Effects of the Playing Surface on Plantar Pressures During the First Serve in Tennis

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Purpose: This study aimed at examining the influence of different playing surfaces on in-shoe loading patterns in each foot (back and front) separately during the first serve in tennis. Methods: Ten competitive tennis players completed randomly five first (ie, flat) serves on two different playing surfaces: clay vs GreenSet. Maximum and mean force, peak and mean pressure, mean area, contact area and relative load were recorded by Pedar insoles divided into 9 areas for analysis. Results: Mean pressure was significantly lower (123 ± 30 vs 98 ± 26 kPa; −18.5%; P < .05) on clay than on GreenSet when examining the entire back foot. GreenSet induced higher mean pressures under the medial forefoot, lateral forefoot and hallux of the back foot (+9.9%, +3.5% and +15.9%, respectively; both P < .01) in conjunction with a trend toward higher maximal forces in the back hallux (+15.1%, P = .08). Peak pressures recorded under the central and lateral forefoot (+21.8% and +25.1%; P < .05) of the front foot but also the mean area values measured on the back medial and lateral midfoot were higher (P < .05) on clay. No significant interaction between foot region and playing surface on relative load was found. Conclusions: It is suggested that in-shoe loading parameters characterizing the first serve in tennis are adjusted according to the ground type surface. A lesser asymmetry in peak (P < .01) and mean (P < .001) pressures between the two feet was found on clay, suggesting a greater need for stability on this surface.

Keywords: tennis serve, plantar loading, clay, GreenSet

The uniqueness of the game of tennis is the possibility to compete on various playing surfaces; a point that is notably illustrated by the fact that the four Grand Slam tournaments are played on different surfaces. Compared with hard courts (eg, GreenSet), competing on clay has been usually associated with longer playing times (ie, greater exercise to rest ratio) and distance ran, a higher number of strokes (topspin backhands and forehands) per game, lesser incidence of lower extremity injuries as well as increased metabolic and cardio-respiratory load (ie, higher blood lactate concentration, heart rate and oxygen uptake responses). In investigating the influence of the playing surface on the amplitude and distribution...
of plantar pressures during tennis-specific movements, we have also reported that clay induced lower loading in the hallux and lesser toes areas but higher relative load on the medial and lateral midfoot.\textsuperscript{5} This is the result of a lower frictional resistance on slow vs. fast surfaces, as evidenced by reduction in ball velocities associated to higher and slower rebounds on clay.\textsuperscript{6}

The serve in tennis is the predominant stroke, accounting for 45\% (French Open) to 60\% (Wimbledon) of the total number of strokes during service games.\textsuperscript{3,4} A forceful lower limb drive is considered as the “starting point” of the kinetic chain and influences directly serve efficiency.\textsuperscript{7} To achieve the different tactical objectives of playing on various surfaces (ie, clay: baseline play; GreenSet: serve and volley play),\textsuperscript{3} it is conceivable that players adapt their lower limb involvement by modifying the nature (ie, magnitude and distribution) of in-shoe loading patterns. During the first serve in tennis, the propulsion of the lower extremities is primarily orientated upward to reach optimal racquet/ball impact heights; this proficiency increases along with playing skill.\textsuperscript{7,8} Although of lesser magnitude, the forward propulsive forces—that allow players to travel a approximately 50 cm distance into the court with the first step, depending on the stance style being used—are known to affect the production of linear and angular momentum.\textsuperscript{9,10} It is therefore likely that the ground surface friction would influence the foot load repartition during the serve, as observed in walking on different slippery surfaces.\textsuperscript{11} It is known that on slippery (eg, oily, snowy or sandy) surfaces, humans tend to maximize the friction between feet and surfaces by shifting the ground reaction forces (GRF) to a more vertical direction.\textsuperscript{11} This is achieved by a subtle increase in toe grip (eg, higher pressures in hallux or toes regions).

To date, however, the role of the tennis surface on loading patterns of the feet during the serve remains unknown. This study aimed at examining the influence of two different playing surfaces on in-shoe loading patterns in each foot (back and front) separately during the first serve in tennis. We hypothesized that, for stability reasons, pressure differences between the two feet would be lower on clay than on GreenSet.

**Methods**

**Subjects**

Ten (7 males, 3 females) competitive tennis players (mean [SD] age 23.8 [6.0] y; height 171.7 [8.1] cm; body mass 65.8 [8.7] kg) of International Tennis Number 3 (ITN 3) standing or higher volunteered to participate in the study. Subjects were eligible to participate if they had no history of injury to the lower extremity within the past year and no previous surgery. They signed a written consent before participation. Approval for the study was obtained from the local ethics committee.

