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Biomechanical Response to Changes in Natural Turf During Running and Turning

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Integrated biomechanical and engineering assessments were used to determine how humans responded to variations in turf during running and turning. Ground reaction force (AMTI, 960 Hz) and kinematic data (Vicon Peak Motus, 120 Hz) were collected from eight participants during running (3.83 m/s) and turning (10 trials per condition) on three natural turf surfaces in the laboratory. Surface hardness (Clegg hammer) and shear strength (cruciform shear vane) were measured before and after participant testing. Peak loading rate during running was significantly higher ($p < .05$) on the least hard surface (sandy; 101.48 BW/s ± 23.3) compared with clay (84.67 BW/s ± 22.9). There were no significant differences in running kinematics. Compared with the "medium" condition, fifth MTP impact velocities during turning were significantly (RM-ANOVA, $p < .05$) lower on clay (resultant: 2.30 m/s [± 0.68] compared with 2.64 m/s [± 0.70]), which was significantly ($p < .05$) harder "after" and had the greatest shear strength both "before" and "after" participant testing. This unique finding suggests that further study of foot impact velocities are important to increase understanding of overuse injury mechanisms.

Keywords: ground reaction force, kinematics, sports surfaces

Despite the growth of artificial surfaces, traditional sports such as football, rugby, cricket, hockey, tennis and lacrosse are still frequently played on natural turf surfaces at a variety of sporting levels. However, a natural turf surface does not withstand the rigors of frequent multi-sport use, is highly influenced by changes in the weather and requires a large area of ground to rotate pitch usage. Therefore, there is a need to continue to develop natural turf surfaces to a) protect green spaces and playing fields in the built environment and b) preserve the fundamental playing characteristics for sports that would otherwise change if they became accustomed to play on artificial turf surfaces.

Several studies have illustrated the danger of engineering artificial sports surfaces on the basis of surface performance and durability, without considering human interaction (Torg et al., 1974; Andreasson & Olofsson, 1983; McCarthy, 1989). Engineering natural turf surfaces for more intensified use and use within enclosed stadium environments has already resulted in significant changes in mechanical properties. Mechanical properties of the impact interface have been found to influence player injury risk, for example, a greater incidence of overuse injuries has been found while running in harder shoes and on harder surfaces (Andreasson & Olofsson, 1983). A harder surface can lead to damage of the cartilage (Orchard, 2001) whereas a too compliant surface can lead to early leg-muscle fatigue (Millet et al., 2006). There is some research evidence that increased ground reaction forces (levels of impact and rates of loading) and altered joint movement patterns (kinematics) yielded when performing on harder surfaces can cause overuse injury (James et al., 1978; Nigg et al., 2003). Peak rate of loading in particular has been shown to increase with increases in shoe or surface hardness (Clarke et al., 1983a, 1983b; Hennig et al., 1996; Stiles et al., 2007). Kinematic adjustments in the form of increased initial knee flexion, reduced heel impact velocity, reduced initial foot sole angle relative to the horizontal and variations in joint angular velocities have been reported in response to running on surfaces of increased hardness (Bobbert et al., 1992; De Wit & De Clercq, 1997; De Wit et al., 2000; Dixon et al., 1998; Dixon et al., 2000).

Increased understanding of player-shoe-surface interaction in relation to impact attenuation and lower limb movement is vital to inform and reveal biomechanical mechanisms of overuse injury (Torg et al., 1974; Nigg & Segesser, 1988). Some analysis of natural turf properties has been achieved in the field, for example the assessment of traction performance during cutting maneuvers (Coyles et al., 1998) and plantar pressures underfoot during sports specific movements (Eils et al., 2004, Ford et al., 2006). Overcoming the challenges of incorporating natural soil media in the biomechanics laboratory to enable more sophisticated laboratory-based equipment

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to be used (Stiles et al., 2006; 2009) will increase understanding of player-shoe-surface interaction.

Producing a suitable natural turf sports pitch to meet player performance and safety requirements is extremely challenging. Mechanical properties of natural turf sports pitches change as a result of soil type, which influences surface hardness, and shear strength. Varying the contribution from clay, sand and silt components within the root zone results in a change in the hardness and shear strength characteristics of the surface at a given water content. Variations in turf construction in-situ can be quantified relatively easily using mechanical tests to assess characteristics such as hardness, shear strength and water content. For example, devices such as the Clegg hammer yield a measure of "peak deceleration (*g*)" to characterize and monitor natural surface hardness (Clegg, 1976, Holmes & Bell, 1986). The bulk shear strength of turf can be quantified using a cruciform shear vane, which is used in situ to measure undrained shear strength by the rotation of a cruciform vane to soil failure (τ, in $kN \cdot m^{-2}$; BS1377–9, 1990). Soil water content is a key factor in soil strength and can be measured using a dielectric probe (e.g., a Theta probe, Delta-T, Cambridge) that determines the volume of water per unit volume of soil as a percentage (vol%) (Gaskin & Miller, 1996). It is not known, however, how humans respond, and overuse injury risk factors alter, with variations in mechanical properties of a natural turf surface. Advances in construction to develop more sustainable natural turf playing surfaces must consider the interaction of the human participant to improve wear and degradation characteristics without increasing overuse injury risk factors associated with unsuitable surface hardness and traction properties.

The purpose of the current study was to integrate kinematic, ground reaction force and engineering assessments to determine how humans respond to measured variations in turf properties underfoot. It has been reported that during a 90 min game of professional soccer, each player performs approximately 50 turns (Withers et al., 1982). Research has also highlighted that within a 15-min period during a premier league soccer match, a mean of 9.3 deceleration type movements occur (Bloomfield et al., 2007). Therefore, in addition to the study of running, the inclusion of a more dynamic movement such as turning would be useful.

It was hypothesized that a turf condition with the highest mechanical hardness and shear strength would yield the highest peak impact forces, peak rates of loading and initial knee flexion (cushioning flexion) during running and turning. It was also anticipated that higher joint angular velocities during stance, a lower initial foot angle and a reduced heel impact velocity would be found during running on the surface with the highest mechanical hardness and shear strength. During turning, it was hypothesized that impact velocities of the 5th metatarsal phalangeal (MTP) joint (monitored as an equivalent and substitute variable to heel impact velocity during running) would be less on the surface with the highest mechanical hardness and shear strength.

