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ORIGINAL ARTICLE

The effect of normal load force and roughness on the dynamic traction developed at the shoe–surface interface in tennis

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Abstract During tennis-specific movements, such as accelerating and side stepping, the dynamic traction provided by the shoe–surface combination plays an important role in the injury risk and performance of the player. Acrylic hard court tennis surfaces have been reported to have increased injury occurrence, partly caused by increased traction that developed at the shoe–surface interface. Often mechanical test methods used for the testing and categorisation of playing surfaces do not tend to simulate loads occurring during participation on the surface, and thus are unlikely to predict the human response to the surface. A traction testing device, discussed in this paper, has been used to mechanically measure the dynamic traction force between the shoe and the surface under a range of normal loading conditions that are relevant to real-life play. Acrylic hard court tennis surfaces generally have a rough surface topography, due to their sand and acrylic paint mixed top coating. Surface micro-roughness will influence the friction mechanisms present during visco-elastic contacts, as found in footwear–surface interactions. This paper aims to further understand the influence micro-roughness and normal force has on the dynamic traction that develops at the shoe–surface interface on acrylic hard court tennis surfaces. The micro-roughness and traction of a controlled set of acrylic hard court tennis surfaces have been measured. The relationships between micro-roughness, normal force, and traction force are discussed.

Keywords Traction · Sport surfaces · Friction mechanisms · Tennis

List of symbols

- c Intercept for linear best-fit between F_t and F_N (N)
- F_N Normal force (N)
- F_t Traction force (N)
- m Gradient of linear best-fit between F_t and F_N
- p Significance level
- R Pearson's correlation coefficient
- R_a Average roughness of a surface profile (μm)

1 Introduction

During tennis-specific movements the traction provided by a shoe–surface combination will influence a player's injury risk and performance [1, 2]. Excessive friction acting between shoe and surface (referred elsewhere in this paper as *traction*) can lead to injury caused by overloading in the lower extremities [3]. Insufficient *static traction* can lead to a *slip* (unwanted movement of the shoe relative to the surface), which will result in a loss of performance or, if the slip is severe, lead to a fall which may cause injury itself [4]. Also, a player may choose to purposefully perform a controlled slide on a tennis surface; a type of movement that is common for clay surfaces, but is becoming increasingly common at elite level on hard courts as well. The success of this type of movement will depend on the *dynamic traction* developed at the shoe–surface interface (the force acting to slow down a shoe moving relative to the surface). The tractional properties of a shoe–surface combination must therefore be within an optimal range [5].

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Elite tennis is played on grass, clay and acrylic hard court surfaces. Nigg [6] reported clay surfaces to have traction/friction coefficients (ratio of horizontal traction force and normal force) of between 0.5 and 0.7, whereas the other surfaces tested had traction/friction coefficients between 0.8 and 1.2. Clay surfaces have generally been reported to have a lower occurrence of injury than acrylic hard court surfaces [6–10]. The difference in injury occurrence between surfaces has been partly attributed to the inherent differing styles of play on each surface caused by differences in ball speed and bounce [6]. However, the differing tractional characteristics of the playing surfaces also affect the risk of accidental injury occurrence [11]. This has lead to the hypothesis that surfaces which do not allow sliding increase the potential to cause injury.

Despite the understanding that shoe–surface traction can influence performance and injury risk there remains a requirement for improved understanding of the tribological interactions at the shoe–surface interface in sport [12]. The aim of this paper is to present experimental data and further investigate the influence the applied normal force and surface roughness have on the dynamic traction developed on acrylic hard court tennis surfaces. Understanding the mechanisms of dynamic traction will aid the improvement of playing surfaces and footwear constructions. Once traction mechanisms are understood, surface properties and/or footwear can be effectively changed to maximise performance and/or minimise injury risk.

