Original Article

A single step analysis of plantar pressure distribution in tennis specific movements

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ABSTRACT

Studies indicate that injury risks in tennis depend on the playing surface type. In order to assess loading during tennis specific movements, plantar pressure parameters are determined and analyzed. So far, only comparisons between whole stride sequences on different surfaces have been performed showing some inconsistent results. We assumed that on the more slippery clay higher vertical forces are required to accelerate, and that on hard-court higher loadings occur during deceleration. Hence, we analyzed the influence of the playing surface on respective types of steps. Eight experienced male tennis players performed two different tennis specific movements on clay and hard-court. We used a Pedar-X insole measurement system for determining selected plantar pressure parameters for the whole foot as well as for the forefoot and rear foot area. Steps were categorized as accelerating or decelerating regarding the path of the center of pressure during impact of the foot on the ground. For accelerating steps, a multivariate analysis revealed significant differences (Pillai-Spur; $p < .05$) for both repeated factors as well as their interaction for both playing conditions. All loading parameters were significantly higher in the forefoot area on clay for one of the two playing conditions investigated. For decelerating steps, the multivariate analysis revealed significant differences for both repeated factors for one playing condition. Higher values were observed for all loading parameters in the rear foot area in both playing conditions on clay. Running styles during tennis specific movements depend on the court surface. Separate analyses of acceleration and deceleration steps may help revealing high-risk parts and periods. **Keywords:** Playing surface; Load; Injury; Hard-court; Clay.

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INTRODUCTION

An increasing number of sports facilities is equipped with synthetic playing surfaces. Reasons, among others, are their versatility, their durability and the lower costs in maintenance (cf. Taylor et al., 2012). Physiological load (Reid et al., 2013) and playing behavior are affected by the surface layer. Surface properties may thus affect injury rates (Miller, 2006; Stiles and Dixon, 2006; Dragoo and Braun, 2010; Clarke et al., 2013; Damm et al., 2014).

In particular, tennis players suffer from playing surface transitions, as they often need to adjust to dissimilar surfaces with every surface having different properties. Several studies indicate higher injury risks when playing tennis on grass or, even more clearly, on hard-court surfaces than on clay (Nigg and Segesser, 1988; Nigg, 2003; Barnett and Pollard, 2007; Fu et al., 2018; Pluim et al., 2018). Moreover, the physiological demands have increased drastically. While in the past a physically gentler serve and volley style was predominant, modern tennis is represented by baseline counter-punchers. This is because tournament operators continue to slow down the surface-speed at any type of surface. Consequently, defenders have more time to prepare for eventual passing shots resulting in longer baseline rallies and a higher number of steps, which probably increases the risk of injury.

Girard et al. (2007) and Girard et al. (2010) compared plantar pressures between clay and hard-court (Greenset) in order to assess loading. They analyzed stride sequences and found that hard-court induced higher loadings in the hallux and lesser toes area. This result is not evident thinking of the properties of a clay court and a hard-court. Due to the more slippery clay, players might need more vertical force to initiate a movement on this particular surface, which would imply a higher loading in the forefoot area. On the other hand, injuries mostly occur at deceleration steps (Griffin et al. 2006), e.g. before or during a directional change, which is typical during tennis play. Here, courts that allow more sliding should result in lower loading parameters. More generally, it is obvious that playing on different surfaces results in different foot strike techniques (Damm et al., 2013).

In order to get a better understanding of the respective relationships, the influence of the playing surface on specific types of steps, in particular as occurring during accelerating and decelerating tennis specific runs, was analyzed.

