ORIGINAL ARTICLE

Effects of the playing surface on plantar pressures and potential injuries in tennis

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Objectives: To examine the influence of different playing surfaces on in-shoe loading patterns during tennis-specific movements.
Methods: Ten experienced male players performed two types of tennis-specific displacements (serve and volley (SV) and baseline play (BA)) on two different playing surfaces; eg, clay vs Greenset. Maximum and mean force and pressure, contact time, contact area and relative load were recorded by an insole with 99 sensors (X-Pedar system) divided into 9 areas.
Results: Regarding the whole foot, mean (SD) force (SV: 615 (91) vs 724 (151) N; −12.4%, $p<0.05$ and BA: 614 (73) vs 717 (133) N; −11.6%, $p<0.05$) was lower on clay than on Greenset, whereas contact time was longer (SV: 299 (113) vs 270 (148) ms; +16.5%, NS and BA: 354 (72) vs 272 (60) ms; +30.3%, $p<0.001$). Greenset induced higher loading in the hallux (SV: +15.3%, $p<0.05$ and BA: +11.4%, not significant) and lesser toes areas (SV: +12.6%, $p<0.05$ and BA: +18.0%, $p<0.01$). In contrast, the relative load on the medial (SV: +27.4%, $p<0.05$ and BA: +16.1%, $p=0.06$) and lateral midfoot (SV: +23.3%, $p<0.05$ and BA: +28.3%, $p<0.01$) was higher on clay.
Conclusions: This study demonstrates that playing surface affects plantar loading in tennis: Greenset induced higher loading in the hallux (SV: +15.3%, $p<0.05$ and BA: +11.4%, NS) and lesser toes areas (SV: +12.6%, $p<0.05$ and BA: +18.0%, $p<0.01$) but lower relative load on the medial (SV: −27.4%, $p<0.05$ and BA: −16.1%, $p=0.06$) and lateral midfoot (SV: −23.3%, $p<0.05$ and BA: −28.3%, $p<0.01$) than clay.

Tennis is one of the world's most popular and widely-played sports by people of all standards.[1] Unfortunately, injuries in tennis are very common, not only in professional players but also in their recreational counterparts.[2 3] Biomechanical analyses of stroke production indicate that the trunk rotation and upper limb drive—that is, shoulder internal rotation, elbow extension, wrist flexion—are key elements leading to optimal racquet speed and positioning at impact, and they originate in the lower limbs (kinetic chain).[4] These studies also argued that repetitive tensile loads from stroke production can lead to injury if the muscles of these body parts are not sufficiently strengthened and flexible.[5] However, most epidemiological tennis studies have shown lower extremity injuries to be nearly equal to or exceeding upper extremity problems.[2 6–9] For example, an injury surveillance amongst elite tennis players during the US National Championships has revealed that nearly 50% of all injuries were located in the lower extremities; an incidence almost twice that for the upper limbs and trunk/back.[10] This is not surprising, given the repetition and intensity of quick starts and stops, changes in direction, running and shuffling side-to-side that are required in tennis.[1 4] In addition epidemiologic studies have indicated that most tennis injuries are chronic and most likely due to the repetitive nature of the sport. However, these comprehensive studies (eg, descriptive and analytic epidemiological, laboratory or case studies) do not comment extensively on the association between extrinsic (eg, equipment, playing conditions, environment) and/or intrinsic (eg, sex, age, level of play, previous injury, inflexibility, lack of strength) risk factors and the occurrence and/or aetiology of tennis injuries.[2 9 11]

Tennis performance is influenced by different parameters according to the playing surface.[12] This is expressed in the four Grand Slam Tournaments, which are played on hard courts (Australian Open and US Open), clay (Roland Garros) and grass (Wimbledon) and regularly feature different finalists. The influence of playing surfaces on injury pattern has been discussed abundantly.[2] Specifically, lower injury rates have been reported on clay courts, probably due to a lower frictional resistance on these particular surfaces, when compared to hard courts. For example, Kulund *et al*[13] observed that senior tennis players have fewer knee problems if they have spent most of their tennis careers on clay courts. However, to the best of our knowledge, there is no quantitative information available concerning the foot-loading characteristics during tennis-specific movements. Data on the location and the magnitude of foot pressures would help to better understand the shoe–surface interface and can also help to prevent overuse injuries.[14]

Therefore, the aim of the present study was to characterise and to compare in-shoe loading patterns during two frequent tennis-specific movements (serve and volley (SV) play and baseline (BA) play) performed alternatively on two playing surfaces (clay and Greenset) to identify the main loading patterns and locations on the anatomical structures of the foot. We hypothesised that playing tennis on different surfaces would have significant influence on the amplitude and distribution of in-shoe plantar pressure patterns, the related potential injury mechanisms and in consequence the preventative strategies.