Methods

Turf Conditions

Portable plastic trays (0.60 m × 0.40 m × 0.05 m) were turfed with ryegrass in three different soils (Table 1). The "clay" and "sandy" conditions were typical of heavy clay football pitches and modern, elite natural surfaces respectively. The "medium" condition provided an intermediate sand content. Trays were positioned widthways in the biomechanics laboratory on nonslip matting (6 mm thick) to form a continuous runway (9 m length) for each condition. Within the runway, the target tray was positioned lengthways on top of the force plate (5 m from the start of the runway with a 4 m run-off). Before testing, the trays of turf were mowed to a length of 29 mm.

Table 1 Turf conditions

	Clay (%)	Silt (%)	Sand (%)	Dry Bulk Density ($kg \cdot m^{-3}$)
Clay	27	44	29	1294
Medium	13	28	59	1517
Sandy	1	1	98	1736

Participants

Nine male rugby/soccer-playing (university/club standard) volunteers consented to participate. However, only eight sets of participant data were assessed for the running (participant 2 removed) and turning movements (participant 2 reinstated and participant 7 removed) due to data inaccuracies. Eight participants were justified based on a power analysis from previous experimental data providing an effect size of 0.87 and statistical power of 0.86 for an alpha level of 0.05 (Stiles & Dixon, 2006). Participants were required to visit the laboratory on two separate occasions to complete running trials (within the first 10 days of the testing period) and turning trials (within the last 10 days of the testing period) on all three conditions wearing studded footwear (UK sizes 10, 11 & 12; Nike Airzoom 90 III). Study procedures were reviewed and approved by Sport and Health Sciences, University of Exeter, Ethics Committee.

Movements

After running familiarization, participants ran at a constant speed ($3.83\ m \cdot s^{-1} \pm 5\%$; monitored using photocells positioned 1 m either side of the center of the force plate), making a right-footed contact with the target tray without adjusting stride or rhythm. Failure to correctly contact the target tray resulted in data being discarded and recollected.

During turning, a standardized 180-degree cutting maneuver required the foot to be placed sideways (approx. 90 degrees) on the target tray before continuing with the turning/push-off action. To monitor movement of a hip marker, all participants were required to flex at the elbow joint to raise their hands in front of their body. The use of timing gates during turning proved problematic due to light beams being broken by hand and torso movements during the turn. Instead, familiarization trials enabled participants to reproduce turns at a self-selected submaximal speed and audio and visual observation was used to check for movement reproduction inaccuracies.

Data Collection

Synchronized three-dimensional kinematic (8-camera Vicon Peak Motus, automatic, opto-electronic system 120 Hz) and ground reaction force (GRF) data (AMTI, 960 Hz) were collected for 10 running and turning trials on each turf condition (total of 30 running and 30 turning trials per participant). After 10 trials on one condition, the target tray and tray from the previous step were removed and preserved for hardness and shear strength assessments.

Peak loading rate (instantaneous loading rate), peak horizontal braking force and the time of peak braking force were analyzed for running and turning foot plants on the force plate. Peak vertical impact force (occurring within the first 50 ms of stance) was also analyzed during turning; however, it was omitted during running due to the inconsistent occurrence of impact peaks for all participants when running on turf. Magnitudes of force were converted into bodyweights (BW) by dividing by participant weight (mass in kg multiplied by acceleration due to gravity [9.81 m/s^2]) to remove the influence of differences in participant mass.

A combined and adapted version of joint coordinate systems presented by Soutas-Little and colleagues (1987) and Vaughan, et al. (1992) and employed previously by Stiles & Dixon (2006) was used to monitor lower limb movement with an additional marker on the 5th MTP (marker placements outlined previously by Stiles and Dixon, 2006). Markers were positioned to enable a local coordinate system for each segment to be constructed. Segment orientation in 3D space was determined by assessing the difference in location between the embedded (local) reference system of a segment and the global co-ordinate system of the laboratory (Vaughan, et al., 1992). Joint coordinate systems enabled rotations (Euler angles) to take place about segmental axes (calculations performed in Vicon Peak Software, Version 9.2). Kinematic data were referenced to a relaxed standing position and filtered using a quintic spline, (Peak Performance default optimal smoothing technique using 5th degree quintic polynomials; Woltring, 1985).

Three-dimensional initial (frame immediately before ground contact) and peak ankle and knee joint angles (during stance) were assessed together with peak joint angular velocities (during stance) and respective times of occurrence relative to the start of ground contact. Heel impact velocity and initial foot angle were assessed for running. Impact velocities for the 5th MTP joint marker (x,y,z and resultant) were assessed for turning as this point was identified as being the leading marker during ground contact and thus an equivalent to heel impact velocity during running.

Measures of surface hardness (peak "*g*") using a 0.5 kg Clegg hammer (thought to be more sensitive to changes in surface condition in a shallow 0.05 m depth profile compared with 2.25 kg) dropped from 0.55 m were performed immediately before and after participant testing on the target tray and the previous step tray. The Clegg hammer calibration certificate identified a typical standard deviation of ±10 *g* based on ten test drop procedures. Three Clegg hammer test procedures were performed on each tray in a diagonal formation; corner one (bottom left), center, corner two (top right). The hammer was dropped three times in each location and the peak deceleration of the third drop recorded. The mean of the three locations for each tray were combined to represent surface hardness for the turf condition during that session. Mean surface hardness was calculated for each surface condition under each movement. Volumetric soil water content was measured immediately before the test session for all trays using a Theta probe. Surface mean soil water content was calculated and presented for each movement based on the degree of saturation as a percentage of the saturation water content (maximum volume of voids in the soil). Shear strength of the target tray was quantified (kPa) before and after the participant testing session using a cruciform shear vane of 16.5 mm width, 33 mm depth (Figure 1). Shear strength assessment requires the shear vane to be inserted to a depth of 33 mm and turned by hand. A measurement of the torsion required to cause shearing is taken as the shear strength of the soil begins to fail (British Standards Institute, 1990). Because the method is semidestructive, a single assessment was made per tray after completion of the biomechanical testing.

