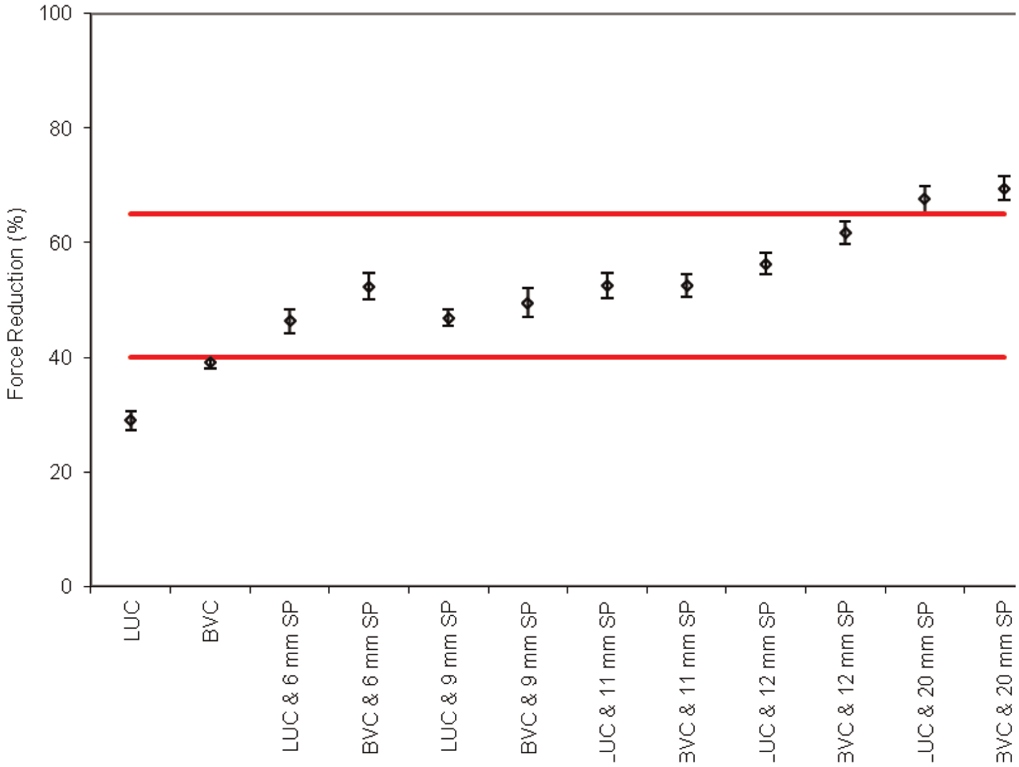

Fig. 5 Mean force reduction measured by the AA on 12 samples of shockpad/carpet system set on a concrete floor in the laboratory. Loughborough University Carpet (LUC) = 11 mm Nylon carpet with a 3 mm integral shockpad and Belle Vue Carpet (BVC) = 11 mm Nylon carpet with 6 mm integral shockpad, shown with increasing thickness of a separate shockpad (SP) system beneath (whiskers show one standard deviation, and the horizontal lines show the 40 and 65 per cent limits for FIH 'Global' level approval). Reproduced from [**20**]

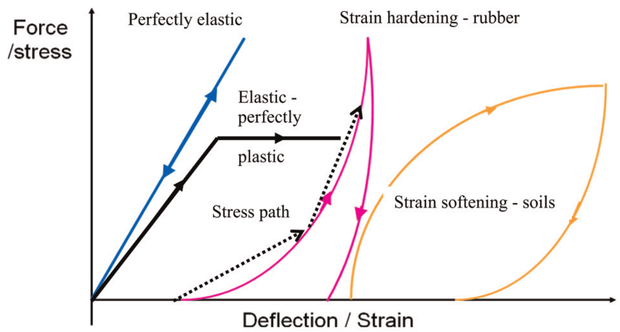

Fig. 6 Material behaviour under load, showing idealized behaviour, elastic and plastic, and 'real' behaviour (hardening/softening) expected for rubber and soil. The two stress path vectors (arrows) attempt to show the variation in rubber stiffness response (non-linearity) expected for the same stress tensor but different initial conditions, whereby when already under some compression/load there is expected a higher stiffness response