**Experimental Setup**

After a standardized warm-up lasting 15 min (ie, submaximal run, sprinting, practice serve with increasing speed), subjects performed five first (ie, flat with minimum spin on the ball) serves from the “deuce” court on clay and GreenSet. All serve trials were completed from the “deuce” or right court with a 30 s rest
between trials. Before initiating any serve action, subjects kept the starting position for 3 s. They were then requested to hit their serves to a 1 × 1 m target area bordering the “T” of the right service box at match pace. Depending on their own preference, physical and technical characteristics but also their style of play, subjects assumed an individual stance— ie, between the foot-up and foot-back techniques—in the starting position. All subjects were right-handed and used their own racquet.

**Instrumentation**

Insole plantar pressure distribution was recorded using the X-Pedar Mobile System (Novel GmbH, Munich, Germany). Each pressure insole consisted of a 2-mm-thick array of 99 capacitive pressure sensors. Before commencement of data collection, the insoles were calibrated according to the manufacturer’s guidelines. This involved loading the insoles to a range of known pressure values, which resulted in an individual calibration curve for all sensors within the shoe (TruBlu Calibration, Novel GmbH, Munich, Germany). The insoles were placed bilaterally inside the subject’s shoes. The data logger for data storage was in a harness on the chest of the subject. Plantar pressures were sampled at 50 Hz via Bluetooth technology. An excellent reproducibility has been reported for this device.  

**Plantar Pressure Data**

A regional analysis of each foot was performed utilizing nine separate “masks” or areas of the foot, ie, medial and lateral heel, medial and lateral midfoot, medial, central and lateral forefoot, hallux and lesser toes (Groupmask Evaluation, Novel GmbH, Munich, Germany). 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 area. 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.  

For each trial, the analyzed period started at the onset of any foot movement and ended at take-off. Analyses were performed with the appropriate software (Novel Win, Novel GmbH, Munich, Germany).

**Statistical Analyses**

Mean (SD) was calculated for all variables. A two-way repeated-measures ANOVA was used to examine the effect of playing surface on the overall plantar pressure differences between front and back foot. In addition, for the front and the back foot (separately), a two-way repeated-measures ANOVA was performed with playing surface (clay vs GreenSet) and foot region (masks one to nine) as the repeated factors and the foot loading parameters designated as dependent variables. A large number of comparisons leads to an inflated Type I error in ANOVA test. Therefore the Holm’s correction was applied. Briefly, it is a procedure recommended in biomechanics that consists in a progressive adjustment in the alpha level based on the number of comparisons and the desired experiment error rate. The statistical analyses were performed using SPSS for Windows (SPSS Inc., version 17.0, Chicago, IL).
Results

Whole Foot

Independently of the playing surface, statistical analysis revealed higher \( (P < .05) \) peak and mean pressures under the back compared with the front foot when examining the overall foot, but only a tendency to be higher for contact area and mean forces (both \( P = .07 \)) (Table 1). The interaction between type of foot and playing surface was significant for peak \( (P < .01) \) and mean \( (P < .001) \) pressures, but not for maximal force \( (P = .09) \).

Foot Pressure Distribution

All parameters displayed a foot region effect \( (P < .001) \) in both feet. ANOVA revealed that playing surface had a significant effect on peak \( (P < .05) \) and mean \( (P < .001) \) pressures of the front foot. The interaction of foot region and playing surface was significant for the maximum \( (P < .01) \) and mean \( (P < .05) \) forces, mean pressure \( (P < .001) \) and mean area \( (P < .01) \) of the back foot as well as for the front foot peak pressure \( (P = .05) \). GreenSet induced higher mean pressures under the medial forefoot, lateral forefoot and hallux of the back foot (+9.9%, +3.5% and +15.9%, respectively; both \( P < .01 \)) in conjunction with a trend toward higher maximal forces in the back hallux (+15.1%, \( P = .08 \)). Peak pressures recorded under the central and lateral forefoot (+21.8% and +25.1%; \( P < .05 \)) of the front foot as well as the mean area values measured on the back medial and lateral midfoot were higher \( (P < .05) \) on clay. A summary of plantar pressure parameters changes for each foot region during the first serve between the two playing surfaces is presented in Figure 1.