An ANOVA with repeated measures and post hoc Tukey test was used to test biomechanical variables for significant differences ($p < .05$). A paired *t* test was used to determine whether significant differences existed within a surface condition before and after participant testing. An ANOVA was used to determine whether mechanical data differed significantly across surfaces ($p < .05$).

Figure 1 — Cruciform shear vane used to measure shear strength.

Results

Mechanical and group mean data for eight participants running and turning on three different natural turf surfaces are presented in Table 2. The sandy condition possessed similar magnitudes of hardness (59.55 peak *g*, ±4.75) compared with the clay condition (62.17 peak *g*, ±14.63) before running tests but was significantly lower ($p < .05$) compared with the medium condition (68.20 peak *g* ±9.07). The sandy condition was least hard (63.96 peak *g*, ±10.17) compared with both clay (71.62 peak *g* ±14.25) and medium conditions (72.88 peak *g*, ± 12.62 [significant difference at $p < .05$]) after running tests. The clay condition yielded the greatest increase in hardness after running tests (+ 9.45 peak *g*); however, this condition also revealed the greatest level of variability and therefore significant differences were not found. Shear strength was lower for the sandy condition compared with the medium condition before running tests. Shear strength was also significantly lower for sandy compared with clay and medium conditions after running tests (significant, $p < .05$).

Hardness across surfaces was similar before turning tests; however, there was a significant difference between the sandy and clay conditions after turning as a result of hardness increasing by 15.25 peak *g* for the clay condition. Shear strength was significantly lower for the sandy condition both before and after turning compared with clay and medium conditions. There was also a significant difference between clay and medium conditions after turning as shear strength for clay increased by the largest magnitude (5.30 kPa) after participant interaction. Differences in shear strength were also significantly higher after participant testing within each condition ($p < .05$).

Typical force-time histories for running and turning are presented in Figure 2. Peak rate of loading, used as a biomechanical indicator of surface hardness during running (presence of impact peaks across participants was inconsistent) was found to be significantly higher (Figure 3) on the sandy condition (the surface with the lowest mechanical hardness and shear strength) compared with clay ($p < .05$). Peak braking force during running was consistently found to be at 0.2 BW across all conditions.

Peak impact force during turning was similar across surfaces inline with similar starting hardness values. In contrast to running, peak rate of loading during turning did not reveal any significant differences between surfaces; however, there was a trend for higher rates of loading to be found on the clay condition, the significantly harder condition after participant testing compared with medium and sandy conditions (Figure 3). Peak braking force was similar across surfaces yielding just under 0.9 BW compared with 0.2 BW for running. The time of peak braking force was also similar across turf conditions during turning.

Typical ankle and knee angle time histories are presented in Figure 4. There were no significant differences in kinematic variables across surfaces during running. During turning, horizontal (y) and resultant impact velocity of the 5th MTP marker (Figure 5) were found to be significantly lower ($p < .05$) for the clay condition (the hardest surface with the greatest resistance to shear failure) compared with the medium turf condition (the least hard surface with a moderate shear strength).

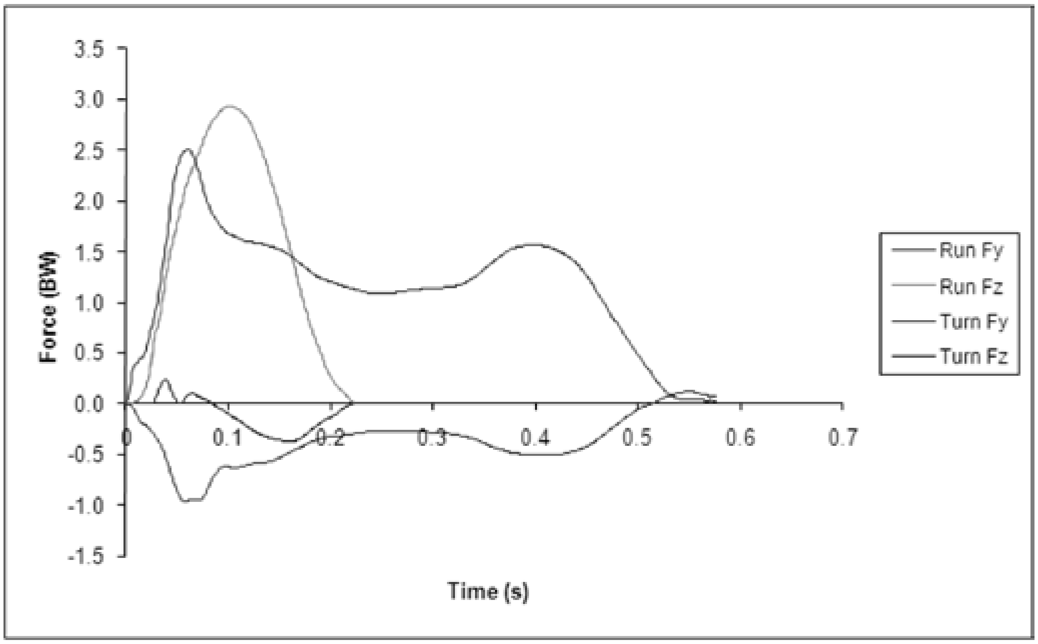

Figure 2 — Typical force-time histories during running and turning on natural turf

Table 2 Mechanical and biomechanical means (± *SD*) for running and turning across turf conditions