In response to the need for low-cost more portable impact testing of surfaces the Clegg hammer (see Fig. 3 – shown with the AA device) has been evaluated and has shown promise for routine measurements. It has demonstrated, in general, good correlations with the AA on sport surfaces. Figure 7 shows two relatively large datasets on a range of pitch systems, one from extensive field testing and with around 100 test positions across a range of five different UK short-pile Nylon (elite level) hockey pitches, with integral and/or *in situ* shockpads beneath [**20**], the other from extensive laboratory evaluation of impact behaviour of a long-pile rubber infilled (3G) soccer surface [**38**]. The two fitted curves show a perhaps surprisingly good similarity in the correlation and overlapping force reduction range. In contrast the sand-based system, medium-pile length of approximately 22 mm, infilled with sand and with a shockpad beneath, shows very little correlation between the impact test devices [**20**]. This is thought to be due to the more rapid rate of loading imparted by the Clegg hammer causing greater inertia reaction effects in the sand-based system and it was also observed that the sand surface was more disturbed and displaced by the Clegg hammer impact than the AA impact. In addition, it was also noted during

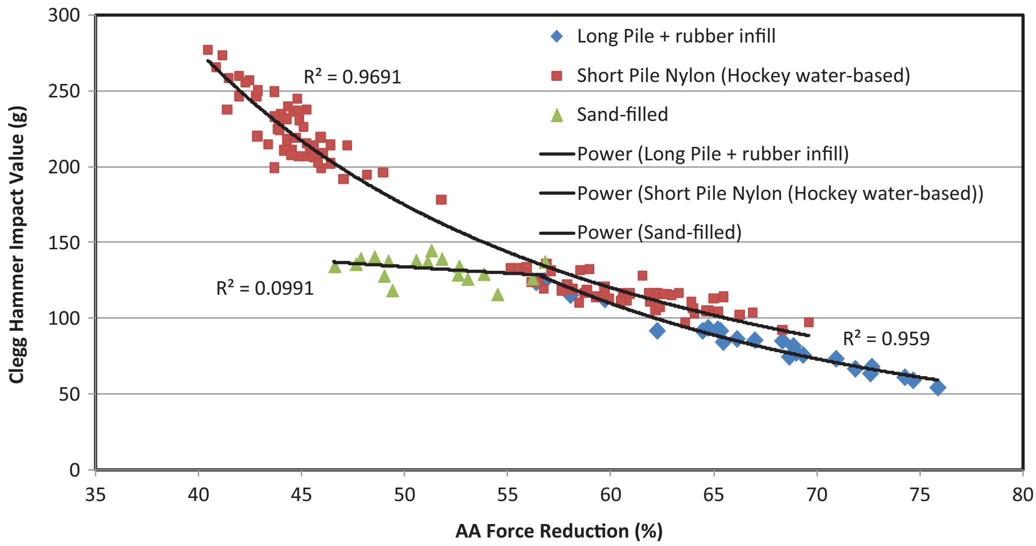

Fig. 7 A graph presenting the relationship between the industry standard AA and the relatively simple Clegg impact hammer, for three different sport surface systems. Note the contrast between the much stronger correlations observed on the more elastic systems and their proximity compared to the sand-based (more plastic) system

fieldwork that large changes in ambient temperature affected the coefficients of correlation between the Clegg and AA for the rubber infilled surfaces, suggesting that estimating an AA force reduction value directly from conversion of the Clegg hammer measurement is inadvisable despite the general correlations presented here. The Clegg hammer is, however, suggested as a useful tool for site monitoring of hardness (e.g. see [**18**] regarding maintenance). If a surface system becomes progressively harder (or softer perhaps but this trend is considered less likely on artificial turf) then the Clegg data, easily collected, could be used to trigger a more detailed inspection, a specific maintenance (e.g. decompaction) process and/or an independent sport surface test specialist to visit and advise.

It should be noted that field testing for compliance is not routinely carried out on all artificial turf pitches installed (in the UK), nor on natural turf, due to costs primarily and a lack of regulation (in the UK and in many countries it is believed) that enforces regular testing for performance or safety aspects, especially for lower level competition and community multi-use surfaces. However, there remains no data on how many pitches are in fact tested.

4.2 Traction behaviour

Players in soccer and rugby use specific footwear with studs to penetrate and interlock with the playing surface, and by so doing generate 'traction' forces. This ability to generate traction between a player's footwear and a sporting surface is a crucial factor influencing the player's movement and performance. The traction force produced contributes to the locomotion of an athlete and their ability to accelerate or decelerate, and to change direction, or in the case rugby help generate scrummage forces between the teams. The level of traction produced at the shoe–surface interface reportedly has the potential to contribute to or cause injury (see section 3) whereby too low a traction resistance force will result in slipping, whilst excessive traction resistance will cause foot 'sticking' to occur [**9**].

