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Friction at the tennis shoe-court interface: how biomechanically informed lab-based testing can enhance understanding

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Abstract

This paper presents some of the methodology, observations and findings from a 30-month study, aiming to improve the understanding of tennis shoe-court interactions and the biomechanical implications of changes in friction between the shoe and surface. A detailed programme of biomechanical player testing on different court surfaces provided the boundary conditions with which to develop a lab-based rig capable of simulating the key aspects of shoe-surface interaction that are required for acceptable performance (e.g. push-off to accelerate) within expected levels of consistency (e.g. for a controlled slide). Large-scale parametric testing could then be carried out for a variety of surface types and components under a range of loading conditions, without the risk of injury to human participants. Two case studies are described to demonstrate the value of a combined approach of biomechanical field testing and lab-based rigs that simulate shoe-court interactions. These include a study that compared different artificial clay court designs; and a study that examined the effect of different acrylic hard court parameters on friction and the tribological mechanisms that explain the observed interaction

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1. Introduction

The interaction between tennis shoes and courts is a highly complicated problem, with a range of player movement requirements (e.g. push-off, side-step, controlled slide) on a variety of surfaces that display very different mechanical properties (e.g. acrylic, grass and clay) under changing conditions (e.g. moisture, wear). The traction provided by a shoe-surface combination will influence a player's injury risk and performance (Frederick, 1986; Reinschmidt & Nigg, 2000). Excessive friction (or *traction*) acting between shoe and surface can lead to injury caused by overloading in the lower extremities (Wannop *et al*., 2010). Insufficient 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. Also, a player may choose to purposefully perform a controlled slide on a tennis surface.

A 30-month research programme was carried out to link biomechanical measurements with a mechanical testing approach, aiming to simulate important aspects of the movements in a repeatable way. This combined approach has potential to improve the understanding of tennis shoe-court interactions and the implications of changes in surface parameters, and consequently, traction. This paper presents some of the methodology used, along with some observations and findings.

Nomenclature

AHC	Acrylic Hardcourt
ACC	Artificial Clay Court
COF_u	Utilised Coefficient of Friction
F_z	Vertical component of Ground Reaction Force (N)
F_{shear}	Horizontal component of Ground Reaction Force (N)
GRF	Ground Reaction Force (N)
R_a	Arithmetic surface roughness (μm)

2. Biomechanical Studies

In order to provide boundary condition data for the mechanical test rig, a number of biomechanical studies were carried out, all incorporating the collection of ground reaction force (GRF) data from tennis players performing typical movements on different surfaces. Data was collected using an force plate sampling at 960 Hz. In one study, twelve competitive tennis players (7 male, 5 female; age 20.5 ± 2 years; body mass 64.4 ± 14.3 kg), who were free from injury volunteered to participate. Their British rating, corresponding to International Tennis rating (ITF, 2004) varied from 3.3 (top division county players) to 8.2 (players competing regularly in singles and/or doubles tournaments). The study was approved by the ethics committee of the School of Sport and Health Sciences at the University of Exeter and appropriate informed consent questionnaires were obtained prior to testing. Three surface conditions were tested; one acrylic hard court (AHC) and two artificial clay courts (ACC1 and ACC2), as described in Table 1. Surfaces were glued to a concrete laboratory floor forming a continuous runway over the force plate. Players wore Adidas Barricade 6.0 shoes for all surface conditions. Further kinematic data was also collected in other studies such as that described in (Damm *et al.*, 2011 and 2013). Five trials were collected for each of three movements: a running forehand, a turn and a stop. Timing gates positioned before the force plate provided an initial indication of trial reliability when running. For the turning and stopping movements, the participants were required to run at a minimum speed of 4 $m.s^{-1}$ ± 5%. Once familiar with the movement and surface, the participants performed 5 movements in each condition.

Table 2 displays the averages of the vertical and horizontal GRF components from the trials (F_z and F_{shear}) and the Utilised Coefficient of Friction (COF_u), calculated as the ratio between F_z and F_{shear}. Comparison of F_{shear} revealed a consistent effect of the surfaces, significant at $p<0.001$ for all three movements. Peak F_{shear} was greater on both clay surfaces compared to the hard court, whereas no significant differences was detected for F_z across the surfaces. Consequently, significantly greater values of COF_u were also found on the clays compared to the hard court, indicating that players were "pushing" these surfaces towards their limiting values of friction. This could be because they were more confident in their safety or were actively trying to slide on the clay surfaces, or even a combination of these factors. Either way, the data showed that the surface types greatly affected the way that players interacted with them.

Table 1. The three surface conditions tested, with slip resistance values obtained using a pendulum test.

