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Advanced Measurement of Sports Surface System Behaviour under Player Loading

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Abstract

Artificial turf sport surface systems are comprised of a number of different materials. Improving the understanding of the sports surface system's response to actual player loading is important for developing enhanced products and system designs for improving play performance and durability. Previous research has tested and compared the mechanical properties of artificial turf systems with relatively simple mechanical tests intended to simulate loading from the player or ball. However, these test methods have known shortcomings in representing real in-service loading and it is often assumed a peak value of force or peak deformation is sufficient to describe the surface behaviour. Little literature exists that describes the force-deflection or stress-strain behaviour of artificial turf system under mechanical or player loading. This paper outlines methodologies developed for surface response measurement under real-time player movements including: the advanced measurement systems and data analysis methods for determining surface deflection/strain under player foot strike during a ground contact, and further evaluating the force-deflection and stress-strain relationships of the synthetic carpet-shockpad composite surface systems. The results show the ability of the surface system to accommodate the player applied loads by deforming to large strains with strong non-linearity and rate-dependent energy loss (hysteresis) in the load-unload phases. The contrast between the surface systems' response to player loading using different shockpads is also presented and discussed. By combining these findings from the development of measurement techniques and the data analysis methods a new surface system evaluation regime is proposed for future studies into mechanical behaviour and cushioning response of artificial turf systems under player loading.

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1. Introduction

There is increasing popularity of artificial turf surfaces globally at community level and through their inclusion into the professional sporting world. The advances in many aspects of sport science associated with improving human performance and understanding/preventing injury has drawn the attention of academic and industry researchers to attempt to better understand the interactions of the players (and ball) with these artificial turf surfaces. However, it is clear that in spite of technological developments in artificial turf systems, and prospective injury cohort studies carried out for sport governing bodies, many scientific questions remain regarding how artificial surfaces (and natural ones) behave during the player (and ball) interactions and how they may influence player loading. There exists a collective body of previous research into the interaction between the player and artificial turf system using human subjects, usually with a primary biomechanical focus on the effects of the surface on the subject. However, the surface utilised is usually presented as a generic type or is categorised based on the industry tests for shock absorbency or traction, and these studies rarely provide any insight into describing or explaining the surface response, nor attempt to comment on the surface design factors in any detail.

There is a clear gap between what is now understood about player loading during different movements on a surface and what the (simple) industry/sport governing body standard tests can and do replicate in light of this. The drop-weight tests used to determine the mechanical properties of sport surfaces under vertical constant energy impacts have the shortcomings that the impact force peaks, rate of loading and contact duration show little correlation with actual player movements (Nigg and Yeadon, 1987; Nigg et al., 1984; Baroud et al., 1999). Furthermore the tests usually only report peak force or displacement magnitudes (Dura et al., 2002) and have little flexibility in test method to simulate differing foot loading styles or movement patterns (Dixon et al., 1999). Most sports surfaces utilise component elastomeric materials that exhibit strong non-linear viscoelastic response (damping or hysteresis) under compressive loading (Walker, 2003; Wang et al., 2012). A common limitation in previous laboratory studies however is inappropriate load and rate of loading control, perhaps through mechanical machine constraints, relative to lower limb kinematic and kinetic data for assessing surface response during player interactions. In addition, current research into sport surfaces engineering behaviour through mechanical and subject testing has largely been focussed on ground reaction forces, and less so on surface deformation or the interpretation of the applied stresses and resultant material strains. The intrinsic engineering properties of stiffness and strength are related to load but also to the area of loading (Yukawa et al., 2011). Few previous research studies have provided any detail of the contact area of the applied load limiting the evaluation of material engineering properties.

To understand the performance aspects of a surface (material), mechanical tests need to be complemented with subject tests (Nigg and Yeadon, 1987; Stiles et al., 2009). There is little if any published literature that describes the engineering behaviour of artificial turf surface system under real player movements, however. The desire to manufacture and play on better safer surfaces that last longer has increased demand for developing new knowledge of how the surface system responds to real player loading scenarios.