METHODS

Subjects

Ten (7 males, 3 females) tennis players (mean (SD) age 23.8 (6.0) years; height 171.7 (8.1) cm; body mass 65.8 (8.7) kg) with an International Tennis Number of 3 or better volunteered to participate in the study. Regarding subjects' style of play, four were familiar with rapid movement toward the net (serve and volleyers) and six preferred rallies from the baseline

Abbreviations: BA, baseline play; MANOVA, multivariate analysis of variance; SV, serve and volley play (defensive/aggressive baseliners). Subjects were eligible to participate if they had no history of injury in the lower extremity within the past year and no previous surgery. They signed a written consent prior to participation. Approval for the study was obtained from the local ethics committee.

Experimental set-up

Subjects performed randomly two different tennis-specific movements (SV and BA play) on clay and Greenset (fig 1). After a standardised warm-up lasting 10 min, the desired technique for running (moving to the target, positioning to the target and moving to the next target (SV) or moving back to baseline (BA) as rapidly as possible) and stroke miming through the slalom courses was demonstrated to each subject. Subjects were then allowed to repeat the course until they felt comfortable performing the instructed technique (approximately three repetitions). In addition, prior to instrumentation the athletes performed a maximum effort trial. Subjects randomly performed the tennis-specific movements on each playing surface with less than an hour between surface conditions. Five successful trials were collected for each movement. The average of the five was used in data handling and subsequent calculations. Players were allowed to recover for 1 min inbetween each of the movements' repetitions.

Tennis-specific movements

The running paths are illustrated in fig 1. SV was a course toward the net. In this situation, subjects were asked to volley the ball so that it would land on the middle backcourt. BA consisted of eight shuttle runs performed from a central basis to one of the six targets located around the court. When the subject arrived at the target, he was instructed to mime a powerful stroke as in a match situation before moving back to baseline after each drive. In both movements, they were asked to use the same running technique (ie, freely-chosen) as in official competition in order to identify the constrains applied on the player's feet surface in a context similar to game play. The trial times were measured for each subject using two photocell gates connected to an electronic timer (Globus Inc, Treviso, Italy). Running times were controlled in order to obtain reproducible foot loading parameters. Inter-trial variability (coefficient of variation, CV) of performance time for SV and BA was lower than 4%.

Instrumentation

Insole plantar pressure distribution was recorded using the X-Pedar insole (Novel GmbH, Munich, Germany) containing 99 sensors in a matrix design. During data collection, the insole was placed between the shoe and the plantar surface of the right shoe. The data logger for data storage was in a harness on the chest of the subject. In addition, data were sent by telemetry to a laptop computer. Plantar pressures were recorded at 50 Hz. An excellent reproducibility was reported for this device.[15]

Plantar pressure data

A regional analysis of the foot was performed utilising nine separate "masks" or areas of the foot as shown in fig 2. The following parameters were determined for the whole foot and the nine selected regions: maximum and mean force, peak and mean pressure, mean area and contact time. In addition, the relative load in each foot region was calculated as the force time integral (area under the force curve) in each individual region divided by the force time integral for the total plantar foot surface.[16] The total number of steps ranged between 15–16 in SV and between 47–50 in BA. An average of 15 and 48 steps were analysed in SV and BA respectively for the five trials for each movement and surface condition. Analyses were performed with appropriate software (Novel Win, Novel GmbH, Munich, Germany).

Statistical analyses

The mean (SD) was calculated for all variables. Statistical significance was accepted at $p<0.05$. Statistical analyses were performed using Sigmastat 2.03 software (Jandel Corporation, San Rafael, California, USA). A repeated measures 2×9 multivariate analysis of variance (MANOVA) was performed with playing surface (clay, Greenset) and foot region (masks