The dynamic traction force will be dependent on the friction mechanisms developed between the footwear and the playing surface. Acrylic hard court tennis surfaces are constructed with a top coating of acrylic paint and silica sand mixture. This gives acrylic hard court surfaces a rough surface topography in comparison to other hard surface/flooring systems. The roughness of acrylic hard courts will be dependent on the paint–silica–sand mixture which has been reported to differ between surface manufacturers [13, 14]. Viscoelastic rubbers are generally used on the outsoles of tennis shoes. In clean, dry conditions, sliding contacts between viscoelastic rubbers and a hard solid substrate will result in a combination of the following friction mechanisms: adhesion and hysteresis [15–18]. During interactions where the shoe slides relative to the surface, the micro-roughness of the surface will undoubtedly affect the dynamic traction force developed.

During a horizontal sliding event the asperities of the solid substrate will cause cyclic elastic deformation of the viscoelastic rubber material. Internal damping causes energy dissipation during the loading and unloading cycle [16, 17, 19]. This loss is the hysteretic component of the contributing friction mechanisms. If local stresses deform the rubber beyond its elastic limit, it will be unable to recover. This results in tearing of the material and leads to additional friction forces at the interface between rubber and surface. Tearing can result in wear and cause the separation of fragments of material from the rubber, this is termed abrasive wear.

Adhesion is the process of junctions forming, due to van der Waals' interaction, between the contacting surfaces and the arising friction force is the force required for the junctions to shear [16–22]. Adhesion friction is more prevalent when rubber slides over a smooth surface and depends significantly on asperity contact and therefore the loading conditions and the roughness characteristics of the surface the rubber is sliding relative to. On increasingly rough surfaces the contribution of the adhesive component of traction has been found to decrease due to reduced asperity contact [18, 20, 22].

Asperity contact is also dependent on the normal loading applied during the dynamic sliding event [16, 22]. Figure 1 (adapted from [22]) illustrates how as the amplitude of the surface roughness is decreased, under the same normal loading conditions, surface contact will increase. The compressibility of a viscoelastic material leads to its area in contact to a surface of the same profile being dependent on the normal loading conditions. As normal force increases the rubber compresses against the surface increasing asperity contact, this is illustrated in Fig. 2. Therefore, increased normal force results in greater asperity contact and an increase in the adhesional and hysteretic components of traction.

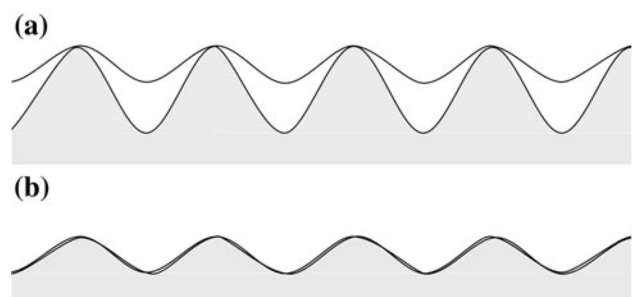

Fig. 1 Rubber–surface contact with identical applied pressure. **a** The rough surface profile prevents the rubber from completely contacting the surface profile. **b** Reduced surface roughness allows increased contact between the two surfaces

Fig. 2 The surface profile shown in Fig. 1a but under increased applied normal load

2 Methods

As discussed, acrylic hard court tennis surfaces are constructed with a mix of silica sand and acrylic paint. The silica sand particle size and the number of acrylic paint coatings can be manipulated to control the roughness of each surface sample. Nine tennis surface samples with different roughness were constructed for this study. Firstly a Perspex sheet (0.5 m $\times$ 0.5 m) was applied with an acrylic paint–silica–sand mix (to provide the surface with its texture) and secondly a coating of only acrylic paint was applied (to provide the surface with an improved aesthetic finish and durability). This resulted in a surface with a long-wavelength surface profile due to the sand particles, overlaid with a finer, short-wavelength surface profile due to the paint [14]. Expertise from a tennis surface construction company (MOR-Sports Tennis Court Construction, Sheffield, UK) was sought to ensure the surfaces were of a professional standard and constructed within a range of roughness/texture that would be accepted for play.

