Biomechanical responses to changes in friction on a clay court surface

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1. Abstract

Objectives: To examine the influence of clay court frictional properties on tennis players' biomechanical response.

Design: Repeated measures

Methods: Lower limb kinematic and force data were collected on sixteen university tennis players during 10 x 180° turns (running approach speed 3.9 ± 0.20 m.s^{-1}) on a synthetic clay surface of varying friction levels. To adjust friction levels the volume of sand infill above the force plate was altered (kg per m^2 surface area; 12, 16 and 20 kg.m^{-2}). Repeated measures ANOVA and Bonferroni's corrected alpha post-hoc analyses were conducted to identify significant differences in lower limb biomechanics between friction levels.

Results: Greater sliding distances (η_p^2 = 0.355, p = 0.008) were observed for the lowest friction condition (20 kg.m^{-2}) compared to the 12 and 16 kg.m^{-2} conditions. No differences in ankle joint kinematics and knee flexion angles were observed. Later peak knee flexion occurred on the 20 kg.m^{-2} condition compared to the 12 kg.m^{-2} (η_p^2 = 0.270, p = 0.023). Lower vertical (η_p^2 = 0.345, p = 0.027) and shear (η_p^2 = 0.396, p = 0.016) loading rates occurred for the 20 kg.m^2 condition compared to the 16 kg.m^2.

Conclusions: Lower loading rates and greater sliding distances when clay surface friction was reduced suggests load was more evenly distributed over time reducing players' injury risks. The greater sliding distances reported were accompanied with later occurrence of peak knee flexion, suggesting longer time spent braking and a greater requirement for muscular control increasing the likelihood of fatigue.

Keywords: Kinematics; loading rate; sliding; lower limb; injury risks

2. Introduction

Tennis court surfaces differ greatly in mechanical properties, particularly in those influencing friction.[1–3] Tennis players must adapt to the varied mechanical properties throughout a season, which can influence player movements and loading.[4,5] Strategies previously suggested to reduce potentially high loading on high friction surfaces have included longer braking time, greater delayed peak knee flexion and altered pressure distribution patterns.[4,6,7] It has been suggested that players' ability to slide on lower friction clay surfaces has resulted in lower loading and therefore reduced injury risks.[4,5,7]

Different playing styles reported between acrylic and clay courts have also been attributed differences in frictional properties of the surfaces.[8] Longer rally lengths, greater player distances covered and greater proportion of baseline points on clay courts have been suggested to lead to greater physiological responses such as increased heart rate and blood lactate.[9,10] However, when duration of rally, proportion of baseline shots and distances covered were maintained, greater physiological response was still apparent on a clay court compared to an acrylic court.[11] Altered movement patterns such as sliding during rapid decelerations or changes in direction on clay court surfaces allows players to reposition quicker following a tennis shot.[12] Sliding has also been associated with increased muscle activity[13], which could provide some explanation to the greater physiological response observed when duration and distance are comparable.

On low friction surfaces, such as clay, it is not unusual to observe players sliding during rapid decelerations such as during changes in direction.[3] Tennis players have been reported to utilise greater shear forces and shear loading rates in order to increase utilised coefficient of friction (COF), allowing for sliding to occur on clay surfaces.[4] Furthermore, sliding on clay surfaces have been reported to result in greater ankle inversion angles and lower initial knee flexion angles,[4] which are associated with ankle inversion injuries and ACL injuries respectively.[14,15] However, the authors suggested that although ankle and knee orientation suggests players were more at risk on a clay surface compared to an acrylic, the lower mechanical friction properties on the clay would minimise risk of sudden stopping and overloading of the joints.[4]

The COF on clay courts can vary between 0.5 and 0.7;[2] as a result of differences in infill properties such as volume of infill, the degree of saturation and infill particle size.[1,16] Previous studies have examined the biomechanical differences between acrylic and clay courts which have distinctly different frictional properties.[4,5,7] Yet, there is a lack of evidence regarding tennis players' biomechanical response to small changes in friction, occurring between and within clay courts, and the implications these may have upon performance or injury risks. Therefore the current study aims to examine the influence of changes in frictional properties of a clay surface on biomechanical response. From the literature evidence, it is hypothesised that the level of friction will influence the tennis players' response such that as friction is reduced, greater shear forces (H_1) and shear loading rates (H_2) will occur. Reduced friction is hypothesised to result in lower initial knee flexion (H_3) and delayed peak knee flexion (H_4). At the ankle, it is hypothesised that ankle inversion angle will increase as a result of reduced mechanical friction (H_5). There is no evidence to suggest changes in sagittal plane ankle movement will occur (H_6) when friction is reduced on the clay surface.

