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Tennis shoe outsole temperature changes during hard court sliding and their effects on friction behaviour

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Abstract

Tennis is a sport played around the world on a variety of surfaces like grass, clay and hard courts. The types of surface and the surface properties influence the movements that are used by players. On hard courts, players have recently increased their tendency to perform sliding movements, possibly to reposition faster and be ready for the next shot. In order to enhance player's performance and reduce injury risk, there is a need to understand the tribological mechanisms occurring at the shoe-surface contact. The present study has developed an effective method to accurately measure temperature changes throughout a sliding movement. Friction and temperature measurements of a commercial tennis shoe outsole were measured during simulated sliding over hard court surfaces. Results indicated how the temperature changed during and after a slide. Additionally, it was found that the temperature of the shoe sole is significantly affected by the vertical load applied, and this varies depending on the shoe location tested. It was also found an inconsistent effect of surface roughness under a range of vertical loads tested. For multiple sliding tests during a rally, the shoe will increase temperature incrementally for each new slide, which could result in large changes in friction behaviour during a slide. The findings from this study could have important implications for the sport of tennis, both in terms of performance and injury-risk.

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Keywords: Temperature; tennis shoes; sport surfaces; friction; tennis

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1. Introduction

Tennis is a sport played around the world on a variety of surfaces like grass, clay and hard courts. Hard court surfaces are commonly used across the world and at all levels. Two of the four Grand Slam tennis events, the Australian Open and US Open are played on this surface. Hard courts are typically made of multiple layers of acrylic paint, some mixed with silica sand, over either a concrete or asphalt base. The level of friction on these surfaces experienced is strongly influenced by the type and amount of sand used and number of layers of paint applied. The surface properties can influence the player movements and affect the risk of injury [1-3].

According to anecdotal sources, elite players have developed an increased tendency to perform sliding movements on hard courts. One study that incorporated a sliding concept shoe, reported that reposition time could be reduced by up to 42% when sliding on hard courts compared with performing traditional adjustment steps [4]. In order to understand possible effects on performance and/or injury-risk due to this trend, there is a requirement for scientific understanding of the tribological mechanisms at the shoe-hard court interface during such movements. The friction force experienced between the shoe sole viscoelastic material and a hard solid substrate in clean and dry conditions is the result of a combination of adhesion and hysteresis friction mechanisms [5, 6]. These mechanisms are affected by other parameters (e.g. roughness, contact area, normal load, shoe orientation), which have been previously studied and showed significant effects on friction [3, 7, 8]. It is possible that temperature changes due to friction during sliding contacts could change shoe sole material properties, with further implications for the tribological mechanisms. Tennis events played in countries where the court temperature can be very high due to environmental conditions could make these changes in material properties even greater.

The aim of this research study was to evaluate the likely changes in shoe sole temperature during sliding movements on hard courts and the influence of these changes on the tribological mechanisms. Understanding how friction is developed can inform the design and development of footwear and playing surfaces, in order to maximise performance and reduce injury risk.

Nomenclature

Ra	arithmetic average roughness
Rq	root mean squared average roughness
Rz	average distance between the highest peak and lowest valley
DMTA	dynamic mechanical thermal analysis
DCOF	dynamic coefficient of friction
E’	storage modulus
tan δ	damping

2. Method

2.1. Shoe outsole temperature measurement

An existing laboratory-based shoe traction device, fully described in [9], was used for a range of tests to determine the behaviour of the shoe outsole temperature distribution of a commercially available hard court tennis shoe under different conditions during a simulated sliding movement. Figure 1 shows the 5 type ‘K’ thermocouples inserted and attached by an adhesive into the grooves of the forefoot segment, to keep them very close to the shoe surface. The thermocouples were connected to a multiple channel data logger which allowed simultaneously recording of the temperatures on different parts of the shoe segment over a pre-set time. The data logger has a conversion time of 100 ms and an accuracy of ±0.2%.

Three bespoke acrylic hard court surfaces (A, B and D) and a commercial tennis surface (C) with different roughness values, as provided in Table 1, were used for the testing. To best replicate a sliding movement, the shoe orientation was positioned at 30° in relation to the sliding direction [8].

An initial study was implemented to test the thermocouples and measure a potential change in temperature. The loads tested ranged from 500 N to 2000 N in increments of 300 N. For each load the temperature of the 5 thermocouples was recorded with the data logger, at regular intervals of 0.62 s throughout the sliding motion.