Fifteen roughness profiles of each surface sample were measured at different locations with a laboratory-based Mitutoyo Surftest SV-600 profilometer and analysed using Mitutoyo Surftest-SV Version 1.3. The measurement distance was 10 mm and the speed of the probe was 0.1 mm s^{-1} giving 10,000 data points for each profile. The R_a roughness value of each profile was then determined, which represents the arithmetic average of the profile and in our surfaces will be mainly affected by sand particle size. The means and standard deviations of R_a for each of the surfaces tests are shown in Fig. 3. This procedure was judged as providing a representative roughness measurement of the area of the sample that was to be tested later using the traction rig.

Traction tests were conducted on each surface using a bespoke laboratory-based traction testing device developed

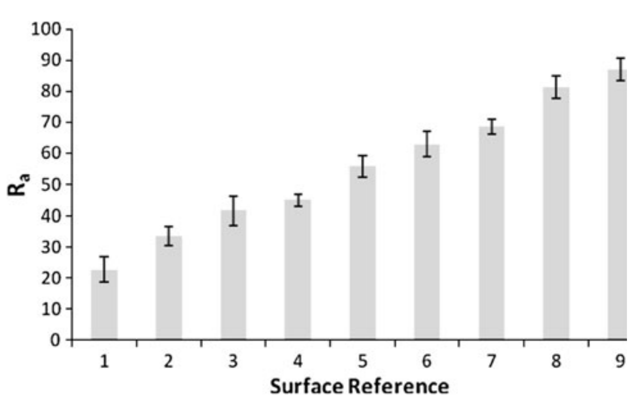

Fig. 3 Plot of mean average surface roughness (R_a, µm) ($\pm$1 SD) for each surface sample (n = 15)

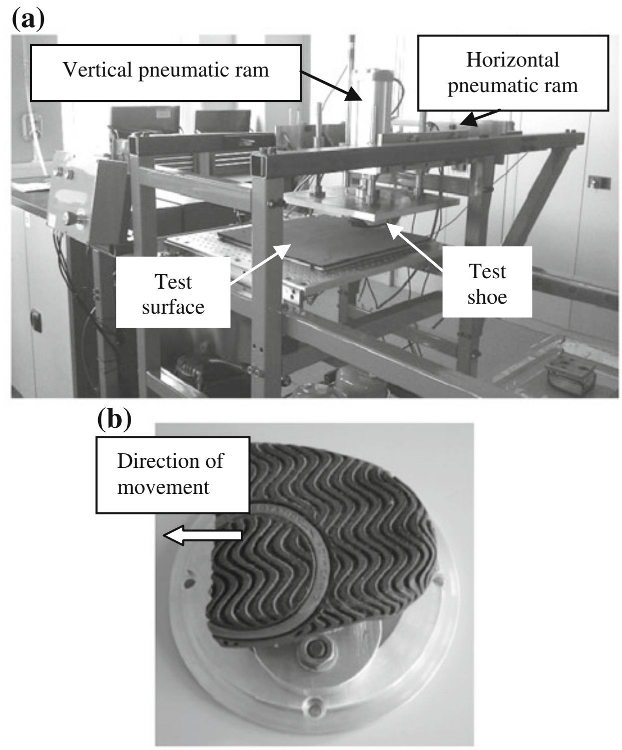

Fig. 4 **a** Bespoke traction testing device. **b** Forefoot segment of the tennis test shoe used for traction testing