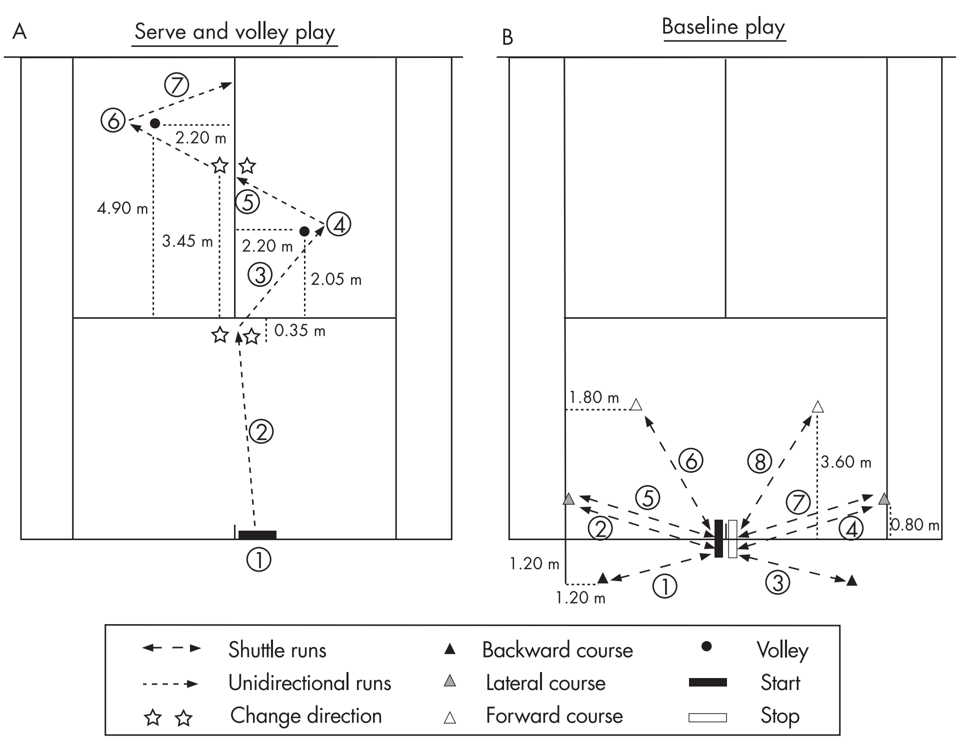

Figure 1 The experimental set-up and running paths for the tennis-specific movements: serve and volley (A) and baseline (B) play. For serve and volley play (A), subjects started from baseline by miming a serve (1), sprinted until the service line (2), operated a change of direction to attain the right cutting area (3), where they were asked to mime a forehand volley (4). Then, they returned back to the centre of the court (5), before moving to the second target to perform a backhand volley (6) and finished when they went back to centre (7). For baseline play, subjects performed eight shuttle runs from a central basis to one of the six targets located around the court in the order one to eight. When they arrived near a target, they were asked to mime a powerful stroke (backhand: 1, 2, 5 and 6; forehand: 3, 4, 7 and 8).

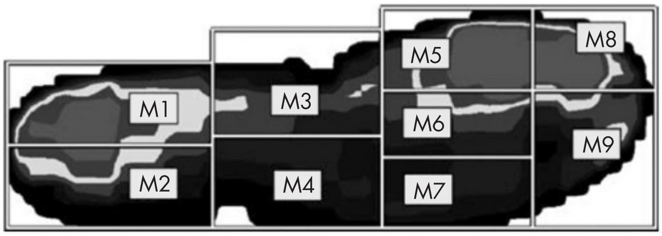

Figure 2 Regions of interest at the foot were masked to the size of the Pedar insole (Groupmask Evaluation, Novel GmbH, Munich, Germany). The regions consisted of the following: M1 medial heel, M2 lateral heel, M3 medial midfoot, M4 lateral midfoot, M5 medial forefoot, M6 central forefoot, M7 lateral forefoot, M8 hallux and M9 lesser toes.

one to nine) as the repeated factors and relative load, maximum and mean force, peak and mean pressure, mean area and contact time designated as dependent variables. This analysis revealed the global effect of playing surface, the global effect of foot region and the interaction between playing surface and foot region conditions. When significant main effects were observed with the 2-way ANOVA, Bonferroni post hoc analyses were used to identify differences among means.[17] An independent samples paired t test was used to examine the differences in plantar loading parameters between clay and Greenset conditions for the whole foot.

RESULTS

There was no statistically significant difference in performance time during SV between the two playing surfaces (mean (SD) 5.3 (0.4) vs 4.9 (0.2) s on clay and Greenset, respectively; $p>0.05$) whereas during BA, performance time was longer on clay (22.8 (0.2) vs 20.7 (0.8) s; $p<0.01$).

Regarding the whole foot, mean (SD) force (SV: 615 (91) vs 724 (151) N; −12.4%, $p<0.05$ and BA: 614 (73) vs 717 (133) N; −11.6%, $p<0.05$) was reduced on clay when compared to Greenset, whereas contact time was longer (SV: 299 (113) vs 270 (148) ms; +16.5%, NS and BA: 354 (72) vs 272 (60) ms; +30.3%, $p<0.001$) (table 1).