Reference	Description	Slip Resistance Value
AHC	Textured acrylic hard court . Thickness of 12 mm (with recycled SBR rubber mat layer).	67.0 ± 1.8
ACC1	Synthetic fibre bonded membrane (carpet) with traditional clay infill and dressing. Clay particle size approx 4 μm diameter, quantity approx 7 kg/m^2 to fill up the fibres completely and cover them with a 12 mm thick layer.	56.7 ± 1.5
ACC2	A polypropylene fibrillated membrane (carpet) with sand dressing. Pile weight is 700 g/m^2 and pile height is 11 mm. Sand particle size approx 70 μm diameter, quantity approx 12 kg/m^2 giving a total height of 13 mm.	60.7 ± 3.5

Table 2. Summarised GRF data for each movement on the three surfaces (* indicate significant differences between surfaces)

Measure	Forehand			Turn			Stop		
	AHC	ACC1	ACC2	AHC	ACC1	ACC2	AHC	ACC1	ACC2
F_z (N)	1481.0 ± 526.2	1331.0 ± 365.1	1237.3 ± 351.3	1431.2 ± 592.8	1318.7 ± 500.0	1245.1 ± 480.5	1832.1 ± 645.7	1679.0 ± 712.2	1661.1 ± 734.2
F_{shear} (N)	205.4 ± 163.1*	519.7 ± 135.0	486.5 ± 84.9	204.8 ± 182.6*	485.8 ± 155.2	468.0 ± 107.2	252.0 ± 179.7*	588.7 ± 178.0	582.3 ± 167.9
COF_u	0.14 ± 0.04*	0.42 ± 0.04	0.42 ± 0.02	0.14 ± 0.04*	0.40 ± 0.03	0.40 ± 0.03	0.15 ± 0.04*	0.40 ± 0.04	0.40 ± 0.05

3. Development of Traction Rig

After comparing different mechanical test approaches (Clarke *et al.*, 2012), biomechanical data, including that discussed here previously, was used to develop a mechanical test device, the UoS Shoe Traction Rig. This was to allow repeatable and reliable traction tests on a range of tennis surfaces with varying parameters (Clarke *et al.*, 2013a). The initial aim of this device was to measure the traction developed at a normally loaded shoe-surface interface, as an applied shear force is gradually increased. The results from this device could then be used to compare the surfaces and predict how they would perform in situations with different traction requirements.

(a) (b)

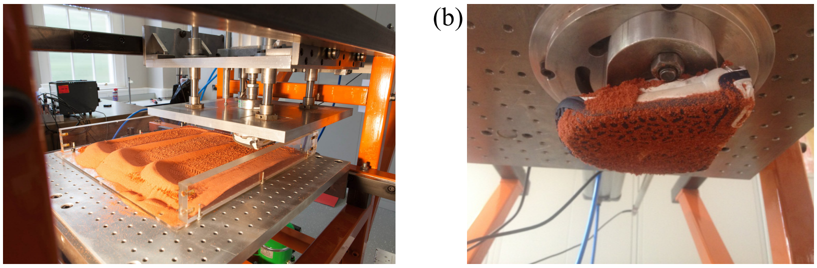

Fig. 1. (a) UoS Shoe Traction rig; (b) Shoe plate with forefoot section of shoe attached.

The rig is shown in Fig. 1. A surface sample is first secured on an adjustable platform and the vertical pneumatic ram then provides a controlled normal force to the shoe plate (with the relevant section of a shoe sample attached, in contact with the surface) which is held rigidly in place via four rods that are only free to move vertically via sealed cartridge bearings. Once the desired normal force has been reached, using a throttle valve, a second pneumatic ram provides a controlled driving force in the horizontal direction. A solenoid valve is then operated, opening the pneumatic cylinder to provide a horizontal force. The applied horizontal force increases until sliding is initiated when the test shoe assembly moves horizontally on low friction roller bearings for a maximum sliding length of 250 mm. Load cells in the horizontal and vertical direction and a horizontal linear variable differential transformer (LVDT) provide the necessary measurements to describe traction behaviour. All measurement data is sampled at 2000 Hz and later transformed into force and displacement measurements (see typical data in Fig. 2).