Many authors have investigated the traction properties of sports footwear, and have evaluated a combination of a variety of shoe types and surface types, concluding that the traction generated at the shoe–surface interface is generally explicit for each shoe–surface combination [**41–46**]. There has been little attempt in this literature, however, to try and explain and understand the outcomes of the testing, or to develop a model for traction to understand and explain the mechanism of interaction and the relationship between the somewhat complex number of variables involved at the shoe–surface interface. Many of these previous studies, to their detriment, have included very limited information detailing the surfaces used in their trials and specifically their constituents and properties which limits any further interpretation of these datasets. There are, in general, very few papers with high-quality

Table 2 Factors considered to influence shoe–surface traction behaviour [**38**]

Sports-specific movement	Footwear	Playing surface	Environment
Mass of athlete	Number of studs	Physical characteristics of the carpet layer	Water
Loading rate	Stud configuration	Physical characteristics of the infill layer	Temperature
Angle of foot	Size of stud	Mechanical properties of the carpet layer	Chemicals
Speed of athlete	Shape of stud	Mechanical properties of the infill layer	Maintenance
Height before contact	Sole/stud material	Shockpad thickness	Wear
	Contact surface area		

quantitative research data with a focus on surface properties and traction behaviour, particularly for artificial turf surfaces. This gap in knowledge is perhaps somewhat surprising in light of the increasing use of artificial turf pitches used in elite-level sport. However, there has been a recent research investigation [**47**] aimed specifically at further addressing the missing link between shoe–surface interface measurements and the consequent effects on the ACL regarding injury susceptibility. This study utilized clinical measurement of strains and moments in ligaments from foot–shoe–surface interaction tests on cadavers.

A small number of recent studies have shed some light on the relatively complex process of player–surface interaction and the extent to which changes in the surface system can affect the measured traction (from using mechanical test methods not human subjects). For example, Villwock *et al.* [**44**] concluded that the infill type, fibre type, and shoe cleat design all affected the peak torque resistance. They also showed that the combination of shorter cleats and looser fill produced lower rotational traction (peak) values. Additionally, fill size and shape had some influence, as did fill to fibre interaction, on their measured values. Their tests were carried out on outdoor samples, approximately a year old, but the reported work lacked details of the stud penetration, infill depth, and did not discuss their thoughts on the mechanism of traction. In addition, in their work the cryogenic rubber infill (frozen during the cutting phase) produced higher traction than the crumbed rubber (often termed styrene butadiene rubber (SBR)) cut under ambient conditions. This was in contrast to the findings of traction focused work by Alacantara *et al.* [**12**] wherein it was reported that the standard crumbed rubber infill gave higher traction than cryogenic rubber infill. The inconsistency between test protocols and analysis may be the cause of such contradictory findings.

Severn [**38**] carried out a comprehensive programme of laboratory tests to evaluate the effects on traction measurements of changes in the physical characteristics of the surface system (i.e. carpet type, fibre length, density, infill type, size, depth and density, temperature, and wet/dry conditions). Space does not permit a full review of this recent doctoral study; however, Table 2 shows the range of factors that were expected to affect the traction behaviour of the surface system from a thorough review of previously published literature. Although some of these factors may be considered to be ‘fixed’ by the initial constructed state of the surface, it is clear that the wear and tear during the surface life, and the maintenance regime applied, are expected to affect the consistency of many of these factors during the years the pitch is in use.

This research [**38**] compared the measurement methods and values derived from different traction test techniques, whilst controlling the surface state, and in particular aimed to evaluate the current FIFA (and IRB) standard rotational traction test.

The industry standard test for rotational traction [**9**] comprises a rigid disc with six equally spaced studs attached to the underside, weighted to achieve a total mass of 46 kg (460 N normal force). The studs used are a standard FIFA size, 13 ± 0.5 mm long, and 12.6 ± 0.5 mm wide. Initially, the weighted disc is lifted and dropped on to the test surface from a height of 60 ± 5 mm to aid penetration of the studs into the surface. Rotational torque is then applied to the torque wrench slowly by the operator (a rate of 12 revolutions per minute is specified) and the maximum value of torque is recorded (but not rotation distance).

Figure 8 shows a set of data [**38**] that compares the FIFA standard test with a bespoke mechanical device that uses a rigid last to attach the full soccer boot under test. This figure also shows an increase in the peak rotational traction with increasing infill density (produced through rolling repeatedly with a studded roller reducing the air void content in the infill) for the tests with the soccer boot (the boot is inclined to control contact at the forefoot only). However, the standard FIFA test shows no clear pattern for peak traction versus infill density. This work on infill ‘state’ [**38**] extends previous work by considering the effect of density and shear strength on the resistance to the boot-stud movement