	Running			Turning		
	Clay^{a}	**Medium^{b}**	**Sandy^{c}**	**Clay^{a}**	**Medium^{b}**	**Sandy^{c}**
Turf Mechanical Data						
Hardness before (peak *g*)	62.17 (±14.63)	68.20*^{c} (±9.07)	59.55*^{b} (±4.75)	58.97 (±20.91)	54.06 (±9.80)	56.79 (±13.38)
Hardness after (peak *g*)	71.62 (±14.25)	72.88*^{c} (±12.62)	63.96*^{b} (±10.17)	74.22*^{c} (±18.15)	59.34 (±13.96)	52.87*^{a} (±9.74)
Difference in hardness (peak *g*)	+9.45	+4.68	+4.41	+15.25	+5.28	–3.92
Shear strength before (kPa)	24.92 (±5.21)	23.73*^{c} (±2.00)	21.65*^{b} (±1.20)	27.65*^{c} (±2.91)	24.53*^{c} (±2.61)	21.62*^{a,b} (±1.37)
Shear strength after (kPa)	25.83*^{c} (±4.08)	25.16*^{c} (±2.51)	22.65*^{a,b} (±2.09)	32.95*^{b,c} (±3.97)	28.09*^{a,c} (±2.65)	23.62*^{a,b} (±2.43)
Difference in shear strength (kPa)	+0.91	+1.43	+1.00	+5.30*†	+3.56*†	+2.00*†
Soil water content (%vol)	30.83 (±4.07)	28.67 (±2.33)	32.03 (±3.67)	29.49 (±3.40)	31.07 (±1.85)	32.41 (±3.13)
Saturation ratio (%)	63.2	66.1	86.5	60.4	71.7	87.5
Force Plate Data						
Peak impact force (BW)	—	—	—	2.28 (±0.21)	2.23 (±0.23)	2.34 (±0.21)
Peak loading rate vertically (BW·s^{-1})	84.67 (±22.9)	96.74 (±29.1)	101.48*^{a} (±23.3)	111.34 (±27.14)	99.45 (±26.37)	99.98 (±15.91)
Peak braking force (Fy) (BW)	–0.20 (±0.07)	–0.20 (±0.08)	–0.20 (±0.08)	–0.88 (±0.07)	–0.89 (±0.07)	–0.88 (±0.06)
Time of peak braking force (s)	0.06 (±0.02)	0.06 (±0.03)	0.06 (±0.06)	0.06 (±0.02)	0.07 (±0.02)	0.07 (±0.01)
Kinematic Data						
Initial foot angle (°)	13.98 (±6.13)	14.33 (±6.38)	15.06 (±6.57)	—	—	—
Initial ankle angle (°)	0.62 (±8.4)	1.18 (7.75)	2.36 (±7.9)	–7.78 (±7.06)	–8.71 (6.20)	–10.23 (±6.79)
Peak ankle angle (°)	14.22 (±8.5)	14.01 (±8.65)	13.90 (±8.6)	17.98 (±7.53)	19.48 (±10.17)	19.16 (±7.87)
Peak ankle angle time of occurrence (s)	0.15 (±0.02)	0.15 (±0.01)	0.15 (±0.02)	0.25 (±0.04)	0.24 (±0.03)	0.23 (±0.04)
Ankle ROM (°)	13.60 (±3.9)	12.83 (±3.5)	11.54 (±3.1)	25.76 (±6.50)	28.19 (±6.60)	29.39 (±5.84)
Initial knee angle (°)	10.53 (±6.0)	10.60 (±4.6)	10.89 (±4.1)	18.90 (±6.67)	19.11 (±6.41)	18.55 (±6.60)
Peak knee angle (°)	35.30 (±6.0)	34.86 (±3.9)	34.64 (±4.9)	56.68 (±4.09)	56.78 (±4.94)	56.20 (±4.56)
Peak knee angle time of occurrence (s)	0.12 (±0.01)	0.11 (±0.01)	0.12 (±0.01)	0.24 (±0.03)	0.23 (±0.02)	0.24 (±0.04)
Knee ROM (°)	24.76 (±5.50)	24.26 (±5.10)	23.75 (±6.00)	37.78 (±5.45)	37.67 (±5.89)	37.65 (±5.11)
Peak foot angular velocity (rad·s^{-1})	–4.23 (±1.08)	–4.27 (±1.15)	–4.13 (±0.99)	—	—	—
Peak ankle angular velocity (rad·s^{-1})	4.28 (±0.37)	4.23 (±0.48)	4.13 (±0.53)	4.12 (±1.19)	4.34 (±1.14)	4.73 (±1.26)
Peak ankle angular velocity time of occurrence (s)	0.10 (±0.01)	0.09 (±0.01)	0.10 (±0.01)	0.06 (±0.01)	0.07 (±0.02)	0.08 (±0.02)
Peak knee angular velocity (rad·s^{-1})	–5.53 (±1.13)	–5.53 (±1.02)	–5.56 (±0.92)	–6.25 (±0.89)	–6.28 (±0.67)	–6.48 (±0.69)
Peak knee angular velocity time of occurrence (s)	0.06 (±0.02)	0.05 (±0.01)	0.06 (±0.01)	0.09 (±0.03)	0.13 (±0.07)	0.16 (±0.07)
Heel impact velocity (m·s^{-1})	–0.51 (±0.08)	–0.52 (±0.08)	–0.51 (±0.07)	—	—	—
5th MTP impact velocity *x*-coordinate (m·s^{-1})	—	—	—	–0.91 (±0.53)	–1.04 (±0.41)	–0.95 (±0.46)
5th MTP impact velocity *y*-coordinate (m·s^{-1})	—	—	—	1.90*^{b} (±0.64)	2.28*^{a} (±0.68)	2.15 (±0.80)
5th MTP impact velocity *z*-coordinate (m·s^{-1})	—	—	—	–0.79 (±0.16)	–0.75 (±0.18)	–0.77 (±0.14)
5th MTP impact velocity resultant (m·s^{-1})	—	—	—	2.30*^{b} (±0.68)	2.64*^{a} (±0.70)	2.51 (±0.78)

Note. Significance, *$p < 0.05$ compared with superscripts a, b, and c, respectively, and *†$p < 0.05$ between "before" and "after" measures.