Plantar pressure parameters for each foot region during SV and BA on Greenset and clay are presented in tables 2 and 3, respectively. The Greenset condition induced a higher loading in hallux (SV: +15.3%, $p<0.05$ and BA: +11.4%, NS) and lesser toes area (SV: +12.6%, $p<0.05$ and BA: +18.0%, $p<0.01$) as compared to clay (fig 3). In contrast, the relative load on the medial (SV: +27.4%, $p<0.05$ and BA: +16.1%, $p = 0.06$) and lateral midfoot (SV: +23.3%, $p<0.05$ and BA: +28.3%, $p<0.01$) were higher on clay.

DISCUSSION

A recent review by Pluim *et al*[9] indicates that only a quarter of studies dealt with lower extremity problems despite that most (>50%) tennis injuries occurred in the lower extremities, followed by the upper extremities and then the trunk.[2 6–9] To date, however, there are very few cohort studies available to analyse the association between occurrence or aetiology of tennis leg injuries and extrinsic risk factors such as playing surface. To our knowledge, the present study is the first to investigate the amplitude and distribution of plantar pressures during tennis-specific movements characteristics of two different surfaces (clay vs Greenset) and related playing styles (aggressive baseliner vs serve-and-volleyer). The observed differences in plantar loading between clay and Greenset might partly explain the specific injury patterns previously reported in tennis played on slow and fast surfaces.[6 18]

Whole foot

When analysing the whole foot, the lower mean force and the longer contact time on clay indicate that the magnitude of external forces on the musculoskeletal system are less important but over a longer duration. Using ground reaction forces measurements, it was recently found that the surface with the lowest mechanical cushioning resulted in the lowest vertical force magnitude during a tennis specific movement.[19] This shows that running techniques differ when playing tennis on slow and fast surfaces. One could speculate that the frictional properties of the tennis shoe–surface interface is a variable directly related to pain/injury frequency and severity.[20] There is also evidence of a reduction in overuse injuries when tennis is predominantly played on slow courts as opposed to faster surfaces.[20] Taken together, these findings suggest that playing on clay, that allow controlled sliding movements (as shown by the longer contact times), could produce lower frictional resistance and will therefore substantially decrease the muscle forces and the loading in the joints, which could in turn reduce the risk of lower extremity injuries.

Foot pressure distribution

For both the playing surfaces, foot loading was higher in the forward and central plantar regions (eg, hallux, lesser toes, medial and central midfoot). Although comparisons with other studies are not relevant due to differences in sport specific footwear, type of movement or defined areas of the foot (masks), the present results generally agree with the findings reported in soccer players.[21 22] However, the type of surface in this study did influence plantar loading at specific foot regions. The hallux and lesser toes areas have a significantly higher relative load on Greenset when compared to clay during SV and BA. A possible explanation is a more aggressive play on fast surfaces than on slow ones, with a front foot landing strategy in an attempt to move forward to the net.[23] In contrast, plantar loading on the lateral and medial midfoot were higher on clay. This might be due to the more defensive nature of the game played on this surface. Specifically, the low frictional

Table 1 Foot loading parameters for the whole foot during tennis-specific movements on clay and Greenset

	Serve and volley play			Baseline play		
Parameters	Greenset	Clay	Changes (%)	Greenset	Clay	Changes (%)
Maximum force (N)	1273 (197)	1213 (308)	−2.7	1303 (172)	1281 (420)	−2.2
Mean force (N)	724 (151)	615 (91)*	−12.4	717 (133)	614 (73)*	−11.6
Peak pressure (kPa)	385 (68)	376 (92)	−0.6	381 (69)	404 (137)	+5.9
Mean pressure (kPa)	112 (18)	108 (23)	−2.5	108 (15)	113 (33)	+3.6
Mean area (cm^2)	90 (12)	91 (14)	+1.6	92 (15)	90 (14)	−1.4
Contact time (ms)	270 (148)	299 (113)	+16.5	272 (60)	354 (72)***	+30.3

Values are mean (SD).
*$p<0.05$; ***$p<0.001$ denote significant difference between Greenset and clay (paired t tests)