MATERIALS AND METHODS

The methodological approach follows that given in Eckl et al. (2011): Eight right handed male tennis players (age: 22 ± 2.6 years; body mass 65 ± 3.2 kg; height: 1.73 ± 0.05 m; similar playing style) with an International Tennis Number (ITN) of 6 or better participated in the study. The ITN is based on ITF (International Tennis Federation) standards and describes and categorizes the playing level of a tennis player. An ITN of 6 or better represents a “well-playing non-professional tennis player”, which appeared to be sufficient for the present study. None of the subjects was restrained by injury or fatigue. Approval for this study was obtained from the local ethics committee. Players had to perform two different tennis specific movements with own shoes (seven players all-court shoes, one player clay-court shoes – also for hard-court use) on the two playing surfaces clay and hard-court: (1) eight shuttle runs as described by Girard et al. (2007) to simulate baseline play and (2) a sequence of ten forehand strokes. To complete the shuttle runs (Figure 1) players had to start from the base and run to every single point (1 to 8 in that order). At reaching each point, players were asked to simulate a groundstroke swing. After reaching a point, players had to return to the base. Measurement started when players left the base for the first time and finished after reaching point 8.

Within the sequence of the forehand strokes (set up shown in Figure 2) players had to try to reach and return ten tennis balls, which were thrown at a defined speed from a ball machine. Players stood behind a mark in the middle of the court in front of the baseline and started when the ball left the ball machine. Balls were thrown as depicted in Figure 2 and bounced about three meters before the baseline and one meter to the sideline. After every attempt to reach the ball, the players had to return to their starting position. Data were analyzed from the first step heading to the first ball thrown out of the machine until the first step after returning the tenth ball.

After a warm up and two trials to familiarize with the conditions of the baseline play, a third trial was used for data recording and evaluation. The forehand play was preceded by five strokes.

