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The influence of surface characteristics on the tribological interactions at the shoe-surface interface in tennis

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Abstract

During dynamic tennis specific movements, such as accelerating and side stepping, the traction provided by a 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 due to an increased traction coefficient. There is a requirement for an improved scientific understanding of the tribological interactions at the shoe surface interface and the effects footwear and surface parameters have on the friction mechanism developed.
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 human response to the surface. A new traction testing device, discussed in this paper, has been developed to mechanically measure the traction force between the shoe and the surface under appropriate loading conditions.
Acrylic Harcourt tennis surfaces generally have a rough surface topography, due to a sand and acrylic paint mixed top coating, and have a deformable under layer to provide impact attenuation. Surface micro-roughness has been found to influence the friction mechanisms presents during viscoelastic contacts, as found in footwear-surface interactions. This paper aims to further understand the influence of micro-roughness on tennis surfaces. The micro-roughness and traction of a controlled set of acrylic hard court tennis surfaces have been measured. The influence of roughness on tennis surfaces traction is discussed.

Keywords: Traction; sport surfaces; friction mechanisms; tennis

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1. Introduction

During dynamic tennis specific movements the traction provided by a shoe-surface combination plays an important role in the injury risk and performance of the player [1, 2]. The tractional properties of a shoe-surface combination must therefore be within an optimal range [3]. Insufficient traction will cause a slip, which will result in a loss of performance or, if the slip is severe, lead to a fall which may cause injury itself.

Tennis is played on a variety of surfaces. Elite tennis is played on grass, clay and acrylic hard court surfaces. Nigg (2003) reported clay surfaces to have traction/friction coefficients (ratio of horizontal traction force and normal force) of between 0.5 - 0.7 whereas the other surfaces tested had traction/friction coefficients between 0.8 – 1.2 [4]. Clay surfaces have generally been reported to have a lower occurrence of injury, whereas acrylic hard court surfaces have been reported to have increased injury occurrence [4-8]. The difference in injury occurrence between surfaces has partly been attributed to the inherent differing styles of play on each surface caused by differences in ball speed and bounce [4]. However, the tractional characteristics of the playing surface also affect the risk of accidental injury occurrence [9]. This has lead to the hypothesis that surfaces which do not allow sliding also increases the potential to cause injury. There is therefore a requirement for improved scientific understanding of the tribological interactions at the shoe-surface interface in sport [10].

The traction force will be dependent on the friction mechanisms developed between the footwear and the playing surface. Viscoelastic rubber is 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 [11-14]. Therefore, during dynamic footwear-surface interactions, the micro roughness of the surface will undoubtedly affect the traction. During a horizontal sliding event the asperities of the solid substrate cause cyclic elastic deformation of the viscoelastic rubber material. Internal damping causes energy dissipation during the loading and unloading cycle [12, 13, 15]. 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 [12-18] and the arising friction force is the force required for the junctions to shear. 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 [14, 16, 18].

This paper presents experimental data with an aim to further investigate the influence surface roughness has on the traction of hard-court tennis surfaces. Understanding how traction is developed 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.

Nomenclature

COT coefficient of traction

c	arbitrary constant
F_t	Traction Force
m	arbitrary constant
F_N	normal force (N)
R_a	average roughness of a surface profile (μm)

2. Method

Acrylic hard court tennis surfaces are made from a mix of silica sand and acrylic paint. Via controlling the silica sand particle size and the number of acrylic paint coatings the surfaces can be manipulated to control the roughness of each surface sample. Nine tennis surface samples with varied roughness were constructed for this study. Ten profiles of each surface sample were measured 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 mms^{-1} giving 10000 data points in total. The mean average arithmetic roughness (R_a) of each surface sample was then determined.

Traction tests were conducted on each surface using a bespoke traction testing device developed at The University of Sheffield (Figure 1a). A pneumatic ram provides a controlled normal force to a test foot. A high-pressure pneumatic ram provides a controlled driving force in the horizontal direction. A solenoid valve is opened, opening the pneumatic cylinder, to provide a controlled dynamic horizontal force. Load cells in the horizontal and vertical direction and a horizontal linear displacement voltage transducer (LDVT) provide the necessary measurements to describe traction behaviour. Voltage signals from the load cells and LDVT are sampled simultaneously, via a data acquisition device (National Instruments) and displayed in real time using LabView (Version 9 National Instruments). The respective signals are sampled at 2000 Hz and transformed into force and displacement measurements. The forefoot segment of a commercially available tennis shoe was attached onto the device for use during traction testing (Figure 1b). Traction tests were conducted under a range of normal forces (500 N – 1000 N) and each repeat was conducted on a different section of the surface. Typical plots of force against horizontal displacement are presented in Figure 2. The traction force remains relatively constant during the horizontal movement of the test foot. Traction was taken as the mean dynamic traction force in the horizontal direction between 10 mm and 30 mm horizontal displacement. The plot is characterised by two particular regions: (I) a region of increasing initial force during a static regime, (II) a period of dynamic traction during which the force remains relatively constant.