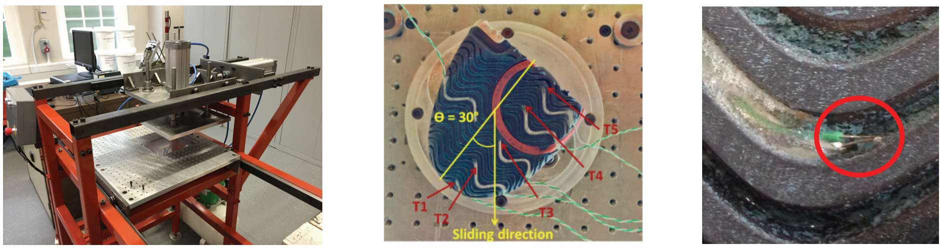

Fig. 1. (a) The lab-based traction device; (b) the position of the 5 thermocouples on the shoe surface; (c) detail of thermocouple in shoe groove.

The second study involved simulating a repeated sliding during a typical tennis rally and measuring how the temperature changed after a number of slides. In order to replicate this as accurately as possible, 7 videos of tennis rallies from two elite hard court tournaments were analysed to see the occurrence of sliding motions during a rally and the average time period between them. One player's shoe was selected for each rally and a slide was counted when the selected player performed a sliding motion with the selected shoe. The average duration of a rally (± 1 SD) was found to be 43.4 ± 8.0 seconds with an average (± 1 SD) of 4.4 ± 1.0 sliding events. It was therefore decided to measure shoe sole temperature during a series of 4 slides of approximately 3 seconds with a rest time period of 10 seconds between each slide at loads of 600, 1200 and 1800 N. Additionally the DCOF was calculated using the mean dynamic friction force in direction of movement between 10mm and 30mm horizontal displacement, according to the protocol from a previous study [9].

Table 1. Average Ra, Rz and Rq values for a range of surface samples

	Ra (µm)		*Rz (µm)*		*Rq (µm)*	
Surface reference	*Before*	*After*	*Before*	*After*	*Before*	*After*
A	5.2 ± 0.6	1.4 ± 0.2	30.9 ± 3.0	9.4 ± 1.5	6.1 ± 1.2	1.7 ± 0.3
B	19.3 ± 3.0	18.0 ± 2.5	88.1 ± 5.7	82.3 ± 9.7	23.2 ± 2.6	21.9 ± 3.1
C	25.3 ± 1.8	26.4 ± 1.3	113.6 ± 7.1	124.5 ± 6.0	31.2 ± 2.3	31.5 ± 2.5
D	32.6 ± 5.0	24.9 ± 2.1	154.8 ± 17.1	106.2 ± 12.0	39.8 ± 5.5	29.8 ± 2.7

A third study involved a repeated sliding over the commercial tennis surface for 15 minutes with a rest interval of 10 seconds between each slide. The temperature change and DCOF were recorded for each of the slides. The shore hardness of the shoe sole was measured before and after the testing to monitor any properties changes of the material.

2.2. Material characterisation

Shore hardness and DMTA testing was performed on samples of the outsole. The mean of five hardness measurements from different positions, at least 6 mm apart, was obtained with a SATRA STD 226 durometer with a Shore A scale module attached. The sample preparation and testing procedure were performed in accordance to the standard test method ASTM D2240 [10]. The DMTA data were collected using a tension-compression test with a frequency of 10 Hz and with a temperature range of -60 to 60 °C. The storage modulus and the damping were obtained.

3. Results

Figure 2 shows an example of the results obtained by the first study, and the temperature change of the 5 thermocouples attached to the forefoot segment of the shoe. Although there is a change in temperature for all the thermocouples, T2, T3 and T4 are the positions with the highest difference in temperature and these were used as the focus for the remaining studies.

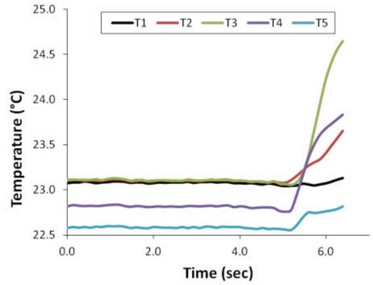

Fig. 2. Temperature at different positions on the shoe sole against time for surface B at 1100 N vertical load

Figure 3 shows the relationship between temperature change (± 1 SD), vertical load and thermocouple location. There is a clear effect of the vertical load (1800 > 1200 > 600 N), and at 1800 N vertical load an effect of the sensor location on temperature change (T2 > T3 > T4). However, there is no obvious consistent trend of a surface effect, even though they had different roughness. It is important to note that for A, B and D the roughness changed through testing (Table 1).