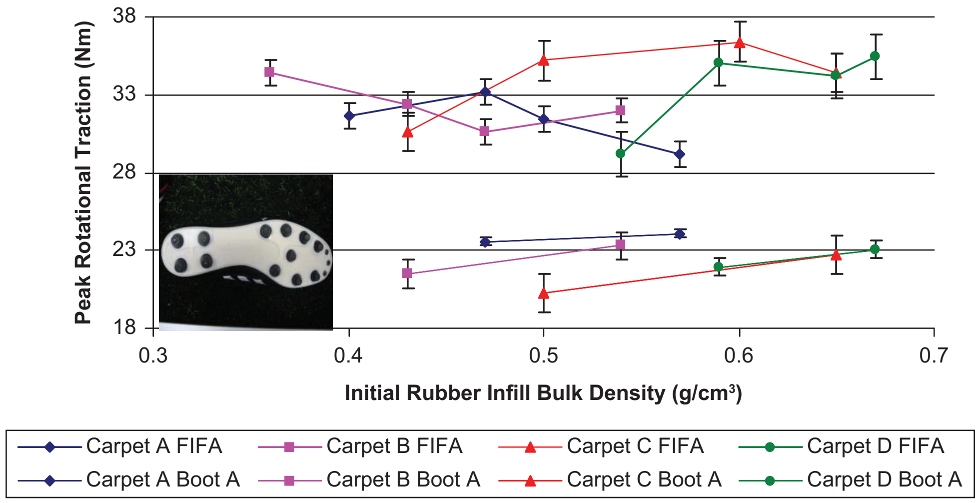

Fig. 8 A graph presenting the relationship between peak rotational traction and surface infill density for the standard FIFA studded disc test and a mechanical test utilizing a studded boot (reproduced from [**38**])

through the infill–carpet system. Observation in the field of rubber crumb infill 'compacting' and pitches becoming 'harder' is a common anecdote from users and operators alike, after several years of use, although it is commonly stated that effective maintenance should delay or recover this effect [**18**, **21**]. In contrast to concerns over increased traction and its perceived injury risk, this recent study [**38**] also demonstrated that traction may be reduced by: loosening the infill; a lower density of carpet fibre spacing; increasing the infill size; and reducing the stud penetration (made possible due to a hard/strong surface, or larger diameter studs, or reducing the static weight of the test device in the case of the FIFA test).

This emerging data and understanding of surface behaviour further highlights that this aspect of surface science has not received much attention in the literature in any detail, and nor has the mechanical behaviour of the crumbed rubber infill. However, laboratory testing and analysis, regarding both recycled rubber shockpad and crumbed infill [**37**, **38**, **48**], has shown the rubber particulate to be relatively complex in terms of its behaviour under compression, compaction, and shear loading. The stiffness response and ultimate shear strength behaviour of the particulate infill was shown [**48**] to be controlled by the loads applied and the amount of strain induced during testing (see Fig. 6). Solid particulate materials, such as natural granular soils that include the sands used in sport surfaces, show dilatant (i.e. increase in volume) behaviour when sheared if in a dense state and this provides a much higher resistance to failure (and is why these materials are compacted to provide better stability in construction applications). However, in sharp contrast the compressible rubber particulate showed little dependence on the initial state, i.e. initial density. An initially loose and dense rubber infill achieved very similar shear strengths and required large shear strains to produce what may be considered a 'peak' value [**48**]. This raises the question as to whether the rubber infill truly shears or is perhaps merely compressed and distorted when providing traction resistance (depending on the strain generated by the foot/boot movement it is suggested).

It is suggested that to further develop the science of artificial turf interactions the rubber infill material behaviour needs to be much more clearly understood. Infill specification is sufficiently 'loose' such that infill size, particle shape, and dust content may vary and the effect of these variations is not known. In addition, the rubber materials are expected to age and the stiffness behaviour to change. To interpret the whole surface system behaviour the infill interaction with the carpet fibres and with the shockpad is also required for the detailed analysis of traction test results. To further explore the infill behaviour, Fig. 9 shows the stiffness response of a rotational traction test on an artificial and a natural surface system [**49**]. This figure shows the greater compression response of the rubber infill compared to the 'stiffer' response of the natural turf soil system, albeit the 'peak' resistance at large rotation angle is similar (note 0.8 rad = 46°).