Artificial turf pitches can and do vary in their system design and the materials used for sport specific applications, though in general most pitches are of similar generic structure comprising key components: an artificial carpet layer (with or without infill of sand and/or crumb rubber); a shockpad layer under the carpet to help absorb impact and provide comfort, and an engineered (pseudo-rigid) foundation of aggregate and asphalt. The foundation layer provides a flat stable load bearing platform for the pitch. The shockpad layer and the artificial carpet layer together are termed as the 'surface system' and provide the required playing characteristics for specific sports (Fleming, 2011). The behaviour of the surface system under player loading, in vertical direction, is the focus of this paper. The purpose of this paper is to report on the investigation of both the surface system deformations and strains under human subject loading and development of the novel measurement systems utilised to make this possible.

2. Methods

2.1. Surface systems and loading patterns

Two distinct artificial turf carpets were selected, one designed for hockey (short-pile, no infill) and one for soccer (long-pile, the 3rd generation turf) and two different prefabricated shockpad products creating four different carpet-shockpad systems. The products' details (manufacturer's data) are shown in Table 1. The 0.24 m² soccer (3G) turf carpet was filled with 2.4 kg (10 kg/m²) sand and SBR rubber infill materials respectively.

Table 1. Specifications of products used

Sample	Product name	Sample size	Height/thickness	Material & structure	Supplier	Density
Rubber shockpad	Regupol® 6010 SP	600×400 mm ²	15 mm	Polyurethane bonded rubber shreds	BSW Berleburger GmbH	550 kg/m ³
Foam shockpad	re-bounce® uni F82.16	600×400 mm ²	12 mm	Open-cell polyurethane foam	Recticel S.A.	250±15% kg/m ³
Sand infill	N/A	0.2 - 0.7 mm	N/A	Silica, round shape	Garside 2EW	N/A
Rubber infill	N/A	1 - 3 mm	N/A	SBR	N/A	N/A
Hockey turf	System 5	600×400 mm ²	18 mm total	12mm long nylon fibres, with a 6mm integral foam backing pad	McCardle Astroturf	N/A
3G turf	Soccer Real 55 MS	600×400 mm ²	55 mm (pile height)	Polyethylene, monofilament	TigerTurf	25200 (tufts/m ²)

One 26 year old injury-free amateur level male soccer player (body weight: 80 kg, height: 1.85 m) provided informed voluntary consent for this experimental programme in accordance to the protocol designed by the Loughborough University Ethical Advisory Committee. The soccer boots worn by the player were designed for artificial turf pitch with moulded short rubber studs on the outsole (Nike FTII 5) in UK size 10. The shod player performed a forefoot contact style 'running' movement at a controlled velocity of 2.7 m/s ± 5%. The mechanical behaviour of the four selected surface systems under one (left) foot strike was analysed and four successful trials were captured for each surface system. The average peak vertical impact force for the forefoot running was recorded as 1915 ± 50 N (in 2.44 ± 0.06 body weight) and average ground contact time was 0.28 ± 0.01 s. The contact area time-history of the player's forefoot running strike with the surface was recorded using a pressure sensing mat (Tekscan Matscan, Tekscan, South Boston, MA) showing the average peak contact area as 70 cm².

2.2. Experimental set-up and data analysis

Running trials were performed on a 10.6 m runway. Artificial turf surface system specimens were placed on top of a force plate (9281CA; Kistler Instrument AG, Winterthur, Switzerland) at 8 m along the runway, fixed with double-sided tape on the edges. Timing gates (Smartspeed, Fusion Sport, Coopers Plains, Australia) were aligned to control the player running speed across the force plate, as shown in Figure 1 (a). Ten retro-reflective markers were attached around the lower part of left boot, as shown in Figure 1 (b). Three-dimensional marker trajectories were collected at 500 Hz using a network of 12 cameras Vicon Nexus Motion Analysis System (Oxford Metrics Ltd, UK) with synchronous collection of the force plate data at 1000 Hz. Prior to the running trials a static trial was captured with the subject standing on the laboratory floor next to the force plate to identify and label each marker.