3. Methods

Sixteen university tennis players (age 19.93 ± 0.96 years, mass 66.75 ± 10.36 kg, height 1.74 ± 0.10 m, and LTA rating 7.48 ± 2.18) volunteered for the present study. All participants were free from injury and trained regularly (at least once a week) on acrylic courts. Players reported that they had minimal experience of playing on clay courts (i.e. playing on clay once a year or less). The study was approved by the Institutional Ethics Committee. Informed consent and physical activity readiness questionnaire results were obtained before any testing occurred.

A 9 m runway, which consisted of a synthetic clay surface, comprising of a carpet base layer (a dense, red, polypropylene fibrillated surface) and a top layer with a red granulate infill,[1] was used in a laboratory setting during the present study. In the area where participants were turning (above the force plate), the frictional conditions were altered through the use of different volumes of sand (Table 1). To enable ease of preparing the infill a removable square of the synthetic clay surface was placed over the force plate and was secured using Velcro® to enable quick removal of the sand and to ensure no movement of the synthetic clay surface during data collection. The three levels of friction were achieved using 12 $kg.m^{-2}$ (as recommended by the manufacturers), 16 $kg.m^{-2}$ and 20 $kg.m^{-2}$ of sand infill. Differences in mechanical friction were determined using a traction test device[16] and provided surface conditions which were within ITF regulations.[17] The traction test device replicated sliding on clay with the forefoot of a clay court shoe set at 7° against the surface and 90° against the direction of movement). Static and dynamic COF were recorded for a range of normal forces (1000 – 1600 N) which were selected based on data from previous research examining tennis-specific skills.[4] Static COF was defined as the peak COF indicating the transition between the static and dynamic regimes. The dynamic COF was taken as the average COF following the peak COF measured between 0.05 m and 0.20 m. Further details on the traction device and methods used to determine the conditions are reported by Clarke et al.[1] and Ura et al.[16]

****Table 1 near here****

Prior to each trial the infill sand on the area of interest (force plate) was removed, the sand for the next condition was then weighed and placed on the area of interest and spread evenly. During all testing participants wore the same tennis shoe model (Adidas Barricade 6.0 clay shoes). Ten successful 180° turning movements were performed, without a tennis racket, for each condition in a random order. Participants approached the turn at 3.9 ± 0.20 $m.s^{-1}$, which was assessed using timing gates set 2.3 m apart and 1.2 m from the force plate. Participants were asked to perform each 180° turn with their dominant leg (i.e. forehand side) and turn as efficiently as possible. Each turn was performed on the force plate (with the required friction condition).

Three-dimensional lower limb kinematic data (120 Hz) were collected to examine ankle and knee movement. Data were collected using a passive marker motion capture system consisting of eight cameras (opto-electronic system; Peak Performance Technologies, Inc., Englewood, CO), placed in an oval shape around the force plate. Eleven lower limb markers (greater trochanter, medial and lateral femoral epicondyle, anterior aspect of shank, proximal and distal bisection of posterior shank, proximal and distal bisection of the calcaneus, lateral malleolus, base of 2nd metatarsal and 5th metatarsal phalange) on the turning leg were used to construct joint coordinate systems with a custom written Matlab code (Matlab, R2011b, MathsWorks, Natrick, MA, USA). A quintic spline filter was applied to the raw data (Peak Performance default optimal smoothing technique using 5th degree quintic polynomials). All kinematic data were presented relative to a relaxed standing trial. Initial and peak angles for sagittal plane ankle and knee rotations, and frontal plane ankle rotations were obtained. Occurrence times of peak angles were reported relative to initial foot contact. Relative occurrence times were also obtained and expressed as a percentage of contact time.

Sliding was determined using the velocity of centre of the foot (determined from the distal calcaneus marker and 2nd metatarsal marker). A sliding phase was determined when the velocity was greater than a threshold of 1 $mm.s^{-1}$ and maintained for more than 10 ms. During this sliding phase, sliding distance was determined by the resultant distance covered by the centre of the foot.