Based on the previous discussions and system behaviour data it becomes clearer that mechanical

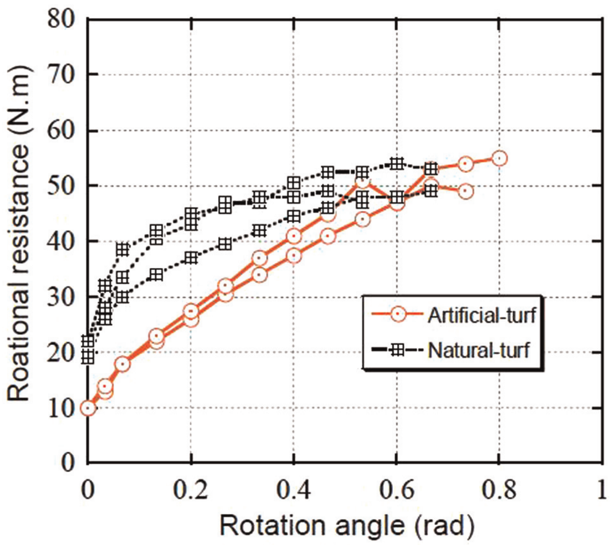

Fig. 9 Interpretation of rotational traction, showing the rotational stiffness behaviour for test on artificial turf and natural turf (reproduced from [**49**]). The data shows an increase in the initial shear stiffness during rotational traction testing of the soil (solid) particles, in comparison to the more compressible rubber particles, although they appear to reach approximately the same 'peak' resistance at maximum rotation angle

test methods, aiming to provide player performance or safety-related data on surface system behaviour, ideally need to be 'biofidelic' (i.e. mimic the athlete loading scenario) in their methodology or they risk being invalid with regard to their interpretation. However, currently the effective measurement of traction and fuller explanation of surface system behaviour in providing traction is somewhat clouded by the many differing test devices used in research around the world that have differing input parameters or test protocols. These variations include: magnitude of normal load applied; area of contact; use of a rigid or flexible foot last to affix a shoe; rate of loading (rotational or translational) applied; use of 'peak' resistance or interpretation at some nominal amount of displacement; and many other issues relating to the surface sample preparation, and its full description, used in the testing. With regard to the analysis of traction behaviour or limits, an informed debate is required regarding the issue of what deformation is deemed appropriate to measure, or what the 'peak' traction represents (translational or rotational) when it may be from several tens of millimetres of displacement. Observations of player foot–surface contact have shown, in the case of a forefoot push off action [**50**], to comprise only a small horizontal movement (of approximately 10 mm) once the standing/leading foot has been planted, for example.

A real limitation of the mechanical test devices currently in use is their application of a constant static normal load during testing, contrary to an athlete's foot contact. It is the combination of vertical load and friction/traction response that develops the surface's resistance to traction movement. It is suggested that replicating 'peak' athlete normal load or some average normal load is dismissing the prospect that foot slippage or 'locking' may occur where the ratios of vertical to horizontal are at their lowest or highest respectively. Figure 10 shows the force plate data from a player executing a 45° cutting manoeuvre on artificial turf to illustrate the high vertical loading, high braking horizontal (shear) loading initially and associated torque, and then the push off forces as the player accelerates away from the turn. The dynamic nature of the action is clearly evident, and the initial impact and braking loads rapidly rise to their peak over around 50 ms duration in this case.

4.3 Optimizing surface design for performance and safety

It appears that much of the advancement from the industry is in response to guidelines for acceptability from the governing bodies and includes some research into performance and injury aimed primarily at the elite/professional markets for sport competition. Some of the guidance has filtered down to the community level and has improved the general advice, guidance, and specifications for community-level selection and aftercare for artificial turf surfaces, in the author's opinion. However, there remain many issues that have not yet been researched regarding user health and safety at the community level. The effect of lower budgets in community schemes on the surface product selected and installation quality in comparison to elite-level facilities have, anecdotally, been the cause of many installed facilities rapidly degenerating or being utilized long past their design life. Many public funding initiatives, in the UK, have focused on widening participation and no national database has been developed that includes any monitoring of the 'quality' of facility provision. However, the Active Places database [**13**] has improved public knowledge of the number and location of sport surface assets. There would be a benefit from feedback on the surface systems that are in use regarding their performance – currently missing from the UK's management procedures of its public facilities in general.