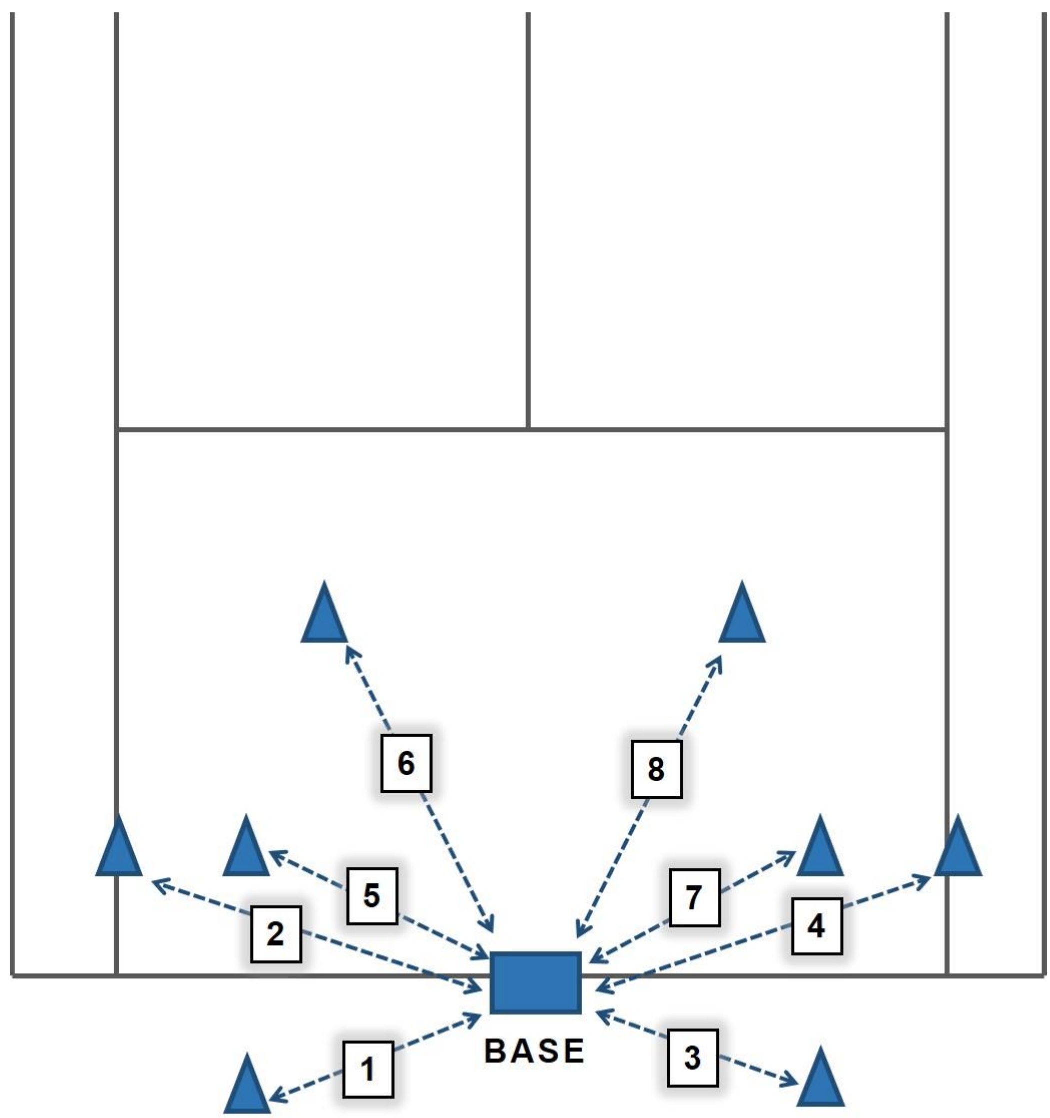

Figure 1. Baseline Play/Shuttle Run. Players start at base and reach points 1-8 as fast as possible

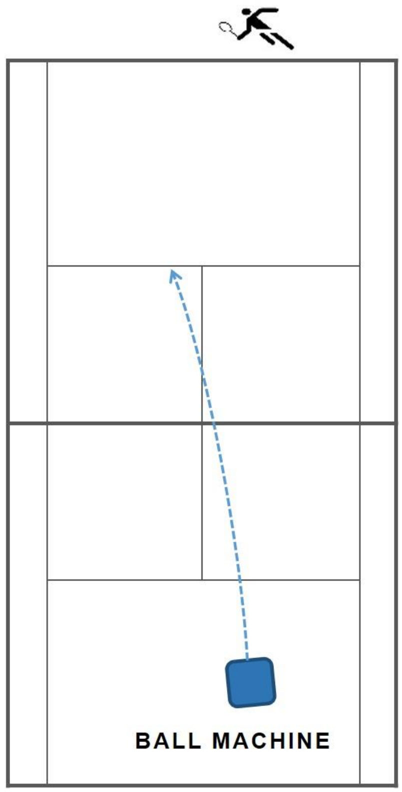

Figure 2. Forehand Play. Players start just behind the middle of the baseline and perform a sequence of 10 forehand strokes

A Pedar-X insole measurement system (Novel GmbH, Munich, Germany) was used for recording plantar pressure distribution. The sensors were placed between the foot and the plantar surface of the right shoe. Pedar software summarizes pressure values continuously (50 Hz) from all activated sensors (up to 99) on the insole. The highest value during the measurement is considered as the maximum force. Peak pressure is the highest load on one particular sensor.

The whole foot was divided into two zones (rear foot and forefoot area as presented in Figure 3).