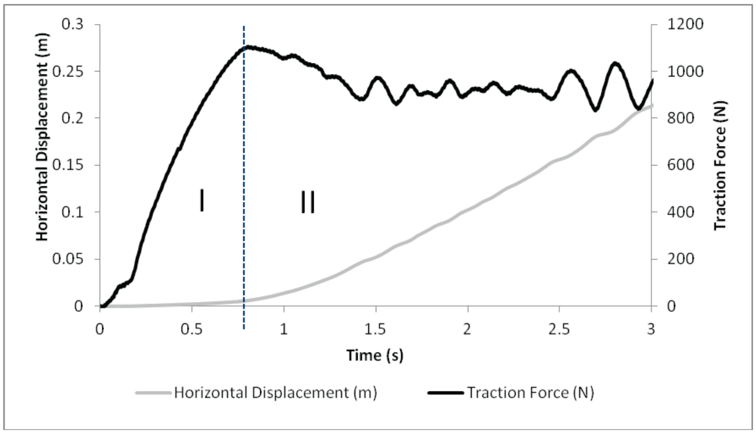

Fig. 2. Typical data collected from UoS Rig using a wet clay surface (ACC1) and a constant normal load of approx. 1.5 kN. (I) a region of increasing initial force during a static regime, (II) a period of dynamic traction during which the force remains relatively constant. Reproduced with kind permission from Clarke *et al.* (2013a).

4. Case studies

4.1. Comparison of Acrylic Hard Court (AHC) and Artificial Clay Court (ACC) surfaces

All three surfaces used in the biomechanical study (see Table 1) were reproduced for use with the UoS Shoe Traction rig and tests were carried out with the same design of shoe (Adidas Barricade 6.0) for a range of normal loads approximately 900 N to 1500 N (see Table 2 for comparison with F_z biomechanical data). The test set-up was designed to best replicate the critical contacts at which traction is essential in most tennis movements (forefoot impact and forefoot propulsion) where flexion of the shoe occurs at the Metatarsal-Phalangeal (MP) joint. The test shoe was therefore cut across the MP joint line and then attached onto the shoe plate so as to set the contact angle between the outsole and the surface at 7° (see Fig. 1b). For these tests, the shoe was rotated 90° to the direction of movement in order to replicate the likely shoe orientation during a side jump movement (Damm *et al.*, 2011). For full details of the testing including shoe and surface preparations see Clarke *et al.* (2013a). It was decided in this study to test the surfaces in completely dry conditions and then add water to each surface to compare wet and dry conditions. The "wet" condition aimed to simulate 24 minutes of play in light rain (total of 1 mm of rainfall) and water was added using a calibrated hand-sprayer.

Many aspects of traction behaviour were examined in the study including the initial 'shear stiffness' of the system, defined as the average ratio of traction force and horizontal displacement during the static regime (see Fig. 2); the peak traction force at the transition between the static and dynamic traction regimes; and the mean dynamic traction, measured between a sliding displacement of 0.05 and 0.20 m. Some example peak traction force data is presented in Fig. 3 showing that the ACC surfaces tested generally provide less traction than the AHC surface, broadly in line with the pendulum slip resistance data in Table 1. Interestingly, as discussed in section 2, players were observed to apply high shear forces on the ACC surfaces, despite the lower level of traction available. This strengthens the argument that they felt confident enough to move safely, or purposefully slide in a controlled manner.

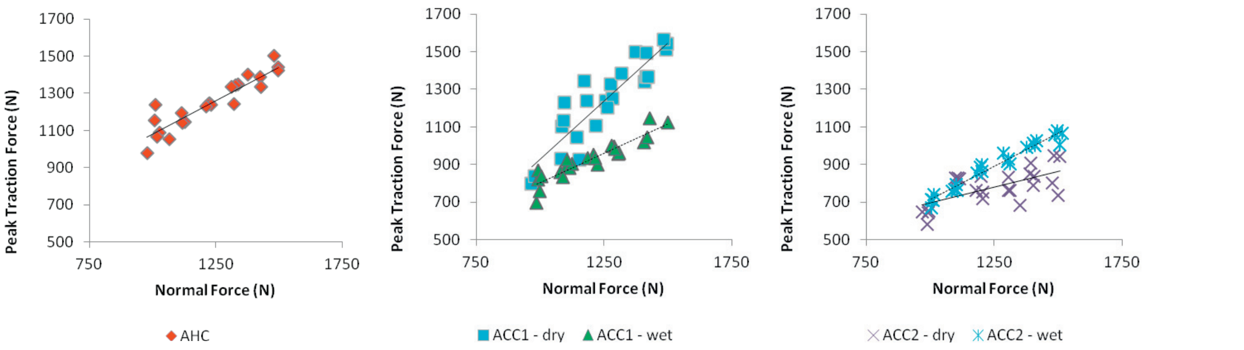

Fig. 3. Peak Traction vs Normal Force data collected from the 1st case study using the five different surface conditions. Reproduced with kind permission from Clarke *et al.* (2013a).