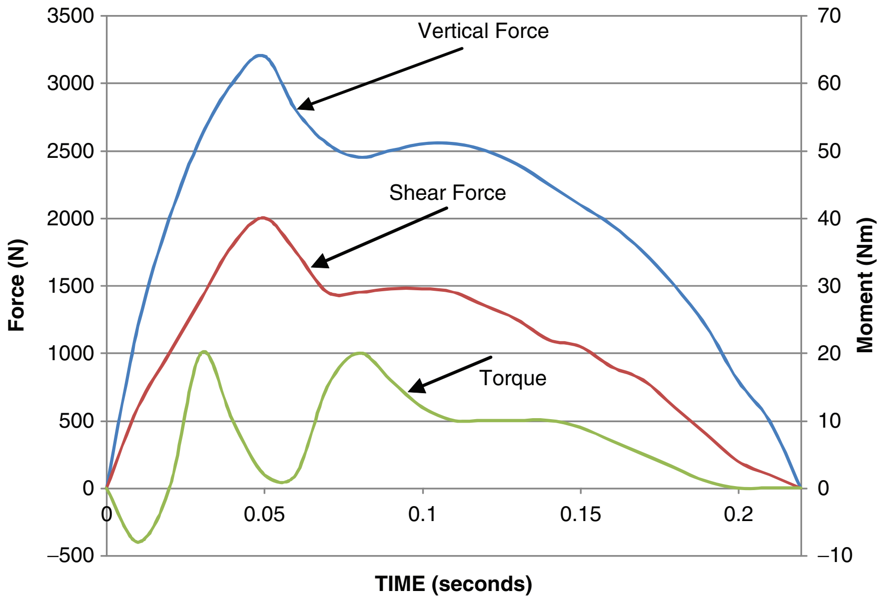

Fig. 10 Typical player loading measured on a force plate during a cutting manoeuvre – a 45° cut on artificial turf (3G)

Player feedback has been a powerful tool in the growth of the newer generation of artificial turfs for soccer and rugby, coupled with better health monitoring (at elite level only) to demonstrate injury occurrence and risks that are shown to be comparable to natural turf (see section 3). However, one study [**51**] showed that in regard to ball bounce in hockey the players were generally more satisfied with having a harder surface to promote lower ball bounce than with regard to any soreness they may have felt on their ankles and knees after matches. It also became apparent from studying the hockey pitches used in the Commonwealth Games – designed at the 'very hard' end of the surfaces monitored (force reduction of between 40 and 45 per cent, see Table 1) – that after the event the local children of middle-school age were also regularly using the facility. It is the author's opinion that National Governing Body (NGBs) and IGBs have a duty to consider their guidance in instances such as this, whereby despite the pitches passing the elite-level hardness test they may not be suited to developing schoolchildren. It is suggested a move to more rational classification of surfaces, such as 'hard', 'medium hardness', or 'soft' within the acceptable range may be more useful to owners and users. However, such a labelling system may be potentially contentious in practice and difficult to introduce to the industry at large. Improved user education regarding products and requirements (such as footwear) is, however, considered to be needed.

There exist shortcomings, recognized in many studies, in the efficacy of many surface performance-related tests in comparison to how players (and balls) interact with a surface. However, there is also clearly a need for devices used in the laboratory and field that achieve a suitable compromise between the complexities of human–surface interaction and the test method's ease of use, repeatability, and robustness. Whilst there has been some debate on this subject [**10**, **52**] by researchers, few studies have attempted to critically appraise the validity of current standard test methods in light of user feedback on a surface. A player perception study on hockey fields [**20**, **51**] appears relatively unique in that it correlated several performance-related mechanical surface tests (such as the AA, rotational traction, ball roll and ball bounce) with the player feedback across six (different) elite-level hockey surfaces in use in the UK, selected based on initial player interview feedback on pitch properties. At each pitch a suite of performance-related tests were done to the FIH standards, though notably there was no rotational traction test in the FIH standard at that time and a modified FIFA traction test was carried out with a dimpled hockey boot sole in place of the standard six stud configuration. Figures 11 and 12 present the correlations for rotational traction and force reduction and show a broad range of results for the mechanical tests and the player perception feedback. The rotational traction data showed quite large standard deviations (shown on the figures) and of interest was that the higher traction measured was for the Nylon fibre carpet systems, and the lower traction for the polyethylene carpet systems as expected from the softer yarn. An exception was at the Cannock site where the Nylon pitch (since replaced)