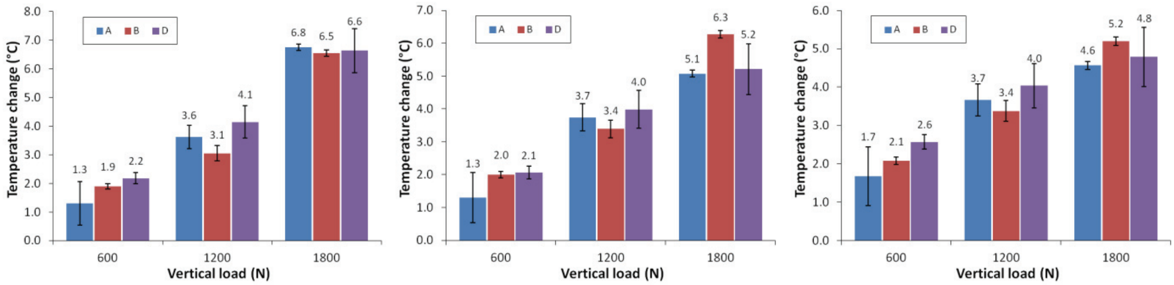

Fig. 3. Plots of temperature change against the vertical load for T2, T3 and T4 (from left to right) on surfaces A, B and D.

Figure 4 shows the change in temperature of T2, T3 and T4, for four repeated sliding movements, with vertical loads of 600, 1200 and 1800 N on the 4 surfaces tested. The surfaces with the highest temperature change were A and D. The behaviour of the temperature is to increase during each slide and then decrease between slides, however, it never decreases completely to the previous temperature value, and the overall temperature increases throughout the tests.

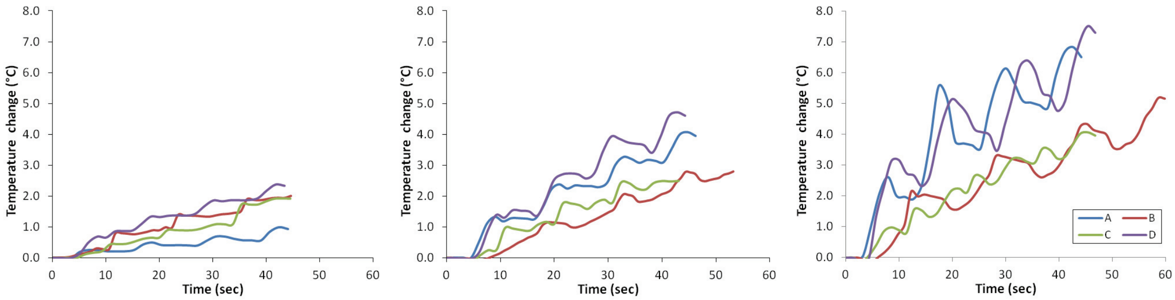

Fig. 4. Plots of the Temperature change against time for T2, on each surface for 600, 1200 and 1800 N (left to right) vertical load.

The average DCOF at 600, 1200 and 1800 N of vertical load was calculated for the sets of four repeated slides on the five different surfaces. Figure 5 shows that the DCOF from surface A increases as the vertical load increases. However, surfaces B and D have a tendency to decrease in DCOF as the vertical load increases (surface C remains relatively constant). For most of the tests the general tendency was for DCOF to decrease with increasing numbers of slides. There is a trend for DCOF to initially decrease, however, as the number of slides increases (approximately slide number 14), there is a trend for DCOF to increase.

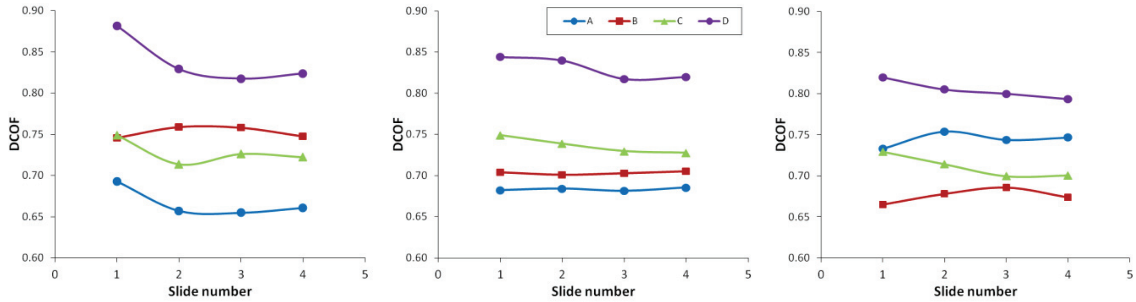

Fig. 5. Average DCOF against slide number for: 600, 1200 and 1800 N (left to right) of vertical load.

The results from the DMTA are provided in Figure 6 (right). The control temperature range was from 20 to 50 °C (region of interest) for E' and tan δ. The graph suggests a decrease in the damping of the material as the temperature increases. The average (±1 SD) hardness value of the rubber before the testing was 75.4 ± 1.1. Immediately after the 15 minutes sliding test, the hardness was 62.1 ± 5.1, confirming a change of the material properties after the testing.