The c3d files containing the raw force plate data and marker trajectories during ground contact from Vicon were imported to Matlab (The Mathworks, Natick, MA) where the analysis of the surface system vertical deflection was completed. For the static trial, a least squares best fit plane was fitted to the 5 forefoot markers to estimate 'z' value in vertical axis which represented the elevation of the forefoot plane above the laboratory floor. For dynamic trials, the kinematic data was low pass filtered at 20 Hz using a 4th order Butterworth zero lag filter and interpolated to the same time base as the force plate data. The force plate data was not filtered. Ground contact was defined by a

vertical force threshold of 10 N; however, to account for errors typically observed in centre of pressure (CoP) position at low forces, further analysis was only performed where the vertical force exceeded 100 N. At each time instant the rigid body transformation matrix between the static and smoothed dynamic marker positions was determined for the forefoot plane. As the surface systems on top of the force plate were compliant, an ‘fmin’ Matlab function was used to optimise the dynamic CoP position at each time instant considering surface system deformation when the transformation matrix was applied. The vertical deflection of surface system was determined as the instantaneous forefoot plane position in vertical axis representing the boot–surface interface relative to the resting surface system level during the identified ground contact phase.

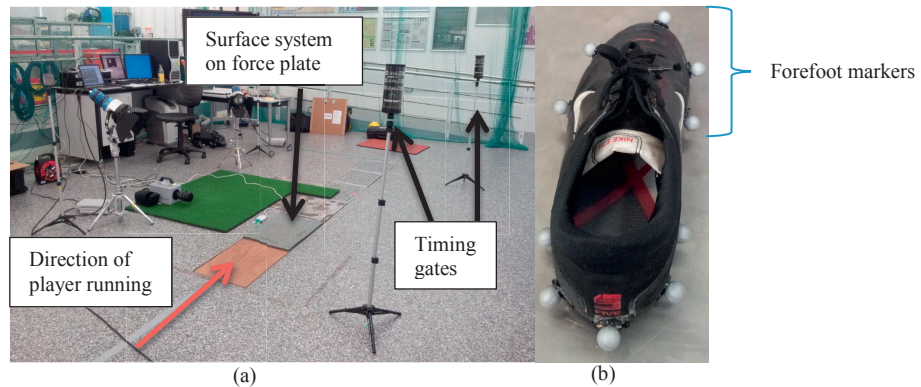


Fig. 1. Experimental set-up (a) and marker positions on the left boot (b)

The force-deflection relationship of each surface system was obtained to show its response to player forefoot running. The instantaneous applied stress was calculated as the vertical force measured by the force plate over the corresponding boot-surface contact area measured by the pressure mat during stance. The resulting strain of surface system was expressed as the ratio of vertical deflection to the original total thickness of the surface system. The total thickness of hockey turf system was determined as the combined thickness of shockpad and height of carpet pile (no infill is used) from the bottom of backing to the top of pile. The total thickness of the 3G turf system was determined as the combined thickness of shockpad and the total infill depth in the carpet before testing (i.e. the fibres protruding above the infill were deemed to have no compressive resistance). Energy behaviour of the four surface systems was compared using a ‘hysteresis energy ratio’ (HER), determined as the ratio of energy loss to the input energy. The area contained below the loading curve equals input energy and the area enclosed by the hysteresis loop equals energy loss. These areas were calculated using the trapezium rule at a time interval resolution of 10 milliseconds.