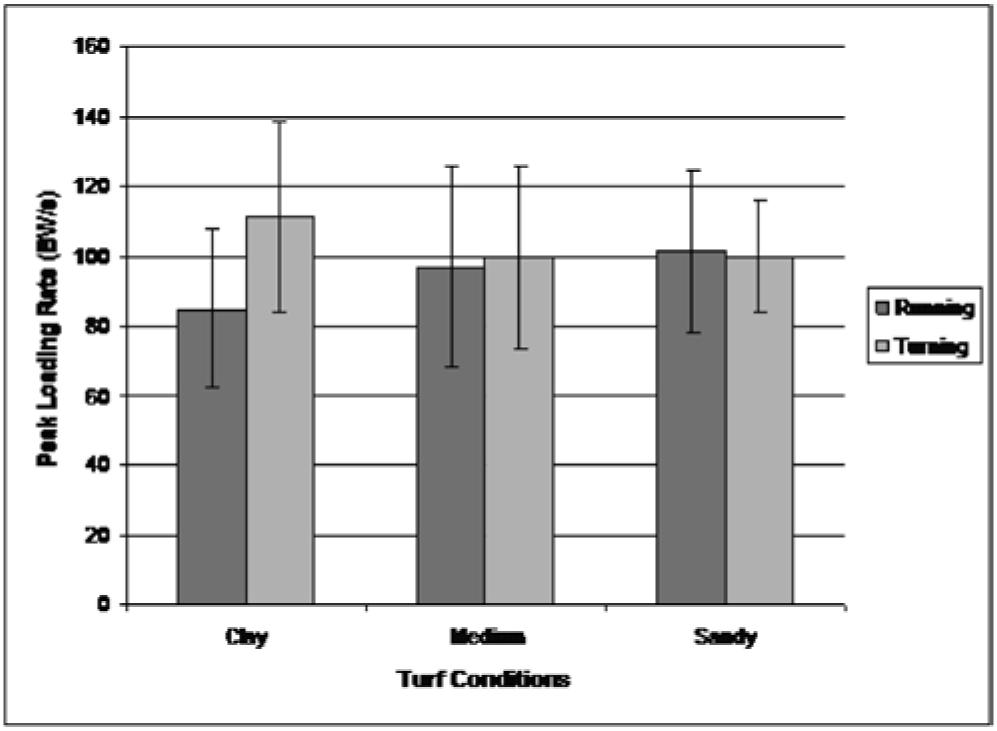

Figure 3 — Peak loading rate during running and turning with changes in natural turf condition (* Significant difference ($p < .05$) between Clay and Sandy conditions)

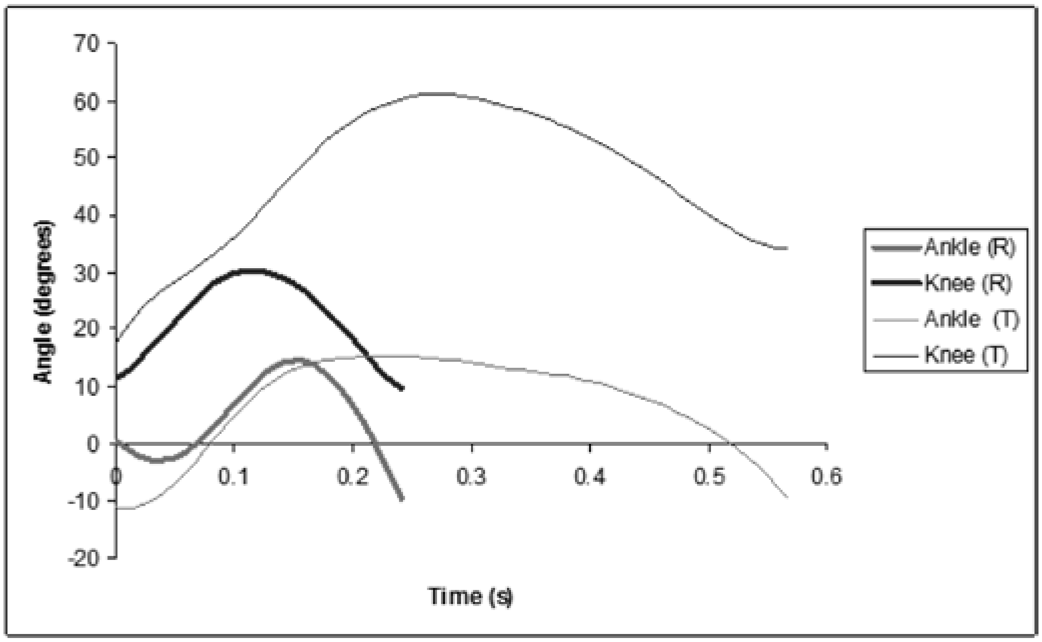

Figure 4 — Typical ankle and knee angle-time histories during running (R) and turning (T) on natural turf