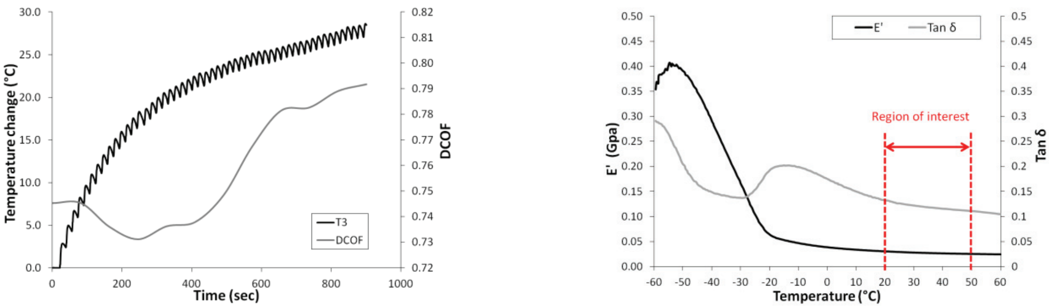

Fig. 6. (a) Temperature change and DCOF against time for 15 minutes sliding test; (b) DMTA data showing E' and tan δ of the shoe material.

4. Discussion

When elastomeric material, such as that tested here, is compressed against a surface with some roughness, there is an interaction between their surface asperities. As the vertical force increases, the shoe sole will deform more, increasing asperity contact and therefore, the adhesion component of friction. During a slide on a hard rough surface, the surface asperities will deform the shoe sole resulting in energy dissipation. This energy will result in local heating and an increase in temperature.

For our experiment, the difference in temperature between the five positions on the shoe sole is dependent of the shoe orientation and the position of the thermocouples relative to the direction of the sliding. For all the tests, T2 is at the front of the shoe during the sliding, experiencing higher deformation and the highest change in temperature in comparison to the other thermocouples. Persson et al. [11] noted that the heat produced in an asperity contact region will result in a 'hot track' on a rubber surface. When this specific region experiences another asperity contact, due to the repeated sliding movement, it will experience an accumulation of heat, which leads to a temperature increase. Due to the difference in temperature after each slide, positions T2, T3 and T4 could be considered as the 'hottest tracks' in the shoe sole.

The difference in temperature change between low (600 N) and high (1800 N) vertical loads in Figure 3 could be explained by the shoe-surface contact area and its asperity contact. Ura et al. [8] reported higher contact areas as the vertical load increases. During sliding, the asperities of the surface deform the shoe sole and the energy dissipation and therefore temperature increases. Under high vertical loads, adhesion dominates the interaction due to an increase of contact area and more elastomeric material inside the cavities of the surface. Under low vertical loads, hysteresis dominates the interaction due to less asperity contact; therefore, there is less deformation of the shoe sole and lower temperature dissipation. Despite the loading conditions, as roughness increases, the sole deforms and recovers, increasing the energy dissipated, which is reflected in an increment of the temperature.

Figure 4 shows that for a test of four repeated slides, the temperature increases as the number of slide increases. Persson et al. [6] stated that in a typical case of a rubber block sliding on a hard rough substrate, the temperature increase results in a decrease in rubber friction. In Figure 5 it is shown in general, that after 4 slides the DCOF decreases or stays similar to the first DCOF value, for the three vertical loads on all the surfaces tested. However, comparing the DCOF between the three vertical loads, for the smoothest surface (A) the DCOF increases as the vertical goes from 600 to 1800 N, suggesting a higher contribution of roughness than temperature change, on the shoe-surface friction. In contrast, for surfaces B and C, DCOF stays similar or reduces as the vertical load increases, in agreement with Persson et al. [6]. This behaviour suggests a bigger influence of temperature change rather than roughness for our study.

Figure 6 results are in good agreement with our previous tests, after the first few slides, the temperature increases and the friction starts to decrease. However, as the number of slides increases, the friction reaches a minimum and then starts to increase and continues until the end of the 52 slides. This differs from the behaviour suggested by Persson et al. [6], but the DMTA and hardness data suggest that the sole material tends to reduce its damping and hardness as the temperature increases, in consequence it will deform more, increasing the heat and contact area and hence the temperature and friction measurement.

5. Conclusions

The vertical force and the location of the thermocouple affect the influence of the temperature and the friction present during a dynamic sliding movement. These effects occurred over a range of surfaces tested; however, the effect of the roughness itself is not consistent as discussed in a previous study [7]. The properties of shoe sole materials can change over the large temperature ranges measured in this study and these effects would be even greater during tennis matches that take place under extreme ambient temperature conditions. These changes could also occur throughout the duration of a long rally, set or match. It is therefore recommended to consider these issues when studying the behavior of shoe friction on acrylic hard-court tennis surfaces.

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