**Figure 1** — The main changes of the plantar loading parameters for front (left) and back (right) feet during the first serve in tennis on clay and GreenSet in each of the nine areas of interest.
Table 1  Plantar pressure parameters for the whole foot during the first serve in tennis on clay and GreenSet under the front (left) and the back (right) foot

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Front Foot (Left)</th>
<th>Back Foot (Right)</th>
<th>Δ GreenSet vs Clay (% GreenSet)</th>
<th>Δ Front vs Back Foot (% Front Foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GreenSet</td>
<td>Clay</td>
<td>GreenSet</td>
<td>Clay</td>
</tr>
<tr>
<td>Maximum force (N)</td>
<td>845 ± 281</td>
<td>921 ± 204</td>
<td>1034 ± 163</td>
<td>951 ± 244</td>
</tr>
<tr>
<td>Mean force (N)</td>
<td>472 ± 212</td>
<td>464 ± 111</td>
<td>623 ± 131</td>
<td>587 ± 182</td>
</tr>
<tr>
<td>Peak pressure (kPa)</td>
<td>240 ± 81</td>
<td>277 ± 110</td>
<td>400 ± 115</td>
<td>366 ± 109</td>
</tr>
<tr>
<td>Mean pressure (kPa)</td>
<td>87 ± 21</td>
<td>95 ± 21</td>
<td>123 ± 30</td>
<td>98 ± 26</td>
</tr>
<tr>
<td>Contact area (cm²)</td>
<td>118 ± 27</td>
<td>119 ± 21</td>
<td>134 ± 33</td>
<td>138 ± 23</td>
</tr>
<tr>
<td>Mean area (cm²)</td>
<td>74 ± 21</td>
<td>76 ± 13</td>
<td>81 ± 19</td>
<td>89 ± 22</td>
</tr>
</tbody>
</table>

* $P < .05$ significantly different between front and back foot (independently of the playing surface).
** $P < .01$; *** $P < .001$ denote significant interaction between playing surface and foot type.
No significant interaction between foot region and playing surface on relative load was found (Figure 2).

**Figure 2** — Mean and standard deviation relative load (%) for each foot region under the front (Panel A) and back (Panel B) feet during the first serve in tennis on clay and GreenSet.
Discussion

Several authors have published studies on the factors (eg, performance level, fatigue, foot arrangement, ergogenic aids) affecting racket speed generation and accuracy in the tennis serve.\(^7\)-\(^9\),\(^14\) By influencing plantar pressures, ground reaction forces and joint kinematics, shoe-surface frictional properties have also the potential to modify the efficiency of tennis on-court movements. For instance, when different types of playing surfaces were compared, evidence of lower relative load on the medial and lateral midfoot\(^6\) in conjunction with lower peak vertical impact force normalized to body weight\(^15\) has been found during tennis specific movements on the hardest surface. In addition, it was reported that the surface with the lowest mechanical cushioning resulted in the lowest vertical force magnitude during the running tennis forehand impact phase.\(^16\) However, it is still unknown whether the ground type surface would influence plantar loading during the serve, and provided as the focus of this study.

Data from this study show that executing first serves on GreenSet vs clay induced a 10% to 15% nonsignificant increase in plantar pressures (eg, maximum force, peak and mean pressures) under the front foot, while loading under the back foot was 7% to 18% lower. This would indicate that the above-mentioned in-shoe loading characteristics are sensitive to changes in surface cushioning during tennis first serves. Nevertheless, increasing the subjects’ sample is needed to confirm these findings. When competing on fast surfaces, players generally develop a more aggressive game style (ie, net-rushers). The greater proportion of rallies played toward the net on these particular surfaces confirms this viewpoint.\(^3\) When examining the entire back foot, mean pressure values determined in this study were 18.5% higher on GreenSet than on clay. The back foot plays a role in the initiation of the move to the net on fast surfaces in getting the center of mass moving toward the net and ahead of the front foot— that is, presumably by increasing mean pressure values under the medial forefoot, lateral forefoot and hallux areas on GreenSet. In contrast, the higher peak pressures recorded on clay under the central and lateral forefoot of the front foot would help to create changes in the amount of linear and angular momentums (eg, ball toss, impact height, racquet path), that will lead to a more defensive game style (ie, long rallies from behind the baseline) on this surface.\(^3\) Nevertheless, research is needed to assess how kinematic adjustments might occur when executing serves on different playing surfaces. It has been argued that the greater number of strokes on clay could contribute to earlier fatigue.\(^4\) Since pedography analysis can be successfully used to detect fatigue-induced changes in plantar surface loading characteristics, as did previously for treadmill running\(^17\) —future studies should determine whether prolonged tennis playing leads to significant changes in magnitude and/or distribution of plantar pressures, which in turn can increase the risk of overuse injury.