at The University of Sheffield (Fig. 4a). This device is force-controlled as opposed to velocity-controlled and a full description of its development is provided in [23]. Firstly a section of a shoe sample was mounted on a plate. A surface sample was then secured on a platform which is slid into place under the shoe sample via a bearing and rail system before being secured. A pneumatic ram provided a controlled normal force to the plate which was held rigidly in place via four rods that were only free to move vertically via sealed cartridge bearings. This provided the device with rigidity and limited deviation in the applied normal force, as reported by Severn et al. [12] with respect to other shoe–surface traction testing methods. Once the desired normal force was reached, through adjustment of a throttle valve, a solenoid valve was opened, allowing the second high-pressure pneumatic ram, to provide a controlled, increasing horizontal force. Load cells in the horizontal and vertical direction and a horizontal linear variable differential transformer (LVDT) provided the necessary measurements to describe traction behaviour. Voltage signals from the load cells and LVDT were sampled simultaneously, via signal conditioning modules (National Instruments model numbers NI9237 and NI9215, respectively) and a data acquisition device (National Instruments model number NI9174) and displayed in real time using LabView (Version 9, National Instruments). The respective signals were sampled at 2,000 Hz and transformed into force and displacement measurements.

The test procedure was designed to best replicate contact between the forefoot of the shoe and the surface. It was assumed that during a push-off movement flexion of the shoe occurs at the metatarsophalangeal (MTP) joint. Therefore, the forefoot segment ahead of the MTP joint of a commercially available hard court tennis shoe (Adidas Barricade 6.0 EU size 42) was attached onto the device for use during all the traction testing (Fig. 4b). The shoe was aligned parallel to the direction of movement and was mounted at an angle 7° between the outsole and the surface. Before testing began the outsole was cleaned with an ethanol solution and allowed to dry at ambient temperature. Prior to testing under each condition, the outsole was prepared by applying P400 silicon carbide paper by hand under minimal pressure as to not change the tread pattern nor the surface texture of the sole. Any debris from the shoe was removed using a clean, soft, dry brush. These procedures are in accordance with parts of BS EN ISO 13287:2007 (International Standard: *Personal protective equipment. Footwear. Test method for slip resistance*). In order to negate the effects of wear, each repeat was conducted on different sections of each surface. Clearly, the surface profile of the outsole is orders of magnitude greater than the acrylic surfaces tested (mm compared to μm) and it was assumed that the roughness of the acrylic surface was able to interact over the apparent contact area of the tread pattern (discussed in further detail in [14]). The deformation in these contacts was also assumed to act predominantly in the shoe outsole, due to its high level of compliance compared to the hard acrylic surface.

As discussed, tribological interactions between visco-elastic material and hard substrate surfaces are dependent on the normal loading condition. In studies investigating shoe–surface traction in sport via mechanical test methods the relationship between normal force and traction is rarely investigated. However, studies have shown that in shoe–surface interactions the normal force will influence the comparative traction between shoe–surface combinations and, therefore, it may be misleading to compare shoe–surface combinations from traction results tested under a single normal load [13, 14, 24]. In order to mechanically test under conditions that best represent real-life play, ground reaction forces from a study conducted by Damm et al. [25] were examined to understand the forces exerted by a tennis player during shoe–surface interactions. Damm et al. [25] measured three-dimensional ground reaction forces of tennis players performing a side jump followed by a push-off movement on an acrylic hard court surface. The mean peak normal force, found during the initial impact phase of the movement, was found to be approximately 1,150 N, and during the phase of forefoot push-off the normal force reduced to relatively constant value of approximately 650 N. Based on this information and the capabilities of the rig it was therefore decided to conduct traction tests in this study under a range of normal forces at intervals from 400 to 1,000 N.

Typical plots of force against horizontal displacement as given by the traction testing device are presented in Fig. 5. The plot in Fig. 5a is characterised by two particular regions: (I) a static region of increasing initial force until a peak is reached and the shoe–surface system effectively fails, (II) a period of dynamic traction during which the traction force remains relatively constant. For this study dynamic traction was taken as the mean dynamic traction force in the horizontal direction between 10 and 30 mm horizontal displacement. Figure 5b shows how the traction force and normal force remain relatively constant during the period where there is considerable sliding motion of the test shoe.