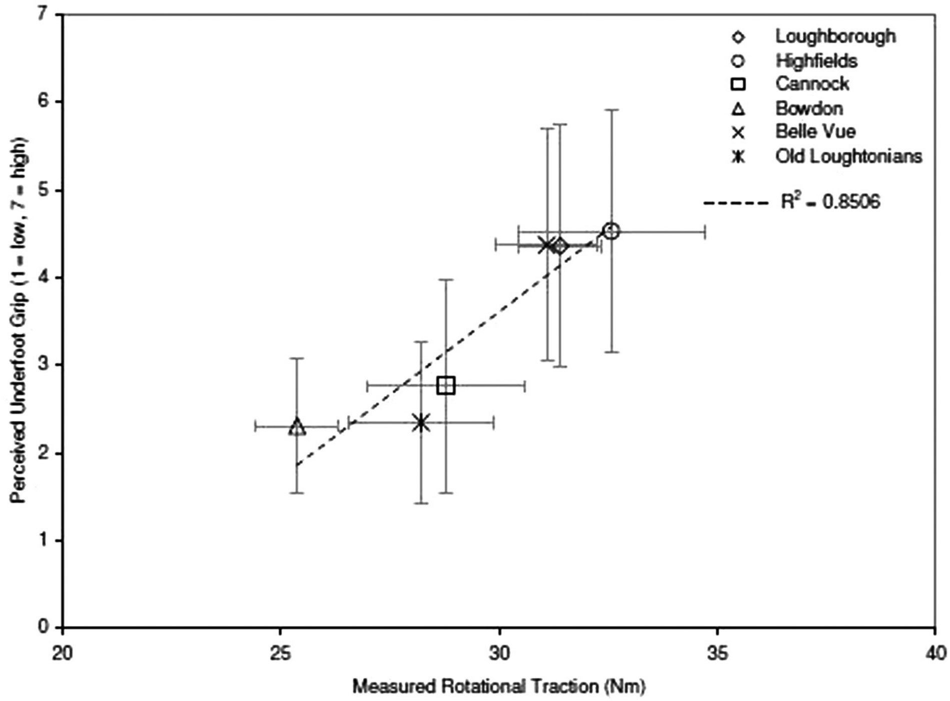

Fig. 11 A graph showing the relationship between the player perception of surface underfoot grip and the mechanical measurement of rotational traction (reproduced from [**20**])

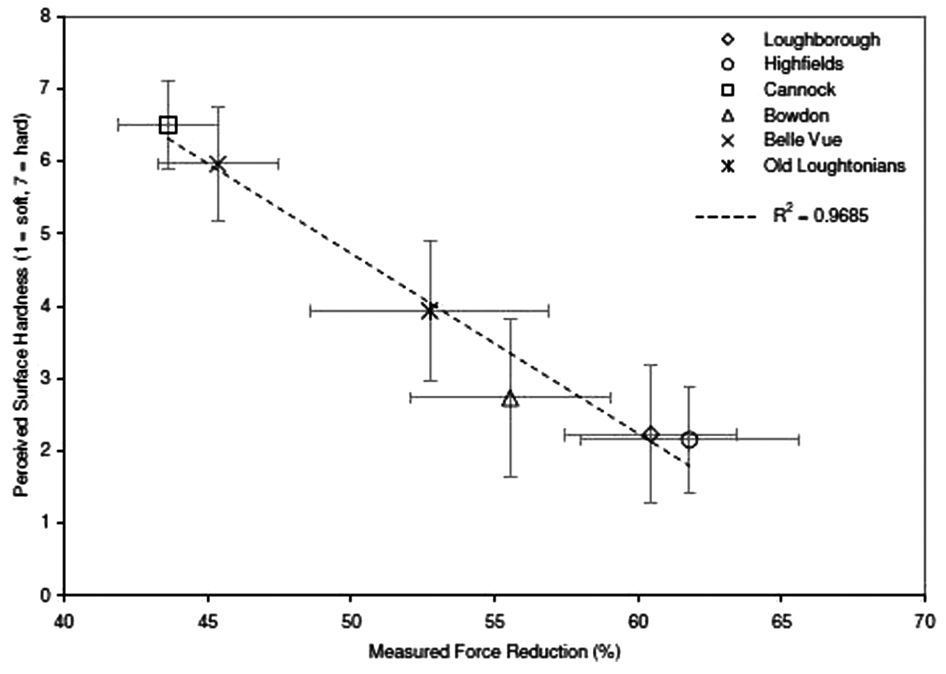

Fig. 12 A graph showing the relationship between the player perception of surface hardness and the mechanical measurement of force reduction (reproduced from [**20**])

was suffering from an algae problem and also some carpet fibre damage, both visually easy to ascertain, which did lead to lower traction results. The force reduction data correlated well with the thickness of shockpad at each site, the thinnest design at Cannock and Belle Vue and a thicker design at Loughborough and Highfields (Nottingham). These data suggest that these two relatively simple devices did differentiate between surface systems that the players also differentiated between. In contrast, although not shown here very poor correlation was found between the simple vertical ball bounce test and users' feedback. More studies similar to this would help both further corroborate these findings and assess other performance-related tests, or for other sports, in regard to their applicability to what the users perceive.