Several studies have investigated the GRF during the tennis serve,\(^7\),\(^8\),\(^10\),\(^18\) and highlighted the paramount importance of the lower limb drive. In examining the lower extremities activity that characterized the first serve of players of different playing standards, Girard et al\(^7\) found elite players to generate higher vertical GRFs than both intermediate and beginner players. However, none of the available source in the literature has differentiated the respective force of each foot, as Impellizzeri et al\(^19\) did for the countermovement jump. Our results showing a higher
asymmetry in forces and pressures between the two feet on GreenSet vs clay is of high interest. Theoretically, a fully symmetrical standing posture provides maximum stability, at least in healthy subjects, while with increasing weight-bearing asymmetry, kinetic and postural regulation increase. Genthon and Rougier demonstrated the negative effects of an asymmetrical body weight distribution on the control of undisturbed upright stance. They reported that the amplitudes of the “center of pressure” under both feet increased with increasing weight-bearing asymmetry in both the lateral and antero-posterior directions. More recently, it has been highlighted that the overall plantar pressure of the preferred foot was higher than that of the nonpreferred foot in four soccer-related movements. Specifically, higher pressure was found in the preferred foot during the take-off phase, whereas this was found in the nonpreferred foot during the landing phase. This has been interpreted as a tendency of the preferred foot for higher motion force and of the nonpreferred foot for a greater role in body stabilization. Due to the different nature of the movement, any comparison between results from this study and our data remains anecdotal. Interestingly, however, it has been proposed that the front foot (ie, nonpreferred for right-handed players) provides the stable post to allow rotational momentum during the serve. Under this scenario, the back foot should represent a large base for force production and the starting point for kinetic chain developing from the ground to the leg, trunk, upper body segments and finally the racquet. Further studies investigating the role of each leg on serve efficiency are worthy of interest.

During explosive movements involving stretch-shortening cycle such as countermovement jumps, it is known that the range of normal bilateral strength asymmetry is ±15%. The asymmetries of forces measured in the current study were more marked (eg, maximum force: +30% and +189% on clay and GreenSet, respectively) indicating functional instead of postural differences between feet during the serve in tennis. Nevertheless, it is unknown if the lesser asymmetry in tennis serve plantar pressures observed on clay is related to the lower serve efficiency (eg, average first serve ball velocity for men: 160 vs 185 km·h⁻¹ at the French Open vs Wimbledon, respectively) commonly reported for this surface. More tellingly, the lowest degree of asymmetry observed on clay may reflect an increased need for stability (due to surface characteristics) that, at the same time, could have detrimental effects on motor performance. In addition, one may argue that the tactics adopted on clay would be, at least partly, under the influence of the slippery characteristics of this surface and initiated from the ground—that is, lower limb drive during the serve—and not due only to the longer time prior the next stroke due to the slower surface. According to this standpoint, due, at least partly, to lower stability and grip, serving on clay would have modified the magnitude and orientation (to a more vertical direction, when compared with GreenSet) of GRF and therefore the effective use of coordinated sequential movements through the kinetic chain and the overall efficiency of the serve. Further research investigating the effects of the friction coefficient of the surface with different players’ level would help to answer the question of whether surface slipperiness is an influencing factor of the lower limb drive and of the serve efficiency in tennis and explain the difference between ball velocities observed in professional tennis on various Grand Slam tournaments.
Practical implications

This study is the first to report plantar loading differences during the first serve between clay and GreenSet. The need to practice regularly on both surfaces is emphasized, especially if players are continuously forced to compete on various ground type surfaces.

Owing to the greater need for postural stability when serving on clay, we suggest that a harder insert—which is known to increase the stability of the human body—should be used (ie, under the back foot to increase the possibility to produce force from the ground) to attenuate the negative impact of a soft surface (clay) on feet asymmetry.

Additionally, different fitness training programs could be used for each foot to increase the bilateral difference in foot loading on a given surface.

Conclusion

In-shoe loading parameters characterizing the first serve in tennis are adjusted according to the ground type surface to account for the different frictional properties between clay and GreenSet. Moreover, the conservative behavior of the players on clay might originate from a greater need for stability on this surface.

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References

11. Fong DT, Mao DW, Li JX, Hong Y. Greater toe grip and gentler heel strike are the strategies to adapt to slippery surface. *J Biomech*. 2008;41:838–844.