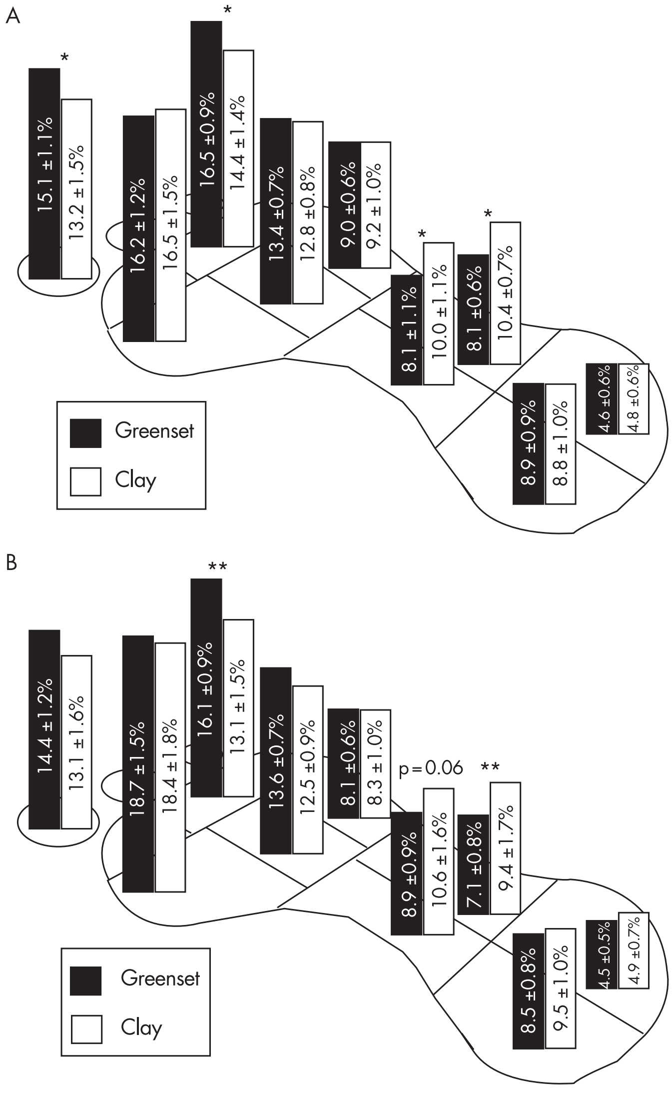

Figure 3 Mean and SD relative load (%) for each foot region during serve and volley (A) and baseline (B) play on Greenset and clay.

characteristics of this surface allows numerous sliding side-to-side movements, with player reacting to their opponent's play slightly further back from the baseline.[23] It is also interesting to observe that mean force values were higher on clay compared with Greenset in the midfoot (lateral and medial) only.

Potential injury mechanisms

In tennis, the majority of lower limb injuries are similar to those observed in running athletes. However, due to the uniqueness and repetitive nature of the tennis displacements, especially the large amount of side-to-side movements, some specific anatomical structures (eg, plantar fascia, Achilles tendon, posterior tibial tendon, flexor hallucis tendon) are under greater risk than in most other sports.[24] Many problems of the hallux (eg, hallux valgus deformity, hallux rigidus) and lesser toes (eg, sesamoid dysfunction, nerve entrapments, Morton's syndrome, metatarsalgia) could occur as the result of excessive pressure when the foot is jammed against the front of the shoe.[24] In addition to purely lateral movements, tennis also involves a lot of twisting and turning movements, which might stress the anterior cruciate ligament and the medial collateral ligament of the knee joint if excessive varus/valgus or internal/external rotation are applied.[25] Overall, the observed changes in midfoot (clay) as well as in hallux and lesser toes (Greenset) areas associated with the cumulative effect of repeated trauma from excessive external loading would be potential mechanisms for the development of stress fractures in bone and micro-damage in cartilage.[24] Furthermore, changes in distribution and magnitude of foot-loading patterns between clay and Greenset observed in this study lead us to suggest that tennis soles could differently affect the aetiology of surface-related injuries.

Greenset

The surface with the higher frictional coefficient enhances the speed of the game but might also induce more frequent injuries as players perform at a greater rate of acceleration, speed and torque, hyperextension and therefore greater potential muscle fatigue.[24] It is well understood that "blocking" type injuries (eg, ankle or knee strains, Achilles or patellar tendonitis, metatarsalgia, knee ligament sprains) are likely to occur on hard surfaces.[25] Specifically, the higher loading recorded in front of the foot on Greenset could be a potential risk for tennis players due to hyperpronation. Plantar fasciitis represents a typical trauma that can occur on fast surface[26] if one consider that fast game play is thought to be related to periodic stress placed on the plantar fascia that assists to maintain the longitudinal arch of the foot.[7] Although the causes of plantar fasciitis is not well understood, the toes are forced into hyper-extension during the push off phase of powerful serves and in aggressive rallies. It is also likely that tendinopathy or partial rupture of the flexor hallucis longus tendon are more frequent on fast surfaces during side-to-side movements due to the hard surface friction.[27]