Ground reaction forces were measured at 960 Hz using an AMTI force plate (Advanced Mechanical Technology, Inc, Newton, MA). Vertical force parameters included peak impact force, peak active force, average loading rate and peak loading rate. Shear forces (FShear) were calculated as the resultant force of the anterior-posterior (Fy) and medio-lateral forces (Fx). Shear force parameters included peak shear force magnitude and loading rate. The utilised COF was determined as the ratio between the shear force (Fshear) and the vertical force (Fz). Peak utilised COF, suggested to indicate the transition between the static and dynamic regimes,[1] was determined as the maximum COF value. Examples of the force data, utilised COF and sliding distance are demonstrated in Figure 1.

****Figure 1 near here****

An ANOVA with repeated measures (SPSS v.11) was conducted to examine tennis players' biomechanical response to the different friction conditions. Bonferroni's corrected alpha post-hoc analyses were applied to establish where differences occurred. An alpha level of 0.05 was used to identify any significant differences. Standardised effect sizes were calculated using partial Eta^2 (η_p^2) to provide the degree to which any differences were present.

4. Results

Friction was a contributing factor that influenced the sliding distances achieved (η_p^2 = 0.355, p = 0.008). For instance, the lowest level of friction (20 kg.m^{-2}; 0.23 ± 0.16 m) produced significantly greater sliding distance compared to the 16 kg.m^{-2} (0.17 ± 0.12 m) and 12 kg.m^{-2} (0.18 ± 0.13 m) conditions which had greater mechanical friction.

The analysis revealed no differences in the initial and peak knee angle between the three friction conditions (Table 2). However, friction level was found to have a significant influence on the occurrence time of peak knee flexion (η_p^2 = 0.270, p = 0.023). Post hoc analysis revealed that the 20 kg.m^{-2} condition (0.34 ± 0.09 s) resulted in a later peak knee flexion than observed for the 12 kg.m^{-2} condition (0.31 ± 0.07 s). When represented as a percentage of contact time, the relative occurrence of peak knee flexion were similar between conditions. As presented in Table 2, no differences in ankle movement were reported between the friction conditions.

****Table 2 near here****

The analysis revealed no significant differences in peak impact force, peak active force and peak shear force between the three friction conditions (Table 2). Peak vertical loading rate was significantly lower during the 20 kg.m^{-2} condition (135.52 ± 23.16 BW/s; η_p^2 = 0.345, p = 0.027) compared to the 16 kg.m^{-2} condition (147.67 ± 25.77 BW/s). Friction level significantly influenced peak shear loading rate (η_p^2 = 0.396, p = 0.016), with lower shear loading rates produced during the 20 kg.m^{-2} condition (53.25 ± 10.45 BW/s) compared to the 16 kg.m^{-2} condition (58.78 ± 10.92 BW/s). The occurrence time of peak utilised COF was later for 20 kg.m^{-2} friction level (0.043 ± 0.004 s; η_p^2 = 0.306, p = 0.040) compared to the 16 kg.m^{-2} friction level (0.037 ± 0.003 s). However, the magnitude of the peak utilised COF was similar between the three conditions.

5. Discussion

Sliding on clay is a common feature of tennis,[3] where players aim to initiate sliding in a timely manner to enable a quick change of direction.[12] In the current study, greater sliding distances, reduced loading rates and later peak knee flexions were achieved when friction was reduced. These findings suggest loading was more evenly distributed over time when clay court surface friction was reduced. In addition, greater sliding distances and later peak knee flexion suggest longer time was spent controlling the slide when friction was reduced, which could increase the likelihood of fatigue.

Sliding occurs when the shear force applied is greater than the static friction force.[1,4] Previous reports have identified higher shear forces on low friction clay surfaces compared to a high friction acrylic surfaces, which resulted in increased utilised COF leading to players sliding on the clay court.[4] However, the present study reported no differences in shear forces and peak utilised COF between the different friction conditions on the clay surface. These different results are most likely due to differences in player movement mechanics on different court surface types. In previous work, Damm et al.[4] examined two distinct levels of friction (acrylic and clay surfaces), resulting in differences in the utilisation of friction. For example, when on the acrylic surface participants reduced their shear loading to reduce coefficient of friction, possibly reducing injury risks associated with loading on high friction surfaces. [4] Whilst, on the clay court the greater shear forces would enable participants to overcome the static friction and initiate sliding.[1,4] However, the present study focused on clay surfaces where participants were able to slide during all conditions. With no differences in shear force observed across the three surface friction levels, the lower friction surfaces allowed greater sliding distances owing to a lower resistance to sliding (lower mechanical COF).