3. Results

The summary data are presented in Table 2. The peak vertical deflections in the forefoot running trials were 8.6 ± 0.2 mm and 12.5 ± 0.2 mm for the hockey turf with rubber shockpad system (HT+RS) and hockey turf with foam shockpad system (HT+FS) respectively. For the 3G turf systems, the 3G turf with rubber shockpad system (3G+RS) experienced the peak vertical deflection at 8.8 ± 0.3 mm compared to 10.2 ± 0.6 mm for the 3G turf with foam shockpad system (3G+FS). The peak surface vertical deflections occurred around mid-stance at the time of peak vertical force.

A comparison of force-deflection relationship for player running on four surface systems is shown in Figure 2 (a). It is observed that initially the surface systems are relatively easily deformed at low values of force, showing low stiffness at applied vertical forces less than 600 N. Thereafter, a clear trend of increasing stiffness is observed for all the surface systems. Surface system stiffness was calculated at the force range from 900N to peak during loading, using the deflection for this range. The stiffness of the HT+RS was 276 N/mm, slightly higher than the 3G+RS of 270 N/mm. The stiffness of the 3G+FS was 234 N/mm compared with 199 N/mm for the HT+FS. The

HER values for surface systems were in the range of 7 – 34%. Carpet layers combined with the foam shockpad exhibited wider hysteresis loops (Figure 2a), i.e. more energy loss, in comparison to surface system with rubber shockpad. The HER for HT+FS was larger than the HER for HT+RS by a factor of 3.4, whilst the HER for 3G+FS was around 2 times the HER for 3G+RS.

Table 2. Summary the measurement results for total thickness, peak vertical force, deflection, strain, stiffness and hysteresis energy ratio of each surface system under player forefoot running. The values of peak vertical force, deflection and strain represent the mean \pm one standard deviation from the four repeated trials. Stiffness in the range of vertical force from 900 N to peak force, and HER calculated from Figure 2.

Surface system	Total thickness (mm)	Peak vertical force (N)	Peak deflection (mm)	Peak strain	Stiffness (N/mm)	HER
Hockey turf + Rubber shockpad	33	1940 \pm 28	8.6 \pm 0.2	0.26 \pm 0.01	276	7.0%
Hockey turf + Foam shockpad	30	1949 \pm 57	12.5 \pm 0.2	0.42 \pm 0.01	199	23.6%
3G turf + Rubber shockpad	54	1915 \pm 64	8.8 \pm 0.3	0.17 \pm 0.01	270	15.7%
3G turf + Foam shockpad	49	1896 \pm 20	10.2 \pm 0.6	0.21 \pm 0.01	234	33.9%

Force-deflection behaviour of the surface systems was converted to stress-strain relationships to observe the mechanical behaviour of the surface systems that were treated as homogenous structures in this investigation, after normalising for their total thickness and considering the development of the boot-surface contact area during stance (Figure 2b). The applied stress was calculated to be in the range of 280 – 310 kPa. Larger peak strains were observed for the hockey turf systems than for the 3G turf systems. HT+FS gave the largest average peak strain of 0.42 and 3G+RS gave the smallest strain of 0.17. As expected, the stress-strain relationship demonstrates a similar nonlinear loading and unloading event to the force-deflection relationship during the ground contact phase.