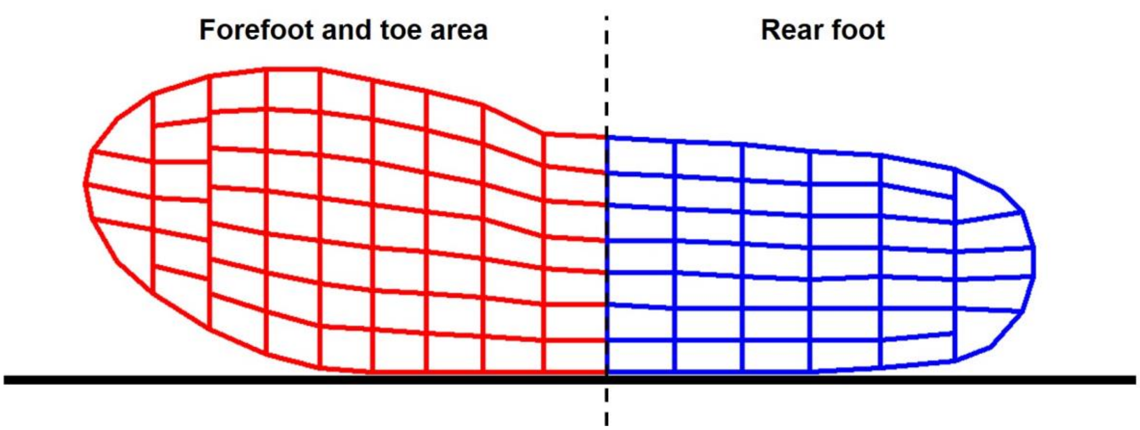

Figure 3. Definition of the two zones used in the analysis

Maximum force (pf), mean maximum force per step (mf), peak pressure (pp) and mean peak pressure per step (mp) were determined for the whole foot and for both zones.

We assumed that due to the short lengths and high intensity of runs players had to perform during the tennis specific movements, there were almost no phases of constant running speed and differentiated between accelerating (ac) and decelerating (dc) steps. The respective classification was based on the initial center of pressure (COP) during impact (ac: COP at toes and forefoot – “forefoot strike”; dc: COP at heel – “heel strike”). The curve shape of the vertical GRF and the path of the COP from the impact until toe off event confirmed this.

The first evaluation included all ac and dc steps. We calculated mean and standard deviation of all parameters for the whole foot, the forefoot and the rear foot and performed paired t-tests between hard court and clay condition. A repeated measures 2×2 multivariate analysis was performed with the surface (clay and hard-court) as well as the two zones as the repeated factors and pf, mf, pp and mp as the dependent variables for all steps. In case of significant main effects, we performed Bonferroni-corrected paired t-tests between surface conditions as post-hoc tests.

Within the second evaluation, the focus of the present paper, we distinguished between ac and dc steps. In addition, we performed separate analyses for the rear foot and forefoot area (Figure 3). We applied the same statistical methods as had been done for all steps.

Statistical significance was set at the 0.05 probability level. We used SPSS 23 (IBM Corpor., USA) for statistical analyses.

RESULTS

Plantar pressure parameters for both types of movements and both playing surfaces for the whole foot, the forefoot and rear foot area for all steps are given in Table 1.

Table 1. Foot loading parameters for the whole foot during tennis-specific movement on hard-court and clay in all steps. Results are reported as the mean (± SD)

	Forehand Play		Baseline Play	
	Hard	Clay	Hard	Clay
Maximum Force (N)	907 (97)	973 (13)	1170 (164)	962 (61) *
Mean Maximum Force (N)	704 (62)	826 (40) ***	823 (99)	760 (53)
Peak Pressure (Pa)	345 (44)	442 (38) **	411 (64)	450 (43) *
Mean Peak Pressure (Pa)	266 (6)	308 (14) ***	280 (31)	318 (23)

, ** and * denote $p < .05$, $p < .01$ and $p < .001$ significant difference between hard court and clay (paired t-test)*

The multivariate analysis revealed significant differences for the zone (Pillai-Spur/partial η^2: .994/.998) and the interaction of surface and zone (.953/.886) under both playing conditions (baseline/forehand). In Table 2, we present mean values and standard deviations of the analyzed parameters as well as observed significant main and interaction effects.