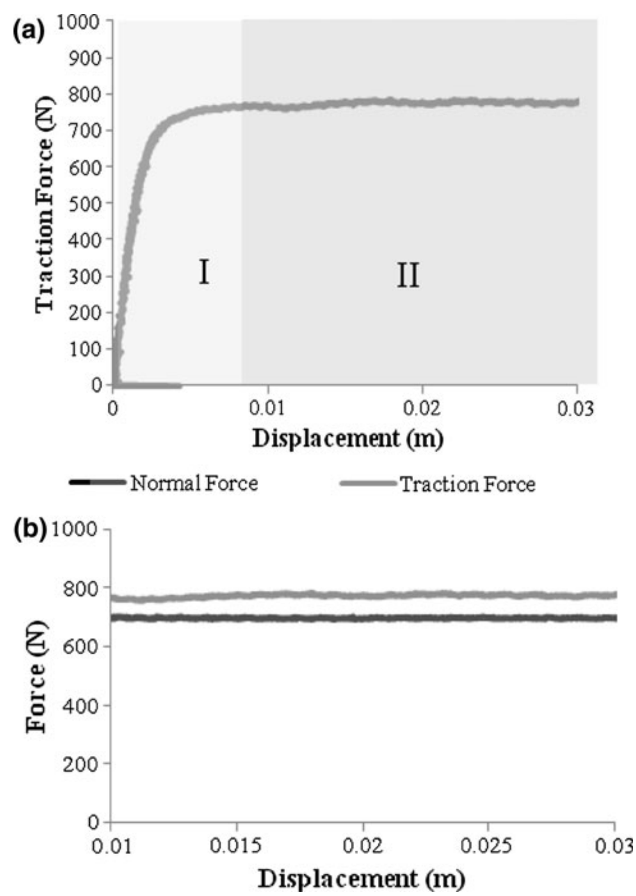

Fig. 5 Typical plots of force against horizontal displacement. **a** Static and dynamic regions. **b** Normal force and traction force during initial dynamic region

3 Results

3.1 Relationship between traction force and normal force

Example plots of normal force against dynamic traction force are shown in Fig. 6. It was found that the relationship between average dynamic traction force and normal force could be described using a linear fit, therefore linear regression analysis was used to analyse the relationships found for the different surfaces. The square of the Pearson correlation coefficient (R^2) was used to determine the strength of the linear correlation between the data sets, as this coefficient tends to 1 the strength of the linear relationship increases. The corresponding p value was used to determine if the linear relationship was statistically significant. If $p < 0.05$ then a significant relationship between the two data sets is said to exist. The results describing the relationships are presented in Table 1.

Strong significant linear relationships were found between normal force and dynamic traction force ($R^2 > 0.9$ and $p < 0.05$) for each surface. The relationships can be described by the equation: $F_t = (mF_N + c)$, where m and c are arbitrary constants and dependent on the particular shoe–surface combination (Table 1). As c is non-zero in the relationships between dynamic traction force and normal force, it can be assumed, there is a region of non-linearity at lower loads. This is in agreement with Tomlinson et al. [26] who reported a two part linear relationship between normal and friction force for viscoelastic contacts.

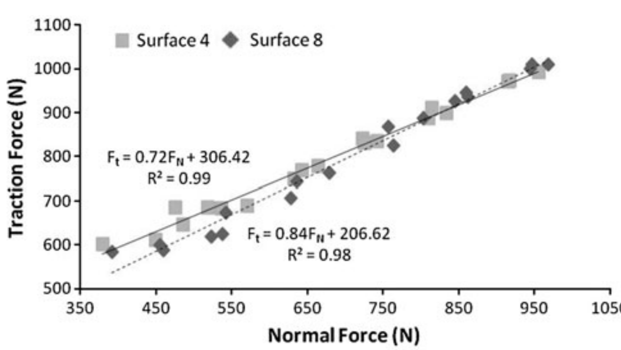

Fig. 6 Plots of normal force against traction force for surfaces 4 and 8

However, the relationships at lower loads are not important when simulating highly loaded sliding movements as carried out in tennis play.