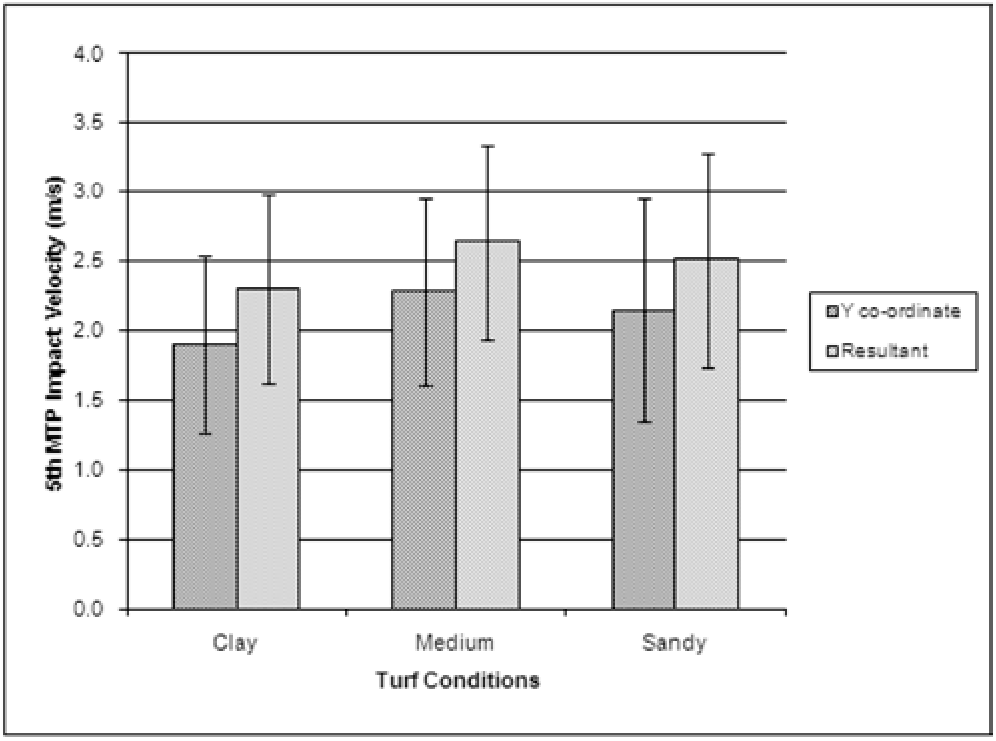

Figure 5 — 5th MTP impact velocity during turning with changes in natural turf condition (* Significant difference ($p < .05$) between Clay and Medium conditions).

Discussion

The present study collected kinematic and ground reaction force data during running and turning on three different natural turf surfaces in the biomechanics laboratory. This study fulfils the recommendation to obtain biomechanical data for sport specific movements on natural turf and increase understanding of player-shoe-surface interaction as a stepping-stone toward engineering a more sustainable natural turf surface (Eils et al., 2004; Orendurff et al., 2008; Stiles et al., 2009).

Turf wear and soil deformation were measured using standard techniques for natural turf sports surfaces (British Standards Institute, 1990). Compared with the medium condition, the sandy condition both before and after running tests, yielded significantly lower magnitudes of "peak *g*." Shear strength was also significantly lower for the sandy compared with the medium condition before testing and the medium and clay conditions after running. The sandy condition yielded significantly lower magnitudes of hardness after turning compared with clay and significantly lower shear strength before and after turning compared with clay and medium conditions. Table 2 shows the saturation ratio (given by the ratio of the soil water content to the total amount of water that can be held in the soil). Because different soils can hold different volumes of water, depending upon their compaction and their particle size distribution, the common water content of 30% results in different saturation ratios—in reality the clay is relatively dry and the sandy soil relatively wet. This highlights an important point regarding the comparison of soil conditions between soil types. Furthermore, the sensitivity of shear strength to water content in soils is dependent upon the soil type; based on the findings of Guisasola and colleagues (2010), if the clay had a greater water content, its shear strength would be significantly lower, whereas the sand would be less affected.

Initial foot angle demonstrated a consistent elevated inclination of the foot relative to the horizontal (heel lower than toe) across all conditions, which confirms a heel-first contact during running for participants. The presence of an impact peak during running for six participants was inconsistent within and across surface conditions and therefore made the analysis and inclusion of the peak impact force variable problematic. A lack of impact peaks may be explained via a detailed analysis of pressure data under regions of the foot. In keeping with previous research, the use of peak rate of loading as an alternative and more reliable indicator of surface hardness compared with peak impact force appears more sensible (Hennig et al., 1996; Stiles & Dixon, 2007). Peak rate of loading was significantly higher for the sandy (least hard) condition during running. This finding creates some confusion given that the biomechanical results do not support the mechanical test findings. While this is not an original feature of this study alone (Nigg & Yeadon, 1987; Dura et al., 1999; Dixon & Stiles, 2003; Stiles & Dixon, 2006) the concept of a surface with the least impact attenuating properties yielding the highest levels of loading on the human body remains difficult to explain. It is suggested based on the current study and the dynamic, mechanical behavior of turf that more sophisticated assessment of surface mechanical properties in the form of dynamic stiffness assessments coupled with analyses of whole leg stiffness (Ferris et al., 1999) and/or joint torsional stiffness may reveal a greater coherence between mechanical and biomechanical data sets for natural turf surfaces.

Kinematic variables assessed during running did not reveal any significant differences between surfaces and therefore do not explain the unexpected finding of a significantly higher peak loading rate on the least hard condition. However, hardness only measures one mechanical property of a surface. It is also recognized that some of the measured differences in hardness may also be outside of the precision limits of the measuring instrument (± 10 *g*). Unless differences in soil mechanical properties are large, the limitations of using the Clegg hammer are obvious. It is therefore suggested that a more complex analysis of surface mechanical behavior incorporating characteristics such as static and dynamic stiffness may correspond more effectively with the biomechanical finding of a higher rate of loading on the least hard surface. The reluctance to alter running geometry yet yield a higher rate of loading on the least hard surface provides further support for the suggestion that an integrated analysis of lower limb kinematics, ground reaction forces, lower limb stiffness and dynamic stiffness of the natural turf material may reveal a greater understanding of player-shoe-surface interaction. Further analysis of peak pressures under the foot, a variable considered to be more sensitive than ground reaction force variables to changes in hardness of the impact interface (Dixon & Stiles, 2003) would also be informative.

Despite the differences in surface mechanical properties, kinematic results also indicate similar turning patterns across surfaces except for the impact velocity of the 5th MTP marker. This variable acted as a substitute for heel impact velocity, a variable that is frequently studied for running (Bobbert et al., 1992; De Wit & De Clercq, 1997; Dixon et al., 2005) but one that does not translate or have relevance during a turning foot-plant. The 5th MTP marker was the lead marker during initial ground contact for turning and was therefore hypothesized to yield lower impact velocities in response to contacting a surface with the highest mechanical hardness and shear strength. The main contributor to resultant impact velocity for this marker was the horizontal (y) component that occurred in the direction of the run-up. Compared with the medium surface, both resultant and horizontal velocities were found to be significantly lower on the clay surface, the surface with significantly harder properties (after participant testing) and the greatest shear strength both before and after participant testing ($p < .05$). This unique finding indicates that the impact velocities of the foot are sensitive to changes in mechanical properties of the impact interface. As a possible adaptation toward reducing forefoot loading, MTP impact velocities during turning should continue to be studied to further increase the understanding of overuse injury mechanisms. This finding also suggests that the use of a more dynamic turning movement as opposed to straight-line running provides greater scope for revealing how changes in the mechanical properties of natural turf surfaces influence human movement.