Clay

By contrast, a higher incidence of muscle strains/spasms is likely on slow courts considering that the lower frictional coefficient leads to longer sliding movements (longer contact times). The tibialis posterior and calf muscles appear to play an important role for the support of the longitudinal arch during side-to-side movements.[24] One can therefore argue that the increased loading under the medial midfoot on clay could be due to a more pronounced pronation,[28] which in turn induces a phenomenon of plantar aponeurosis. This mechanism would reduce the shock-absorbing effect of the leg muscles during the loading response with an increased loading of the medial forefoot and midfoot.[29] Furthermore, the landing movements or the braking actions resulting from the side-shuffle movements on clay could be associated with a high constraint on the musculoskeletal complex due to the elevated slipperiness (instability) of the surface. This could lead to muscle tears and elongations (eg, gastrocnemius, biceps femoris) or joint pathologies. Regarding the ligaments at risk on clay, one can argue that excessive inversion during a purely lateral side-shuffle movement could result in an ankle sprain.[24]

Preventive measures

Most lower limbs problems in tennis competition are chronic in nature and occur from repetitive stress of the many quick starts, stops and changes of direction.[9] As a consequence, proper conditioning can assist in the prevention of injury, as well as improvement of actual tennis performance. In this view, stretching the muscles of the lower extremities is critical in the prevention of acute and chronic injuries and helps generate force from a variety of body positions.[30] Coaches and conditioning coaches should also include a significant amount of lower body strength and endurance training as prevention against overuse injuries of lower limbs and feet.[31] Because current research indicates that players achieve best results when training methods replicate the actual demands of the

Table 2 Plantar pressure parameters for each foot region during serve and volley play on Greenset and clay

Parameters	Surface	Foot zones: Medial heel	Lateral heel	Medial midfoot	Lateral midfoot	Medial forefoot	Central forefoot	Lateral forefoot	Hallux	Lesser toes	Significant main effects and/or interactions
Maximum force (N)	Greenset:	247 (62)	138 (49)	155 (51)	145 (36)	227 (65)	185 (53)	123 (25)	210 (53)	213 (42)	
	Clay:	226 (92)	122 (60)	157 (57)	183 (124)	253 (81)	195 (67)	151 (95)	210 (77)	219 (92)	F, I
Mean force (N)	Greenset:	61 (21)	32 (13)	56 (24)	56 (17)	122 (42)	98 (27)	64 (21)	115 (39)	121 (36)	
	Clay:	49 (21)	27 (12)	60 (30)	62 (32)	105 (38)*	80 (18)*	57 (20)	85 (35)***	91 (28)***	F, S, I
Peak pressure (kPa)	Greenset:	180 (48)	143 (41)	151 (42)	123 (24)	286 (85)	231 (76)	161 (45)	313 (88)	235 (67)	
	Clay:	165 (58)	131 (58)	153 (42)	148 (85)	330 (118)	251 (113)	192 (108)	333 (124)	256 (118)	F, I
Mean pressure (kPa)	Greenset:	111 (24)	83 (21)	67 (12)	63 (11)	177 (51)	130 (36)	92 (19)	189 (53)	113 (22)	
	Clay:	105 (40)	78 (27)	68 (11)	74 (34)	195 (59)	134 (39)	106 (54)	187 (49)	115 (34)	F
Mean area (cm^2)	Greenset:	8 (3)	5 (3)	11 (5)*	11 (2)	10 (2)	11 (1)	9 (2)	9 (2)	15 (3)	
	Clay:	8 (3)	5 (3)	14 (7)	13 (5)	10 (2)	11 (3)	9 (1)	8 (2)	13 (3)*	F, I
Contact time (ms)	Greenset:	220 (176)	172 (86)	259 (154)	247 (162)	262 (150)	264 (150)	259 (153)	263 (150)	264 (150)	
	Clay:	247 (149)	241 (145)	277 (122)	266 (134)	290 (116)	291 (116)	279 (118)	281 (100)	286 (106)	F

Values are mean (SD).
F and S indicate significant main effects of foot region and surface; I indicates a significant interaction between foot region and surface.
*$p<0.05$; ***$p<0.001$ denote significant difference between Greenset and clay.

sport,[1] practice sessions should challenge the same muscle groups of the foot[24] and the loaded areas (present study) identified for a particular tennis surface.

Modifications to the shoe–playing surface interface through increased lateral stability or better shock absorption should also be aimed at reducing the risk of lower extremity injuries in tennis.[32] Data presented in this study might help shoe companies to further design tennis shoes taking into account the specific characteristics of a given playing surface. Specifically, shoes could help reduce impacts (shock absorption) on a particular tennis surface where excessive loading was found to be a potential danger for overloading specific areas of the foot (clay: midfoot; Greenset: hallux and lesser toes areas). In this way, shoes with different stiffness characteristics can be designed in an attempt to reduce stress on the Achilles tendon, posterior tibialis tendon and plantar fascia. This can also be performed with the possible use of orthotics, as it has been reported that it can reduce peak pressure (~20%) at specific plantar regions.[33] Orthotics can also be designed to support the longitudinal arch and to support the heel during landing to keep the foot out of hyperpronation.[34] Finally, the information presented here could be useful for defining a return-to-play protocol for players who have had specific injuries.