3.2 Relationship between surface roughness, traction force, and normal force

In order to investigate the relationship between surface roughness, traction force, and normal force, the linear relationships described in Table 1 were used to plot the dynamic traction force against mean average roughness (R_a) for normal loading conditions at 100 N intervals (Fig. 7). Figure 7 shows how the relationship between roughness and traction force is dependent on normal force. Under high loading (e.g. 1,000 N) there is a trend for the traction force to initially decrease with roughness, reach a minimum and then increase again. However, as the normal load decreases (e.g. 500 N) there is a trend for the traction force to initially increase with roughness, reach a maximum and then decrease. This behaviour can be explained using the theory of hysteretic and adhesive friction mechanisms for rubber–surface sliding contacts.

4 Discussion

The compressibility of a viscoelastic material, such as rubber, leads to its asperity contact interaction with a surface being dependent on the normal loading condition. As normal load increases, rubber compresses against the surface increasing asperity interaction. Therefore, as observed in the results, the traction force increases linearly with increased normal force.

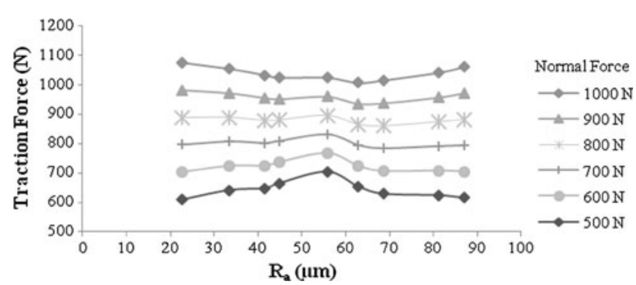

Fig. 7 Plot of the mean average surface roughness (R_a) against dynamic traction force for each normal loading condition

Table 1 Relationships between normal force and traction force for each surface

Surface	1	2	3	4	5	6	7	8	9
m	0.93	0.83	0.77	0.72	0.64	0.71	0.77	0.84	0.89
c	143.77	228.91	262.22	306.42	383.36	299.60	243.28	206.62	169.27
R^2	0.99	0.97	0.98	0.99	0.95	0.98	0.92	0.98	0.96

It might be expected that traction force, under all normal loading conditions, would increase with surface roughness as the energy dissipated via hysteretic friction mechanisms increases. However, under high loads (e.g. 1,000 N), initially (22.72 μm ≤ average R_a ≤ 62.89 μm) the opposite trend is observed in the results. Persson [16, 22] notes that the influence of adhesion on friction increases with normal load as asperity contact, and hence adhesional bonds, increase. Also, Palasantzas [17, 20] shows that the adhesion component of traction dominates at low roughness values. Therefore, under high normal loading and low roughness conditions, the adhesion component of the friction mechanisms is likely to be dominant. What the results in this study may be showing, therefore, is that under these conditions, as roughness is initially increased the rubber is less able to fully interact with the surface profile and the asperity contact is reduced. Hence a reduced number of adhesional junctions form, explaining the initial decrease in the dynamic traction force observed in the results. However, as roughness continues to increase at high loading conditions (e.g. average R_a > 62.89 μm at the 1,000 N condition) there is then a transition point at which the traction force begins to increase. This transition will be at the point at which the hysteretic component of friction begins to dominate the interaction. As roughness increases the hysteretic component of friction becomes increasingly dominant, hence the traction force increases.