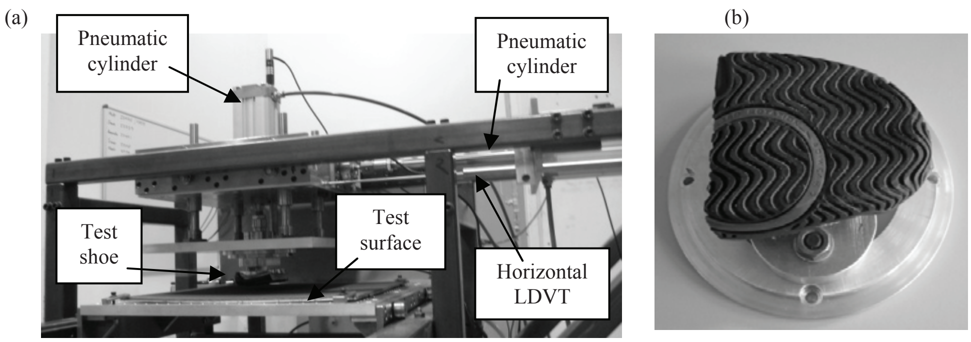

Fig. 1. (a) Bespoke traction testing device; (b) Forefoot segment of the tennis test shoe used for traction testing

(a) (b)

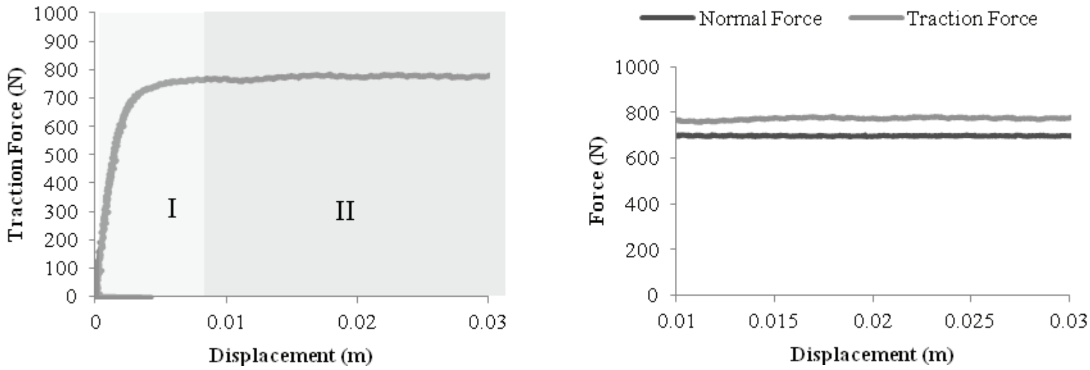

Fig. 2. Typical plots of force against horizontal displacement. (a) Static and dynamic regions. (b) Normal Force and Traction force during initial dynamic region

3. Results

Strong significant linear relationships were found between normal force and dynamic traction force ($R^2 > 0.95$ and $p < 0.05$) for each surface. Each relationship was specific to the particular shoe-surface combination. The relationships can be described by the equation: $F_t = (mF_N \pm c)$, 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. However, the relationships at lower loads are not relevant when simulating high loading dynamic movements carried out in tennis play.

The relationships were used to plot the mean average roughness (R_a) against dynamic traction force for each loading condition (Figure 3). Figure 3 shows the relationship between roughness and traction force is dependent on the normal load. There is a trend for the traction force to initially decrease with roughness, reach a minimum and then increase as normal load increases. However, as the normal load decreases there is a trend for the traction force to initially increase with roughness, reach a maximum and then decrease.

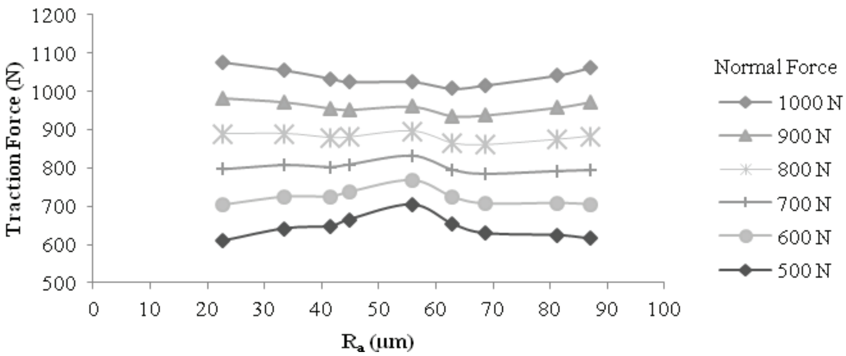

Fig. 3. Plot of the mean average surface roughness (R_a) against dynamic traction force for each normal loading condition

4. Discussion

The compressibility of a viscoelastic material leads to its asperity contact interaction with a surface of the same roughness being dependent on the normal loading condition. As normal load increases, rubber compresses against the surface increasing asperity interaction. Therefore, increased load is likely to increase the influence of the adhesion component of the friction mechanisms.

Under high loads (e.g. 1000 N) the adhesion effect initially decreases the dynamic traction force with increased surface roughness, as the rubber is unable to fully interact with the surface and asperity contact is reduced. However, 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. Reduced asperity interaction under the lower applied load reduces the influence of adhesion. Hence the dynamic traction force initially increases as additional energy is dissipated as the viscoelastic rubber outsole deforms and recovers as it slides over increasingly rough surface profiles. However, as the surface roughness continues to increase the dynamic traction force decreases and may plateau with further roughness. Persson (1998 and 2001) 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 [17, 18]. The effect will result in a plateauing of the hysteretic component of friction and a reduction in adhesion. This effect explains the reducing dynamic traction force observed in the results.

5. Conclusions

Significant linear relationships exist between normal force and traction force under the normal loading conditions investigated in this study (500 N – 1000 N).

Surface roughness and normal force affect the influence of the friction mechanisms (adhesion and hysteresis) present during a dynamic 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. 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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