CONCLUSIONS

This study demonstrates that playing surface significantly affects plantar loading during tennis activities. Regarding the whole foot, mean force was reduced on clay when compared to Greenset, whereas contact time was longer. The Greenset condition induced also higher loading in hallux and lesser toes area as compared to clay. In contrast, the relative load on the medial and lateral midfoot were higher on clay. The differences in loading patterns based on tennis-specific courses are important for understanding potential injury mechanisms and designing appropriate preventive strategies (eg, Achilles tendon stretching, foot strengthening and/or adapted footwear).

Table 3 Plantar pressure parameters for each foot region during baseline play on Greenset and clay

Parameters	Surface	Foot zones: Medial heel	Lateral heel	Medial midfoot	Lateral midfoot	Medial forefoot	Central forefoot	Lateral forefoot	Hallux	Lesser toes	Significant main effects and/or interactions
Maximum force (N)	Greenset:	218 (42)	117 (34)	164 (47)	130 (44)	253 (73)	198 (54)	119 (26)	195 (54)	206 (50)	
	Clay:	237 (143)	137 (116)	177 (82)	168 (119)	285 (108)	207 (93)	153 (111)	205 (80)	211 9103)	F
Mean force (N)	Greenset:	57 (23)	29 (12)	61 (21)	50 (18)	135 (50)	101 (23)	59 (15)	108 (38)	116 (25)	
	Clay:	49 (14)	26 (13)	63 (29)	58 (33)	117 (41)*	80 (18)**	53 (22)	84 (37)**	84 (31)***	F, S, I
Peak pressure (kPa)	Greenset:	164 (29)	131 (25)	167 (48)	119 (18)	326 (91)	251 (71)	157 (36)	299 (79)	226 (54)	
	Clay:	176 (97)	142 (89)	167 (52)	146 (91)	377 (158)	283 (159)	202 (155)	353 (158)	271 (164)	F, I
Mean pressure (kPa)	Greenset:	100 (17)	74 (9)	72 (12)	59 (10)	195 (53)	136 (31)	89 (15)	176 (47)	108 (21)	
	Clay:	112 (64)	86 (53)	78 (27)	70 (33)	222 (88)	143 (62)	109 (67)	190 (66)	118 (45)	F
Mean area (cm^2)	Greenset:	8 (3)	5 (2)	13 (6)	12 (3)	11 (2)	11 (2)	9 (1)	9 (2)	15 (2)	
	Clay:	8 (3)	6 (3)	14 (6)	13 (5)	10 (2)	11 (3)	9 (2)	8 (2)	12 (3)**	F, I
Contact time (ms)	Greenset:	214 (97)	203 (62)	256 (70)	249 (71)	266 (63)	266 (59)	258 (64)	266 (62)	266 (61)	
	Clay:	293 (107)	280 (78)	327 (86)	322 (85)	345 (73)	338 (72)	319 (83)	344 (73)	342 (73)	F, S

Values are mean (SD).
F and S indicate significant main effects of foot region and surface; I indicates a significant interaction between foot region and surface.
*$p<0.05$; **$p<0.01$; ***$p<0.001$ denote significant difference between Greenset and clay.

What is already known on this topic

- Playing surface has been shown to influence injury rates dramatically in tennis.
- Significantly fewer injuries are generally observed on clay courts or synthetic surfaces when compared to hard courts.
- The frictional characteristics of the tennis court–shoe interface is a major risk factor for lower extremity injuries in tennis.

What this study adds

- Foot loading is affected by playing surfaces during tennis activities.
- Greenset induced higher loading in the hallux and lesser toes areas but lower relative load on the medial and lateral midfoot than clay.
- These results suggest different injury prevention strategies should be applied for different surfaces.