Under low normal loads (e.g. 500 N) the hysteretic component of the friction mechanisms may be dominating the interaction as the number of adhesional junctions decrease and have less influence than when under high normal loading [16, 21]. Reduced asperity interaction under the lower applied load reduces the influence of adhesion. Under the 500 N loading conditions, Fig. 7 shows the dynamic traction force initially increases with roughness (22.72 μm ≤ average R_a ≤ 55.77 μm) as additional energy is dissipated as the viscoelastic rubber outsole deforms and recovers when sliding over increasingly rough surface profiles. However, as the surface roughness continues to increase (average R_a > 55.77 μm at the 500 N condition) the dynamic traction force decreases. Persson [21, 22] notes that if the normal load is not sufficiently high, as roughness increases, the rubber may not deform and interact with the full surface profile, reducing asperity contact. The effect will result in a plateauing of the hysteretic component of friction and a decrease in adhesion caused by a reduction in asperity contact. This effect explains the reducing dynamic traction force observed in the results. If roughness was increased to values higher than those in this study (average R_a > 86.97 μm) a plateauing of the traction force might be observed at low normal loading as the roughness reaches a point at which the hysteric component plateaus and asperity contact (adhesion friction) becomes constant.

The results highlight the influence that the average roughness and applied normal force will have on the dynamic traction experienced in tennis play. During the impact phase of a typical jump and push-off movement, a time at which the player exerts a peak normal force, the player requires traction to decelerate [25, 27]. Whereas during the push-off phase, the player exerts a lower, controlled, and relatively constant normal force [25]. High traction forces during the impact phase may lead to injury caused by excessive forces in the lower extremities. During either the impact or push-off phase, insufficient static traction may lead to the onset of an unwanted slip and coupled with insufficient dynamic traction would lead to development of considerable slipping (or sliding that is uncontrolled). It could be argued, from analysing the results in this study, that surface 5 provides optimal properties. During high loading it offers comparatively low traction (reduction in injury risk during impact phase) but under low loading it provides high traction (increased performance during push-off phase). However, the severity of a slip will depend on the dynamic traction force developed at the shoe–surface interface and its low traction under high loading means surface 5 may cause slipping during the impact phase. Further work is required, with appropriate rig development, to better understand the traction thresholds at which players might slip, or lose control of a sliding movement, to the extent that injury risk becomes unacceptable. This may require a more combined approach between biomechanics studies and mechanical testing, such that a test rig is capable of changing the loads applied as would occur in response to the loads experienced during an actual movement.

Any wearing of an acrylic hard court over time will lead to a reduction in roughness as the surface material deteriorates. A court will generally experience sporadic wear as during play some regions of the court (e.g. the baseline regions) are occupied by the players for greater periods of time. The results in this study show that a tennis court with significant variations in its surface roughness could be dangerous to the player as any sudden changes in traction that the player fails to adapt for could lead to either excessive or insufficient traction forces.

Sporadic wear will also influence any attempts by a player to purposefully perform a controlled slide on a surface as part of their technique during play. Such sliding technique is extremely common on clay courts of low traction characteristics and has recently been increasingly observed during play on acrylic hard courts, especially by highly experienced players at the elite level of the game. For example, should the player succeed in sliding by exerting 500 N normal force on a region of the court with mean average roughness of 22.72 μm (surface 1) and then attempt the same slide on a region with mean average roughness of 55.77 μm (surface 5) they will experience a higher dynamic traction force which may lead to injury. It is therefore recommended that the traction characteristics over the entire court be examined as part of any measures taken to assess the traction of a tennis court.

5 Conclusions

Significant linear relationships exist between normal force and traction force under the normal loading conditions investigated in this study (400–1,000 N).

Surface roughness and normal force affect the influence of the friction mechanisms (adhesion and hysteresis) present during a sliding movement. The applied normal force during a tennis slide and the surfaces average roughness (R_a) will therefore significantly affect the traction force experienced by a tennis player during play. It is therefore recommended that these parameters are considered when understanding the traction of acrylic hard court tennis surfaces in relation to the performance and injury risk of players.