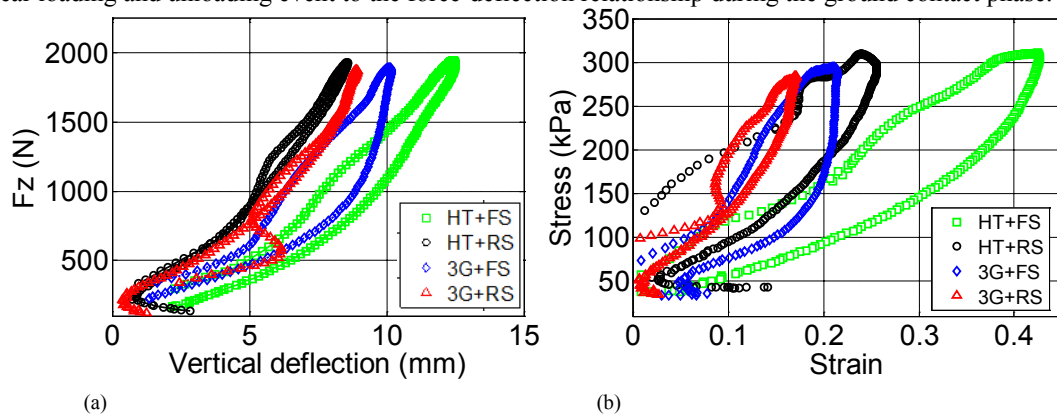


Fig. 2. Force-deflection relationship (a) and stress-strain relationship (b) for player forefoot running on hockey and 3G turf surface systems

4. Discussion

Measuring the surface system deflection underfoot during player movements, by tracking the position of the segment plane fitted through markers on the boot, provided the ability to characterise the surface system deformation behaviour under real player loading. The effectiveness of this method was analysed by calculating the root mean square fit error (RMSFE) for the rigid body transformation of the forefoot (the only segment stayed in contact with surface) ranged on average from 0.4 to 2.2 mm during stance (stance average 1.0 ± 0.4 mm). In this case, larger errors were towards the end of stance caused by the heel lifting off the ground and significant extension of the metatarsophalangeal joint. The small errors in the RMSFE for the rigid body transformation throughout the stance support the validity of the forefoot plane model used to analyse surface system deflection.

Differences in HER between the variants of rubber and foam shockpads used in surface systems are explained by considering the more elastic response (less energy loss) within the rubber shred particles in the open textured

rubber shockpad. The intrinsic stiffness of the bonded rubber shreds and lower volume of air voids in the rubber shockpad resulted in a stiffer response and smaller compressive strain of the surface system and therefore led to a relatively lower energy loss than the foam (see Table 2). The rubber shockpad absorbs the impact energy primarily by elastic buckling of the bonded rubber shred structure and returns the majority of this energy upon unloading through elastic recovery. The foam shockpad has open cells and a lower mass density with a higher volume of air relative to solid (porosity). McCullagh and Graham (1985) explained energy loss in compressed foam materials in terms of the heat generated in the air pockets due to deformation of the cell walls. It is clear that the initial compression of the high porosity shockpads is associated with only small compression of the solid particles and large reduction in volume as the air is compressed and it escapes through the inter-connected (pore) spaces. As further compression occurs the intrinsic stiffness of the solid fraction plays a larger part in resisting the deformation. The rubber with a relatively higher Poisson's ratio can deform through distortion into the regular void space. As the void space is reduced further under very high loads the stiffness increases in line with that expected of a more 'solid' block of rubber. The foam shockpad is less easy to evaluate as it is made of flocculated particles and blocks to make up the solid fraction. It appears that the entrained air is distributed in uneven size pockets. As such under increasing compressive loads the air flows from cell to cell through the large and small channels and may give rise to a further source of energy loss due to shearing of the exchanging air. Further work could explore how the microstructure of a shockpad is associated with energy behaviour by using the scanning electron microscope to support this discussion. It is apparent however that the two key properties of an open cell shockpad matrix is the intrinsic stiffness of the solid fraction, and the distribution and total air void space within the matrix. However, under large compressive loads that produce large (vertical) strains the compressed matrix will increase its stiffness significantly in comparison to the low strain behaviour. Thickness of the shockpad is a further important design factor that can help control the surface deformation under load.

5. Conclusions

This study quantified the deformation responses, and the force-deflection relationships of artificial turf surface systems under player forefoot running movement. This appears to be the first research study that has achieved this. The surface system behaviour was also evaluated for properties of stiffness, stress versus strain, and energy losses. These parameters are relevant to the engineering quantification of the elastic and viscous properties of the materials, and relevant to the real behaviour regarding the users. The measurement systems and data analysis methods presented permit simultaneous assessment of the mechanical behaviour (vertical) response of sport surfaces during various player movements in the laboratory.

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