Sliding reported for the lowest friction condition resulted in reduced shear and vertical loading rates compared to the 16 kg.m^{-2}. The lower rate of loading on the lower friction surface as a result of further sliding suggests a reduced risk of injury by increasing the time spent applying the shear and vertical loads.[18] Reduced mechanical friction reduces the initial shear stiffness of the surface, i.e. lower resistance to movement or sliding, therefore reducing the load experienced by the players during impact[1] The reduced loading rate reported in the current study occurred in conjunction with later occurrence of peak knee flexion. Longer braking phases, through later peak knee flexion, have previously been suggested to result in reduced loading to accommodate the potential high loading when turning on high friction surfaces, therefore reducing the risk of injury.[6] However, findings in the current study suggest later peak knee flexion, and thus later braking occurred on the lower friction clay condition rather than for the higher friction clay conditions. It is important to note that the surfaces reported in the Durá et al.[6] study had a greater range of mechanical friction (0.43 - 0.93) which span those previously observed for clay and acrylic courts[2]. However, the present study focused on low friction levels on a clay surface where the coefficient of friction ranged between 0.54 - 0.63, similar to that previously reported for clay court surfaces[2]. Marked differences in friction (acrylic and clay) have previously resulted in distinct differences in technique and pressure distributions to enable sliding on clay.[4,7,19] This may explain the contrasting results with those of Durá et al.[6] The present study reported players sliding for all conditions, which was not reported by Durá et al.[6] When occurrence time was represented relative to contact time, no differences between conditions were reported. These findings suggest that a similar technique was used, but sliding increased the total time of the step.

Sliding movements in tennis have been demonstrated to require greater muscular control compared to regular footwork.[13] Greater sliding distances and later peak knee flexions reported in the current study are likely to be associated with longer eccentric muscle contractions in order to control the movement, which is likely to increase physiological demands, such as increased heart rate and blood lactate accumulation. These findings suggest that reductions of friction below the manufacturer's recommendations could increase the physiological demand placed on players and therefore increase the likelihood of fatigue. Therefore, on surfaces such as clay that result in longer rally lengths and permit sliding, players could experience even greater increases in physiological strain, therefore increasing the likelihood of fatigue. Fatigue in tennis has been associated with reduced performance[20,21] and increased risk of injury.[22,23]

It must be noted that the current study was undertaken within laboratory conditions which limited the movements analysed, therefore reducing the ecological validity of the data. However, the turning movement was selected to reproduce a typical movement seen in tennis. The composition of the synthetic clay surface (carpeted base layer and red granulated infill) used in the current study differs to outdoor clay courts. Mechanical properties of these surfaces may differ and therefore alter players' response. However, the current study provides an insight to players' response to changes in friction on a surface that permits sliding.

6. Conclusions

Sliding is an influencing factor in players' response when examining clay court surface friction. Contrary to the study hypothesis, the current study did not report changes in shear force magnitudes (H_1), whilst shear force loading rates were reduced as friction decreased (H_2). Greater sliding distances accompanied by reduced shear loading rates on the lower friction conditions suggests reduced injury risks. In contrast to the study's hypothesis, no differences in knee flexion angles (H_3) and ankle inversion angles (H_5) were identified. Sagittal plane ankle kinematics remained similar between friction conditions (H_6), as expected. As hypothesised, later knee flexion (H_4) was observed during the lower friction conditions when greater sliding distances were also observed. Although sliding on clay enables efficient changes of direction and reduces injury risks through lower forces and longer time applying these forces, the current study's findings suggest that prolonged sliding on clay surfaces with low shoe-surface friction may lead to greater physiological strain. Therefore, it is important to maintain the manufacturer recommendations for infill volume, between and within matches, to limit excessive physiological strain due to greater sliding whilst still allowing players to benefit from sliding on the low friction surfaces.

7. Practical implications

- Clay court frictional properties influence player movement and loading during sliding, likely affecting injury risks and physiological responses
- It is important to maintain manufacturer recommendations for infill volume, between and within matches, to allow the benefits observed from sliding to be maintained but limit the physiological strain associated with lower friction surfaces

8. Acknowledgements

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10. Tables and captions

Table 1: Range of static coefficient of friction (COF) during a range of normal forces (1000N – 1600N) for three volumes of sand infill

	COF
12 $kg.m^{-2}$	0.61 - 0.64
16 $kg.m^{-2}$	0.59 - 0.65
20 $kg.m^{-2}$	0.54 – 0.59

Table 2: Means and standard deviations for kinematic and kinetic data collected for each friction condition