Biomechanical assessment of participants tends to be performed on surfaces that are uniform and, aside from microscopic changes in tribology, will remain uniform for the duration of the testing. Properties of a natural turf surface, however, change on a scale more obvious to the eye throughout the testing period. Turf is easily deformed; changing in appearance and form as a result of a single footstep let alone a repeated number of steps within the same localized test tray dimensions. A number of suggestions can therefore be made to try and understand why changes in the mechanical properties of a surface are not more readily detectable using biomechanical measures of human response. Firstly it is suggested that the nonuniformity of the test tray surface throughout the participant testing session may have prevented changes in human response across conditions. Even though soil components were substantially different between the extreme conditions of clay and sand, the fact that properties of the natural turf testing tray were subject to small changes on a step-by-step basis may have occluded some potential study findings that would otherwise have been revealed by assessing target trays after each consecutive step or replenishing the target trays after each foot-plant. Secondly, the natural turf surfaces assessed may have been too similar and therefore the differences between them, while mechanically sensitive, may have been too subtle to influence biomechanical parameters. However, even a comparison between synthetic (third generation) and natural turf found that total loading under the foot was similar for each surface (Ford et al., 2006). This is encouraging given that the mechanical properties of third generation synthetic turf are designed to mimic natural turf characteristics. However, in Ford and colleagues' work, peak pressures on the medial forefoot were found to be higher when performing a cutting maneuver on natural compared with synthetic turf; a finding suggested to relate to a greater rigidity of the supporting natural turf structure. In addition, peak pressures in the central forefoot and lesser toes were found to be higher on synthetic compared with natural turf, which Ford and colleagues suggested could be due to synthetic turf allowing the foot to invert to a slightly greater extent thus increasing pressure in the central to lateral regions compared with natural turf (Ford et al., 2006). The nature of these findings would be useful to explore further with changes in mechanical properties of turf.

Turning and accelerating movement tasks have previously been found to yield approximately four times the magnitude of peak braking force and horizontal (braking) loading rate compared with running on natural turf (Stiles et al., 2007) which supports present study results. Compared with running, turning imparts greater horizontal forces and rates of loading on the turf thus placing greater reliance on the shear strength of the surface in order for the participant to successfully and consistently perform the movement in a stable manner. Turf properties do change—they are susceptible to wear and degradation which is demonstrated by significant differences in shear strength after turning. Although few significant differences in biomechanics were observed in the current study in response to changes in turf, the mechanical differences occurring as a result of use are likely to have implications for performance and injury risk during prolonged participation associated with match play.

Given the increased need for the participant to use mechanical properties of the turf surface during turning and the greater influence of turning on turf shear strength, it is suggested that the continued assessment of turning provides more scope to study player-shoe-surface interaction on natural turf. This is supported by the unique kinematic finding of a significantly lower 5th MTP impact velocity during turning on the hardest surface, the study of which is important, to further understanding of overuse injury mechanisms. The assessment of natural turf surfaces at greater mechanical extremes would also maximize the opportunity for establishing how variations in soil properties respond to and influence human interaction. Future study of the biomechanics of turning across a variety of natural and artificial surfaces will yield important information regarding player-shoe-surface interaction, applicable to understanding mechanisms of overuse injury, sports surface engineering and shoe manufacturers.

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References

Andreasson, G., & Olofsson, B. (1983). Surface and shoe deformation in sport activities and injuries. In B.M. Nigg & B.A. Kerr (Eds.), *The Biomechanical aspects of sport shoes and playing surfaces* (pp. 51–61). Canada: The University of Calgary.

British Standards Institute. (1990). Soils for civil engineering purposes—Part 9: In-situ tests. *British Standards Institute*, p. 20. BS1377-9:1990. London: British Standards Institute.

Bloomfield, J., Polman, R., & O'Donoghue. (2007). Deceleration movement performed during FA Premier League soccer matches. *Journal of Sports Science and Medicine, S10,* 6.

Bobbert, M.F., Yeadon, M.R., & Nigg, B.M. (1992). Mechanical analysis of the landing phase in heel-toe running. *Journal of Biomechanics, 25*(3), 223–234.

Clarke, T.E., Frederick, E.C., & Cooper, L.B. (1983a). Biomechanical measurement of running shoe cushioning properties. In B.M. Nigg & B.A. Kerr (Eds.), *The biomechanical aspects of sport shoes and playing surfaces* (pp. 123–134). Canada: The University of Calgary.

Clarke, T.E., Frederick, E.C., & Cooper, L.B. (1983b). Effects of cushioning upon ground reaction forces in running. *International Journal of Sports Medicine, 4,* 247–251.

Clegg, B. (1976). An impact testing device for in situ base course evaluation. *Australian Road Research Bureau Proceedings, 8,* 1–6.

Coyles, V.R., Lake, M.J., & Patritti, B.L. (1998). Comparative evaluation of soccer boot traction during cutting manoeuvres – methodological considerations for field testing. In S.J. Haake (Ed.), *The Engineering of Sport* (pp. 183–190). Cambridge: Blackwell Science.

De Wit, B., & De Clercq, D. (1997). Differences in sagittal plane kinematics between barefoot and shod running. *Proceedings of the Second Annual Congress of the European College of Sports Sciences* (pp. 790–791). Copenhagen, Denmark.

De Wit, B., De Clercq, D., & Aerts, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics, 33,* 269–278.

Dixon, S.J., Batt, M.E., Collop, A.C., & Singleton, T.M. (1998). The biomechanical and mechanical performance of Sureflex sports surface material. In S.J. Haake (Ed.), *The Engineering of Sport* (pp. 191–198). Cambridge: Blackwell Science.