Table 2. Plantar pressure parameters for each foot zone during forehand and baseline play on hard-court and clay in all steps. Results are reported as the mean (± SD)

			Foot Zones		
	Playing Condition	Surface	Forefoot	Rear foot	Significant effects†
Maximum Force (N)	Forehand	Hard	810 (53)	671 (72)	Z, I
		Clay	931 (17) *	593 (33)	
	Baseline	Hard	1000 (129)	806 (108)	S, Z, I
		Clay	950 (56)	422 (103) *	
Mean Maximum Force (N)	Forehand	Hard	613 (56)	288 (62)	Z, I
		Clay	741 (36) *	219 (43) *	
	Baseline	Hard	690 (108)	256 (57)	Z, I
		Clay	728 (68)	105 (32) *	
Peak Pressure (Pa)	Forehand	Hard	332 (42)	287 (51)	Z, I
		Clay	442 (38) *	277 (15)	
	Baseline	Hard	389 (72)	314 (64)	Z, I
		Clay	450 (43)	190 (54) *	
Mean Peak Pressure (Pa)	Forehand	Hard	256 (10)	132 (12)	S, Z, I
		Clay	305 (15) *	99 (17) *	
	Baseline	Hard	264 (37)	122 (24)	Z, I
		Clay	314 (25) *	61 (17) *	

** denotes p < .05 significant difference between hard court and clay (paired t-test)*

† Z and S indicate significant main effects of foot zone and surface; I indicates a significant interaction between foot zone and surface

The concrete number of steps performed at baseline play per trial was quite similar for all players and surfaces (33 on average both on hard-court and on clay). At forehand play players tend to take more steps on hard-court, likely due to its non-slippery properties (72.5 for the forehand play on hard-court and 68.3 on clay).

Analysis of ac and dc steps

Considering ac steps, the multivariate analysis revealed significant differences for both repeated factors and their interaction for both playing conditions (surface: partial η^2: .973/.983; zone: .999/.999; interaction: .944/.984). For dc steps, we observed significant differences for both repeated factors and their interaction for forehand play (surface: .957; zone: .925; interaction: .891) and an interaction effect for baseline play (.992). Mean values and standard deviations of the analyzed parameters as well as observed significant main and interaction effects are given in Tables 3 (ac steps) and 4 (dc steps).

Table 3. Plantar pressure parameters for each foot zone during forehand and baseline play on hard-court and clay in acceleration steps. Results are reported as the mean (± SD)

			Foot Zones		
	Playing Condition	Surface	Forefoot	Rear foot	Significant effects†
Maximum Force (N)	Forehand	Hard	810 (53)	94 (33)	S, Z, I
		Clay	931 (17) *	117 (70)	
	Baseline	Hard	1000 (129)	137 (61)	Z
		Clay	950 (55)	121 (88)	

Mean Maximum Force (N)	Forehand	Hard	415 (57)	62 (26)	S, Z, I
		Clay	837 (27) *	51 (20)	
	Baseline	Hard	802 (113)	51 (22)	Z
		Clay	760 (52)	35 (22) *	
Peak Pressure (Pa)	Forehand	Hard	316 (19)	73 (11)	S, Z, I
		Clay	442 (38) *	75 (12)	
	Baseline	Hard	395 (80)	86 (24)	Z, I
		Clay	449 (43)	84 (39)	
Mean Peak Pressure (Pa)	Forehand	Hard	266 (11)	55 (12)	S, Z, I
		Clay	341 (20) *	45 (3)	
	Baseline	Hard	295 (53)	45 (9)	Z
		Clay	327 (25)	35 (13)	

** denotes p < .05 significant difference between hard court and clay (paired t-test)*
† Z and S indicate significant main effects of foot zone and surface; I indicates a significant interaction between foot zone and surface

Table 4. Plantar pressure parameters for each foot zone during forehand and baseline play on hard and clay in deceleration steps. Results are reported as the mean (± SD)