Variable	12 $kg.m^{-2}$	16 $kg.m^{-2}$	20 $kg.m^{-2}$
Kinematic data			
Knee flexion angle			
At impact (°)	17.3 ± 13.6	13.6 ± 13.6	16.5 ± 12.0
Peak (°)	40.0 ± 5.2	39.5 ± 5.7	39.6 ± 6.2
Time of peak (s)	0.31 ± 0.07	0.30 ± 0.07	0.34 ± 0.09*
Relative time of peak (%)	53.44 ± 9.81	51.94 ± 9.20	57.46 ± 9.92
Ankle flexion angle			
At impact (°)	4.4 ± 12.6	3.0 ± 11.3	4.6 ± 12.0
Peak (°)	-12.2 ± 7.3	-10.9 ± 8.9	-12.3 ± 7.4
Time of peak (s)	0.26 ± 0.12	0.19 ± 0.12	0.22 ± 0.12
Relative time of peak (%)	53.32 ± 7.10	53.41 ± 7.38	50.37 ± 6.19
Ankle inversion angle			
At impact (°)	-4.6 ± 17.2	2.2 ± 13.3	-2.8 ± 17.0
Peak (°)	-30.4 ± 8.5	-29.3 ± 7.5	-27.9 ± 8.7
Time of peak (s)	0.24 ± 0.09	0.23 ± 0.08	0.19 ± 0.08
Relative time of peak (%)	49.72 ± 8.00	48.03 ± 8.40	45.60 ± 8.67
Kinetic data			
Peak impact force (BW)	1.80 ± 0.49	1.92 ± 0.55	1.90 ± 0.50
Peak active force (BW)	1.32 ± 0.24	1.33 ± 0.88	1.28 ± 0.27
Peak shear force (BW)	0.76 ± 0.28	0.81 ± 0.23	0.78 ± 0.22
Average loading rate (BW/s)	37.75 ± 19.31	42.19 ± 21.18	41.67 ± 19.78
Peak vertical loading rate (BW/s)	140.22 ± 87.74	147.67 ± 25.77**	135.52 ± 23.16
Horizontal peak loading rate (BW/s)	54.94 ± 26.84	58.78 ± 10.92**	53.25 ± 10.45
Peak utilised COF	0.62 ± 0.13	0.55 ± 0.08	0.53 ± 0.14
Time of peak utilised COF (s)	0.035 ± 0.002	0.040 ± 0.003**	0.043 ± 0.004

***denotes a significant difference with the 12 $kg.m^{-2}$ condition, ** denotes a significant difference with the 20 $kg.m^{-2}$ condition**

11. Figure and captions

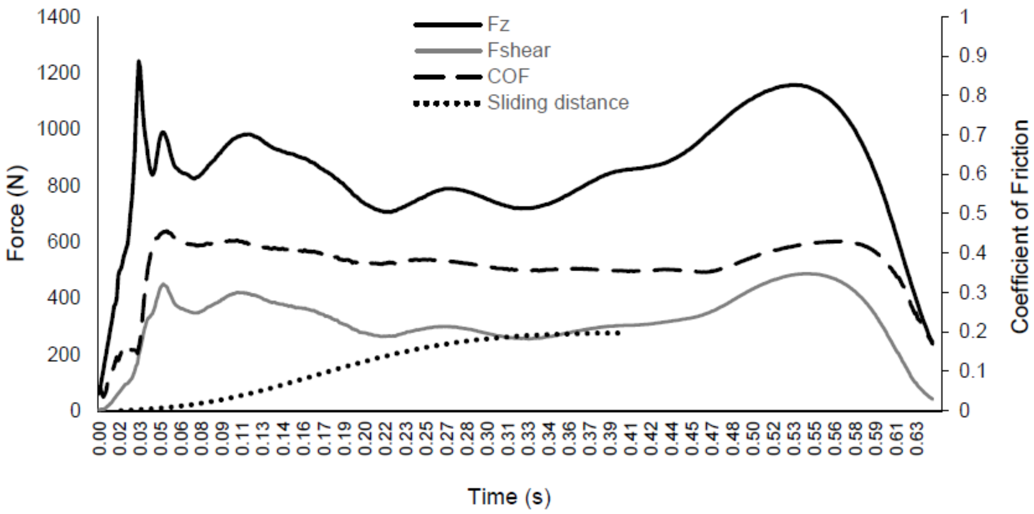

Figure 1: Examples of vertical (Fz) and shear (Fshear) ground reaction forces, utilised coefficient of friction (COF) and associated sliding distance for one subject during the turning movement