5 DISCUSSION – THE DEVELOPMENT AND FUTURE FOR 'SPORT SURFACE SCIENCE'

This paper has presented a broad overview of synthetic turf classification and evaluation within the context of current sport governing body requirements. There have been many advances in recent years in terms of surface products and fibre technology in particular. 3G infilled surfaces, better suited to rugby and soccer, have become prolific since the 1990s. However, surface systems that need little or no infill, and for the fibres to retain durability and resilience throughout the operating life, is still a goal as is multi-use surfaces that satisfy all sports. In addition, maintenance technology and practice has improved, with many treatment processes aimed at prolonging the playable life of these costly leisure assets. The applicability of artificial surfaces to a wider range of sport-specific requirements has been achieved, with a somewhat iterative process between product development and sport governing body requirements. Sports governing bodies have advanced their own knowledge, in general, such that guidance has been improved, and also new tests have been developed and implemented aimed specifically at improved player experience (e.g. for skin friction and angled ball bounce in soccer). The soccer and rugby communities have embraced artificial turf for training and at nearly all levels of competition. The future seems to be that this amenity will increase and that artificial turf will become an important income-generating asset at many amateur and professional club venues. However, that is not to say that natural turf will lose its place or relevance at many high-profile sporting venues, nor in many community amenity plans. The large initial capital cost of an artificial turf pitch is still a significant barrier to many clubs and communities.

In response to the growing interest in, and uptake of, artificial turf there will inevitably be further technological developments that may need careful acceptance and approval within governing body policies and with appropriate safeguards for end users. Recent examples of health scares have been touched upon in this paper such as the release of toxins from recycled rubber and the persistence of MRSA-infecting bacteria in artificial turf, and thus far increased health risks are unsubstantiated it appears. The increasing demand and relative high cost of these specialist sport surface products is already leading to a more and more confusing array of available products on the market – some of which may be inferior in quality. For many clients the safeguard against sub-standard products and work should be by appointing qualified consultants, ensuring compliance testing is followed up periodically, and that proper maintenance regimes are in place. It is the author's opinion these are all areas requiring further improvement in the UK practice, and probably elsewhere in the world, for this niche industry.

The impact of climate change and the sustainability agenda can provide both momentum and some barriers to artificial turf. The momentum will come from increasing pressure to reduce water usage in parks and leisure amenities such as for natural turf sports facilities [**53**]. The difficulty of growing and maintaining grass in parts of Australia has already recently had the effect of a sudden interest and move to artificial turf in community football [**3**]. The barriers may come in the form of issues regarding recycling and reuse of artificial turf products, currently in the UK they are land-filled at the end of their useful life in general. The 'carbon footprint' of sports amenities, including the raw construction materials, manufacturing, and maintenance processes, is under increasing scrutiny as clients and funders look to show their 'green' credentials (see [**54**] for a study on golf courses).

Notwithstanding the social and economic aspects of sport surfaces and their appropriate provision for an increasingly health-conscious society, there remain many scientific questions that will keep researchers busy for some time to come. Research into the science of surface behaviour and user and ball interactions has lagged behind many other aspects of advancing athletic performance and enhancements to the design and engineering of equipment, providing an 'edge' to the athlete in competition. It is also argued that without multidisciplinary approaches to understanding the player–surface interaction in particular, and without suitable research funding, many important questions will remain unanswered. For the industry, to fully optimize the design of sport surfaces and enhance the user experience many aspects of their behaviour and durability need to be more fully understood and implemented into their design, construction, and aftercare. These broad research aims require many complementary experimental programmes of research work, for a number of years, comprising teams of research engineers and material scientists, and the integration of suitable elements of epidemiology and biomechanics to measure (understand) the (likely) effects on users (and balls).

It is the author's opinion that what is required to move the research domain forward for example with the further development of mechanical tests, is more 'in-game' loading measurements from players/athletes during their interaction with surfaces to develop a useful 'state of the art' (live) database. This would then enable the enhanced development or modification of test devices that can more closely recreate these loading conditions and also contribute to more reliable testing procedures wherein the players themselves are used as the test devices. In addition, and concurrently, a separate strand of research is required that moves the science forward in both measuring and modelling surface behaviour under load and its 'ageing' process(es). Studies that measure the response of the system, at a suitable level of detail for each of the respective component's behaviour is required for the development and validation of numerical modelling of sport surface systems. From the development of suitable models will come the more powerful predictive tool for determining the likely effects of material and/or system design changes, and the prediction of the likely loading effects on the user for performance and their safety. Epidemiological studies are required, perhaps concurrently, to better understand the importance of the surface properties, and changes in properties, on traumatic and chronic (overuse)-related injuries that can arise in the users, at all levels of ability and performance. However, a major challenge for injury studies is the proper measurement of surface properties that are relevant to injury as such tests are currently missing from the portfolio of mechanical tests available.

It is also the author's opinion that the sport governing bodies need to play a larger part in driving forward the research programmes required, focused on either performance or safety or both, in accordance with their duty to their members and sport participants in general – ideally in partnership with government health departments and the public funding bodies for sport. Without the sport governing bodies/funders taking some leadership and helping set and drive (and fund) the research agenda the current situation of isolated pockets of good research will remain largely perpetuated and the benefits of larger integrated studies will not be realized.

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