			Foot Zones		
	Playing Condition	Surface	Forefoot	Rear foot	Significant effects†
Maximum Force (N)	Forehand	Hard	591 (110)	671 (72)	S, Z, I
		Clay	810 (63)	593 (33) *	
	Baseline	Hard	593 (83)	806 (108)	S, I
		Clay	789 (46)	422 (103) *	
Mean Maximum Force (N)	Forehand	Hard	474 (68)	569 (67)	I
		Clay	602 (30) *	463 (37) *	
	Baseline	Hard	498 (93)	600 (98)	S, I
		Clay	639 (137)	348 (81) *	
Peak Pressure (Pa)	Forehand	Hard	302 (62)	287 (51)	Z
		Clay	327 (49)	277 (15) *	
	Baseline	Hard	285 (29)	314 (64)	S, Z, I
		Clay	347 (46)	190 (54) *	
Mean Peak Pressure (Pa)	Forehand	Hard	242 (22)	237 (27)	S, Z, I
		Clay	246 (24)	177 (13) *	
	Baseline	Hard	213 (23)	251 (38)	Z, I
		Clay	277 (55)	152 (37) *	

** denotes p < .05 significant difference between hard court and clay (paired t-test)*
† Z and S indicate significant main effects of foot zone and surface; I indicates a significant interaction between foot zone and surface

DISCUSSION

Considering all steps, we identified no clear tendency in baseline play, but significantly higher load parameter values for clay in forehand play for the whole foot (Table 1). These results do not agree with those given in Girard et al. (2007), who observed significantly lower mean maximum force values for clay in baseline play (identically performed as in our study) as well as serve-and-volley play. They also show some differences to the findings of Damm et al. (2014), who observed significantly lower mean and peak pressure values for two tennis specific motions on clay (side jumps out of stance and running forehand foot plants) and no significant differences for open stance forehand movements. The magnitude and direction of differences in loading parameters obviously not only depends on the surface, but, moreover, on the tennis specific movement performed (Damm et al., 2014). Besides of that, a limiting factor in all the studies based on plantar pressure measurements is that loads due to horizontal ground reaction forces cannot be assessed.

Outcomes that were more expressive resulted from a separate analysis of the forefoot and rear foot areas. During forehand play, we found significantly higher loadings in the forefoot area, as well as lower loadings (two parameters significant) in the rear foot area on clay. Baseline play revealed significantly lower loading parameters for the rear foot area on clay, whereas no clear indications were found for the forefoot area (Table 2). These results do not support the finding of Girard et al. (2007) that on hardcourt higher loads occur in the hallux and lesser toe areas. It may be assumed that the different findings are partly caused by the different areas investigated: The hallux and lesser toe area analyzed by Girard et al. (2007) covers a considerably smaller part from the foot than the forefoot area investigated in the present study. However, the results from the forehand play indicated quite the contrary. As expected, loading parameters on clay were higher.

From the single step analysis, we gained deeper insights. As expected, ac steps (Table 3) showed small loadings in the rear foot area in all playing conditions. We observed significantly higher loadings in the forefoot area on clay during forehand play, but no significant differences for baseline play. The latter did not confirm our expectations, since we assumed significantly higher parameter values on clay in both playing conditions. However, these results again confirm the assumption of a dependency of the loading behavior on the movement type analyzed, which might also be the reason for the peculiar results of Girard et al. (2007). While forehand play clearly demonstrates the necessity of higher force and pressure parameters on clay because of the smaller static coefficient of friction, the results for baseline play are less unambiguous. Different combinations of movement types, surfaces and shoe properties lead to different levels of friction affecting safety (Ura & Carré, 2016). We conclude that step sequences for representing typical behavior in tennis should carefully be selected or be a combination of different tennis specific tasks covering a wide range of typical running activities. In addition to the study of representative parameter values, a detailed analysis of pressure distributions might therefore provide more elucidative information on the differences observed in baseline and forehand play. Figure 4 illustrates pressure distributions for baseline as well as forehand play for one exemplary subject. Average pressure values for all ac and dc steps are shown. At baseline play as well as at forehand play the hallux area apparently needs more pressure to initiate a movement on the more slippery clay. We found no indications allowing explaining the differences observed in baseline and forehand play.