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References

1. Frederick EC (1986) Kinematically mediated effects of sport shoe design: a review. J Sports Sci 4:169–184
2. Reinschmidt C, Nigg BM (2000) Current issues in the design of running and court shoes. Sportverletzung-Sportschaden 14(3): 71–81
3. Wannop JW, Worobets JT, Stefanyshyn DJ (2010) Footwear traction and lower extremity joint loading. Am J Sports Med 38(6):1221–1228
4. Tisserand M (1985) Progress in the prevention of falls caused by slipping. Ergonomics 28(7):1027–1042
5. Milburn PD, Barry EB (1998) Shoe–surface interaction and the reduction of injury in rugby union. Sports Med 25(5):319–327
6. Nigg B (2003) Injury and performance on tennis surfaces. The effect of tennis surfaces on the game of tennis. http://es.hartru.com.planitapps.com/uploads/downloads/Doc_7.pdf. Accessed 22 April 2013
7. Hutchison MR et al (1995) Injury surveillance at the USTA Boys' Tennis Championships: a 6-yr study. Med Sci Sports Exerc 27(6):826–830
8. Nigg BM, Segesser B (1988) The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. Sports Med 5(6):375–385
9. Kulund DN et al (1979) Tennis injuries: prevention and treatment. Am J Sports Med 7(4):249–253
10. von Salis-Soglio G (1979) Sportverletzungen and Sportschäden beim Tennis (sport injuries in tennis). Deutsche Zeitschrift för Sportmedizin 8:244–247
11. Dixon SJ, Batt ME, Collop AC (1999) Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects. Int J Sports Med 20(4):209–218
12. Severn KA et al (2011) Science of synthetic turf surfaces: investigating traction behaviour. Proc Inst Mech Eng Part P J Sports Eng Technol 225(3):147–158
13. Clarke J et al (2011) Understanding the traction of tennis surfaces. Procedia Eng 13:402–408
14. Clarke J et al (2012) Understanding the influence of surface roughness on the tribological interactions at the shoe–surface interface in tennis. Proc Inst Mech Eng Part J J Eng Tribol 226(7):636–647
15. Gronqvist R et al (2003) The validity and reliability of a portable slip meter for determining floor slipperiness during simulated heel strike. Accid Anal Prev 35(2):211–225
16. Persson BNJ (2001) Theory of rubber friction and contact mechanics. J Chem Phys 115(8):3840–3861
17. Palasantzas G (2004) Influence of self-affine roughness on the adhesive friction coefficient of a rubber body sliding on a solid substrate. Surf Sci 565(2–3):191–196
18. Persson BNJ (2006) Rubber friction: role of the flash temperature. J Phys Condens Matter 18(32):7789
19. Persson BNJ, Bucher F, Chiaia B (2002) Elastic contact between randomly rough surfaces: comparison of theory with numerical results. Phys Rev B 65(18):184106
20. Palasantzas G (2005) Comparison of hysteric and adhesive coefficient of friction for rubbers sliding onto self-affine rough surfaces. J Appl Phys 97(3):4
21. Persson BNJ (2001) Elastoplastic contact between randomly rough surfaces. Phys Rev Lett 87(11):116101
22. Persson BNJ (1998) On the theory of rubber friction. Surf Sci 401(3):445–454
23. Clarke J et al (2013) The development of an apparatus to understand the traction developed at the shoe–surface interface in tennis. Proc Inst Mech Eng Part P J Sports Eng Technol. doi: 10.1177/1754337112469500
24. Nigg BM (1990) The validity and relevance of tests used for the assessment of sports surfaces. Med Sci Sports Exerc 22(1): 131–139
25. Damm L et al (2011) Modulation of tennis players' frictional demand according to surface traction characteristics in International Society of Biomechanics Congress XXIII. Brussells
26. Tomlinson SE, Lewis R, Carré MJ (2009) The effect of normal force and roughness on friction in human finger contact. Wear 267(5–8):1311–1318
27. Stiles VH, Dixon SJ (2006) The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant. J Appl Biomech 22(1):14–24