Dixon, S.J., Collop, A.C., & Batt, M.E. (2000). Surface effects on ground reaction forces and lower extremity kinematics in running. *Medicine and Science in Sports and Exercise, 32*(11), 1919–1926.

Dixon, S.J., Collop, A.C., & Batt, M.E. (2005). Compensatory adjustments in lower extremity kinematics in response to a reduced cushioning of the impact interface in heel-toe running. *Sports Engineering, 8,* 47–56.

Dixon, S.J., & Stiles, V.H. (2003). Impact absorption of tennis shoe-surface combinations. *Sports Engineering, 6*(1), 1–10.

Dura, J.V., Hoyos, J.V., Martinez, A., & Lozano, L. (1999). The influence of friction on sports surfaces in turning movements. *Sports Engineering, 2,* 97–102.

Eils, E., Streyl, M., Linnenbecker, S., Thorwesten, L., Volker, K., & Rosenbaum, D. (2004). Characteristic plantar pressure distribution patterns during soccer-specific movements. *American Journal of Sports Medicine, 32*(1), 140–145.

Ferris, D.P., Liang, K., & Farley, C.T. (1999). Runners adjust leg stiffness for their first step on a new running surface. *Journal of Biomechanics, 32,* 787–794.

Ford, K.R., Manson, N.A., Evans, B.J., Myer, G.D., Gwin, R.C., Heidt, R.S., Jr., et al. (2006). Comparison of in-shoe loading patterns on natural grass and synthetic turf. *Journal of Science and Medicine in Sport, 9,* 433–440.

Gaskin, G.J., & Miller, J.D. (1996). Measurement of soil water content using a simplified impedance measuring technique. *Journal of Agricultural Engineering Research, 63,* 153–160.

Guisasola, I.N., James, I.T., Llewellyn, C.A., Stiles, V.H., & Dixon, S.J. (2010). Quasi-static mechanical behaviour of soils used for natural turf sports surfaces and stud force prediction. *Sports Engineering, 12,* 99–109.

Hennig, E.M., Valiant, G.A., & Liu, Q. (1996). Biomechanical variables and the perception of cushioning for running in various types of footwear. *Journal of Applied Biomechanics, 12,* 143–150.

Holmes, G., & Bell, M.J. (1986). A pilot study of the playing quality of football pitches. *Journal of Sports Turf Research Institute, 63,* 74–91.

James, S.L., Bates, B.T., & Osternig, L.R. (1978). Injuries to runners. *American Journal of Sports Medicine, 6,* 40–50.

McCarthy, P. (1989). Artificial Turf: Does it cause more injuries? *The Physician and Sportsmedicine, 17,* 159–164.

Millet, G., Perrey, S., & Foiussac, M. (2006). The role of engineering in fatigue reduction. In I.E.F. Moritz & S. Haake (Eds.), *The Engineering of Sport 6* (Vol. 3, pp. 209–220). New York: Springer.

Nigg, B.M., Cole, G.K., & Stefanyshyn, D.J. (2003). Impact forces during exercise and sport activities. In B.M. Nigg, G.K. Cole, & D.J. Stefanyshyn (Eds.), *Sport Surfaces: Biomechanics, injuries, performance, testing, installation* (pp. 13–29). Calgary: University of Calgary.

Nigg, B.M., & Segesser, B. (1988). The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. *Sports Medicine (Auckland, N.Z.), 5,* 375–385.

Nigg, B.M., & Yeadon, M.R. (1987). Biomechanical aspects of playing surfaces. *Journal of Sports Sciences, 5,* 117–145.

Orchard, J. (2001). The AFL Penetrometer study: work in progress. *Journal of Science and Medicine in Sport, 4,* 220–232.

Orendurff, M.S., Rohr, E.S., Segal, A.D., Medley, J.W., Green, J.R., & Kadel, N.J. (2008). Regional foot pressure during running, cutting, jumping, and landing. *American Journal of Sports Medicine, 36*(3), 566–571.

Soutas-Little, R.W., Beavis, G.C., Verstraete, M.C., & Markus, T.L. (1987). Analysis of foot motion during running using a joint co-ordinate system. *Medicine and Science in Sports and Exercise, 19*(3), 285–293.

Stiles, V.H., & Dixon, S.J. (2006). The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant. *Journal of Applied Biomechanics, 22*(1), 14–24.

Stiles, V.H., & Dixon, S.J. (2007). Biomechanical response to systematic changes in impact interface cushioning properties while performing a tennis specific movement. *Journal of Sports Sciences, 25*(11), 1229–1239.

Stiles, V.H., Dixon, S.J., Guisasola, I.N., & James, I.T. (2007). Biomechanical response to variations in natural turf surfaces during running and turning. In *"STARSS 2007" Proceedings of the First International Conference of the SportSURF Network*. Loughborough. Retrieved October 1, 2009 from http://www.sportsurf.org/workshops/STARSS/S1/VS.pdf

Stiles, V.H., Dixon, S.J., & James, I.T. (2006). An Initial Investigation of Human-Natural Turf Interaction in the Laboratory. In E.F. Moritz & S. Haake (Eds.), *The Engineering of Sport 6* (Vol. 3, pp. 255–260). New York: Springer.

Stiles, V.H., James, I.T., Dixon, S.J., & Guisasola, I.N. (2009). Natural Turf Surfaces: The Case for Continued Research. *Sports Medicine (Auckland, N.Z.), 39*(1), 65–84.

Torg, J., Quendenfeld, T., & Landau, B. (1974). The shoe-surface interface and its relationship to football knee injuries. *The Journal of Sports Medicine, 2,* 261–269.

Vaughan, C.L., Davis, B.L., & O'Connor, J.C. (1992). *Dynamics of Human Gait* (pp. 10). Champaign: Human Kinetics.

Withers, R.T., Maricic, Z., Wasilewski, S., & Kelly, L. (1982). Match analysis of Australian professional soccer players. *Journal of Human Movement Studies, 8,* 159–176.

Woltring, H.J. (1985). On optimal smoothing and derivative estimation from noisy displacement data in biomechanics. *Human Movement Science, 4*(3), 229–245.