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REFERENCES

1 **Fernandez J**, Mendez-Villanueva A, Pluim BM. Intensity of tennis match play. *Br J Sports Med* 2006;**40**:387–91.
2 **Nigg BM**, Segesser B. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. *Sports Med* 1988;**5**:375–85.
3 **Perkins RH**, Davis D. Musculoskeletal injuries in tennis. *Phys Med Rehabil Clin N Am* 2006;**17**:609–31.
4 **Lees A**. Science and the major racket sports: a review. *J Sports Sci* 2003;**21**:707–32.
5 **Zecher SB**, Leach RE. Lower leg and foot injuries in tennis and other racquet sports. *Clin Sports Med* 1995;**14**:223–39.
6 **Bylak J**, Hutchinson MR. Common sports injuries in young tennis players. *Sports Med* 1998;**26**:119–32.
7 **Feit EM**, Berenter R. Lower extremity tennis injuries. Prevalence, aetiology and mechanism. *J Am Podiatr Med Assoc* 1993;**83**:509–14.
8 **Kibler WB**, Safran MR. Musculoskeletal injuries in the young tennis player. *Clin Sports Med* 2000;**19**:781–92.
9 **Pluim BM**, Staal JB, Windler GE, *et al*. Tennis injuries: occurrence, aetiology, and prevention. *Br J Sports Med* 2006;**40**:415–23.
10 **Hutchinson MR**, Laprade RF, Burnett QM, *et al*. Injury surveillance at the USTA Boys' Tennis Championships: a 6-yr study. *Med Sci Sports Exerc* 1995;**27**:826–30.
11 **Kibler WB**, Safran M. Tennis injuries. *Med Sport Sci* 2005;**48**:120–37.
12 **Girard O**, Millet GP. Effects of the ground surface on the physiological and technical responses in young tennis players. In: Lees A, Kahn JF, Maynard IW, eds. *Science and racket sports III*. London: Routledge, 2004:43–8.
13 **Kulund DN**, McCue FC, Rockwell DA, *et al*. Tennis injuries: prevention and treatment. A review. *Am J Sports Med* 1979;**7**:249–53.
14 **Hockenbury RT**. Forefoot problems in athletes. *Med Sci Sports Exerc* 1999;**31**:S448–58.
15 **Kernozek TW**, Zimmer KA. Reliability and running speed effects of in-shoe loading measurements during slow treadmill running. *Foot Ankle Int* 2000;**21**:749–52.
16 **Eils E**, Streyl M, Linnenbecker S, *et al*. Characteristic plantar pressure distribution patterns during soccer-specific movements. *Am J Sports Med* 2004;**32**:140–5.
17 **Bland JM**, Altman DG. Multiple significance tests: the Bonferroni method. *Br Med J* 1995;**310**:170.
18 **Lehman RC**. Surface and equipment variables in tennis injuries. *Clin Sports Med* 1988;**7**:229–32.
19 **Stiles VH**, Dixon SJ. The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant. *J Appl Biomech* 2006;**22**:14–24.
20 **Nigg BM**, Yeadon MR. Biomechanical aspects of playing surfaces. *J Sports Sci* 1987;**5**:117–45.
21 **Ford KR**, Manson NA, Evans BJ, *et al*. Comparison of in-shoe foot loading patterns on natural grass and synthetic turf. *J Sci Med Sport* 2006;**9**:433–40.
22 **Wong PL**, Chamari K, Mao de W, *et al*. Higher plantar pressure on the medial side in four soccer-related movements. *Br J Sports Med* 2007;**41**:93–100.
23 **Coe A**, Miley D. Adjusting to different surfaces. In: Roetert P, Groppel J, eds. *World-class tennis technique*. Champaign, Illinois: Human Kinetics, 2001:41–60.
24 **Lynch SA**, Renström P. Foot problems in tennis. In: Renström P, eds. *Tennis*. Oxford, UK: Blackwell, 2002:155–64.
25 **Renstrom AF**. Knee pain in tennis players. *Clin Sports Med* 1995;**14**:163–75.
26 **Middleton JA**, Kolodin EL. Plantar fasciitis-heel pain in athletes. *J Athl Train* 1992;**27**:70–5.
27 **Trepman E**, Mizel MS, Newberg AH. Partial rupture of the flexor hallucis longus tendon in a tennis player: a case report. *Foot Ankle Int* 1995;**16**:227–31.
28 **Nigg BM**. The role of impact forces and foot pronation: a new paradigm. *Clin J Sport Med* 2001;**11**:2–9.
29 **Clement DB**. Tibial stress syndrome in athletes. *J Sports Med* 1974;**2**:81–5.
30 **Sobel J**, Ellenbecker TS, Roetert EP. Flexibility training for tennis. *Strength Cond* 1995;**17**:43–50.
31 **Deutsch E**, Deutsch SL, Douglas PS. Exercise training for competitive tennis. *Clin Sports Med* 1988;**7**:417–27.
32 **Gerritsen K**, Nigg BM, Wright IC. Shoes and surfaces in tennis: injury and performance aspects. In: Renström P, eds. *Tennis*. Oxford, UK: Blackwell, 2002:39–45.
33 **Hodge MC**, Bach TM, Carter GM. Orthotoc management of plantar pressure and pain in rheumatoid arthritis. *Clin Biomech* 1999;**14**:567–75.
34 **Wolgin M**, Cook C, Graham C, *et al*. Conservative treatment of plantar heel pain: long-term follow-up. *Foot Ankle Int* 1994;**15**:97–102.