The case study also revealed that infill particle size used in an artificial clay surface will significantly influence the traction developed at the shoe surface interface (e.g. comparing Fig 3 b and c). Clay particles (ACC1) will bond in wet and dry conditions and the initial stiffness and peak traction will be dependent on the normal force applied to the surface by the shoe. Larger sand particles (ACC2) will exhibit reduced traction caused by a reduction in shear strength. Surfaces with large sand particles will develop lower traction in dry than in wet conditions as the particles are unable to cohere and therefore act as single entities. In dry conditions and under increased normal loading, the traction developed at the shoe-surface interface on an artificial clay surface may be greater than an acrylic hard court surface.

4.2. Acrylic Hard Court study

A 2nd case study (Clarke *et al.*, 2013b) included nine different acrylic hard court tennis surface samples constructed with a mix of silica sand and acrylic paint where the particle size and the number of paint coatings were manipulated to control the roughness. Traction testing was carried out in a similar way to the 1st study, with the same test shoe. This time the range of normal loads was 500 to 1000 N and the shoe was orientated to be in line with the direction of sliding (i.e. travelling backwards when driven to slip during a push-off movement).

For all tests on these AHC samples the peak traction force was very similar to the average dynamic traction force, i.e. there was no pronounced peak as seen in Fig. 2. The relationship between dynamic traction force and surface roughness (measured as R_a) is shown in Fig. 4. The study highlighted the complex combined influence that the roughness and applied normal force (F_z) will have on the traction experienced in play. Theoretical tribological mechanisms were considered and it was hypothesised that for low normal loads (e.g. 500 N) the hysteretic component of the friction mechanisms dominated the shoe-surface interaction, as reduced asperity interaction reduces the influence of adhesion. Under these low normal loads the traction force initially increases with roughness as additional energy is dissipated through hysteresis (loading and unloading of the elastomer in the shoe sole). However, as the surface roughness continues to increase the shoe may not deform sufficiently to interact with the full surface profile, reducing asperity contact and the adhesion component of friction. For this reason, slightly different behaviour may be found with shoes of another material or with different tread profiles.

Under high loads (e.g. 1000 N), the opposite trend is observed in the results (see Fig. 4). Now it was hypothesised that the adhesion component of the friction mechanism is likely to be dominant and as roughness is initially increased the shoe is at first less able to fully interact with the surface profile reducing the number of adhesional junctions formed. However, as roughness continues to increase there is a transition point at which the hysteretic component of friction begins to dominate the interaction and the traction force increases. These hypotheses are explained more fully in Clarke *et al.* (2013b).

It should be pointed out that the non-linear behaviour of the elastomer shoe materials also mean that loading rate is likely to have an effect - something which has not been examined in detail in the studies described here. Further work is needed on this subject to allow better comparisons of test rig and player data.

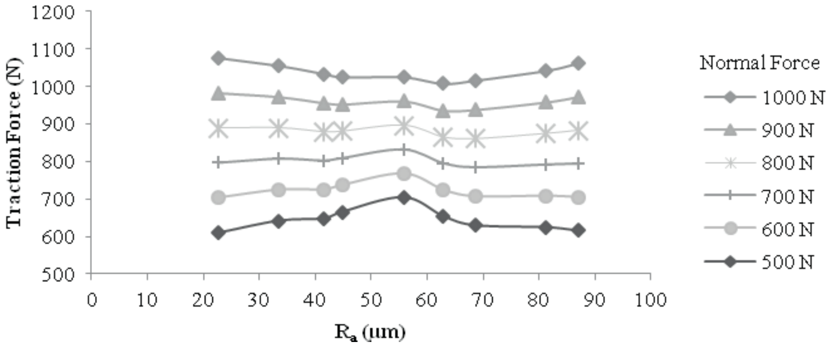

Fig. 4. Data collected from the 2nd case study showing how Traction Force varies with hardcourt surface roughness, under differing levels of Normal Load. Reproduced with kind permission from Clarke *et al.* (2013b).

5. Conclusions

The findings from the case studies described above demonstrate the potential for a biomechanically-informed test rig approach to improving the understanding of tennis shoe-surface interactions.

The 1st case study demonstrated how different court surface types behaved and the effect of particle size and moisture in artificial clay court designs, which could be compared with a biomechanical study on the same surfaces. The 2nd case study showed how surface roughness of acrylic hardcourts and the applied normal force affect the influence of the friction mechanisms (adhesion and hysteresis) present during a sliding movement. This shows the importance of testing at relevant loads, as informed by biomechanical testing. All these parameters need to be carefully considered in relation to traction of tennis surfaces and the consequent performance and injury risk of players.

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