Dc steps (Table 4) showed significantly higher loads in the rear foot area both in forehand and baseline play on hard court. The larger static coefficient of friction on hard court enables a more dynamic foot strike thereby allowing a better traction. On clay, the friction coefficient is lower allowing a more slippery motion and therefore resulting in lower peak load values (Pluim et al., 2017; Damm et al., 2014). In addition, all loading parameters were higher on clay for the forefoot in both playing conditions. However, just one significant difference was observed. Moreover, it should be noted that on clay all loading parameter values are higher for the forefoot compared to the rear foot, while on hard court the opposite was observed in almost all cases. The heel obviously has to absorb a larger load on hard court whereas on clay the loadings allocate nearly equal over the whole foot. The foot strike on clay is less dynamic and more controlled. This different behavior can clearly be recognized in the presentation of the pressure distributions for the dc steps of the exemplary subject (Figure 4). It is also illustrated in Figure 5, where time curves of dc steps at baseline play are depicted for the same subject on hard court and clay. While on hard court the impact is sudden and intense in the beginning of the step, curves on clay are more smoothly.

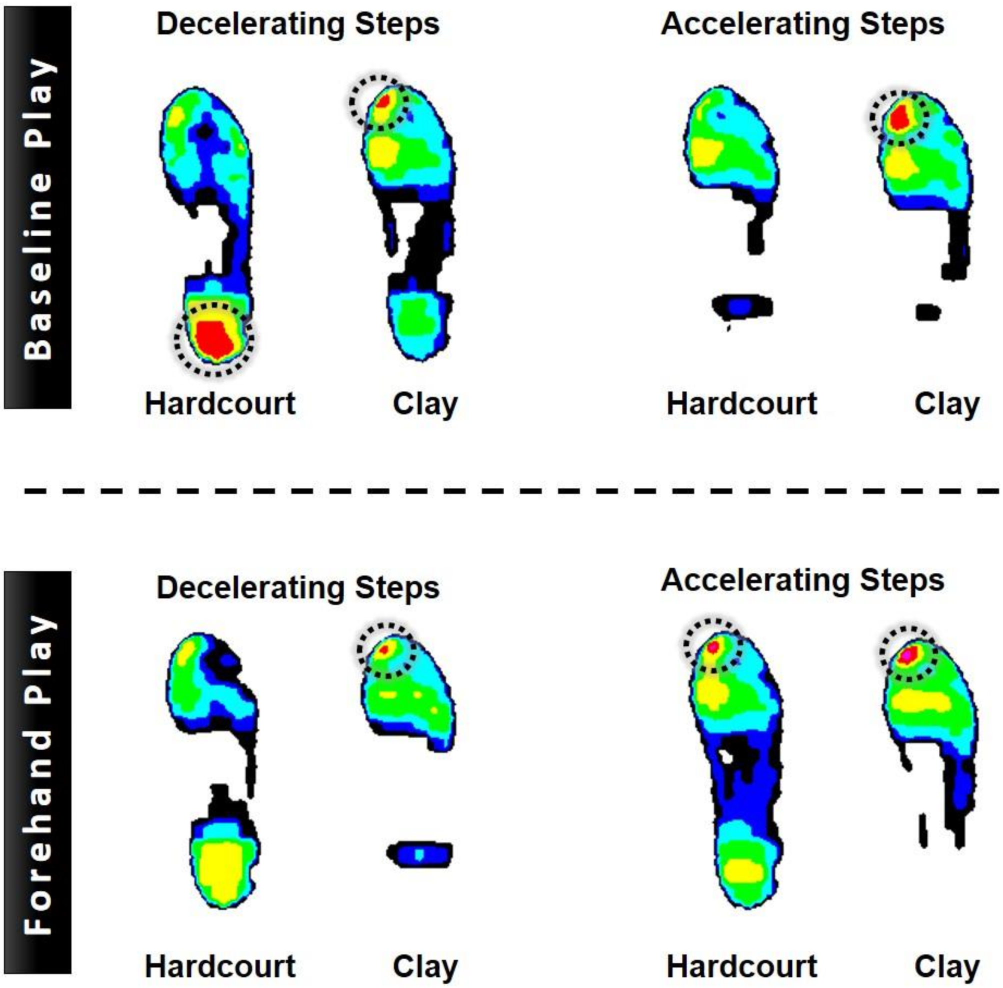

Figure 4. Pressure distributions for one exemplary player. Average pressure values for all steps analyzed are shown. Encircled areas represent high values, black areas low values

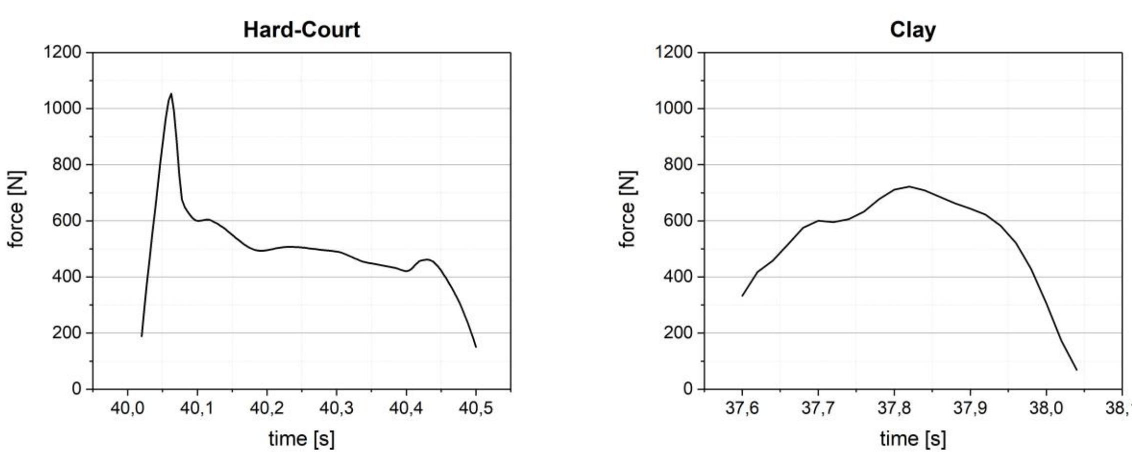

Figure 5. Time curves for pressure and force for dc steps. Same exemplary player as in Fig. 4

In addition, higher pressure values on the rear foot in baseline play compared to forehand play can be recognized in Figure 4. This becomes even clearer from Table 4: All parameter values for the rear foot are higher in baseline play. This clearly indicates different demands for the players in both playing conditions.

CONCLUSION

Plantar pressure measurements have been performed in order to get more insight into the effect of the playing surface on the load in tennis. There are some indications which can be derived from this investigation. Significantly higher force and pressure values could be observed for the rear foot area on the hard court. In the hallux and lesser toe as well as the forefoot area the results partly show significantly higher values on clay in forehand play. This confirms the assumption that higher pressure and force are essential for starting movements on the more slippery clay.

Higher loads on hard court in the front foot area could not be confirmed. Girard et al. (2007) gave a more aggressive play with an intensified forefoot running strategy as possible explanation for their findings. Other comparisons might not be expressive as Girard et al. (2007) did include serve-and-volley play in their study whereas in the present study a sequence of baseline-forehand-strokes was the second tennis specific movement. As already mentioned, serve-and-volley players are rarely around these days. This led to the decision to not include respective movements in the present study.

A more detailed analysis of the single steps within a movement brings more insight into these discrepancies. On hard court players have to absorb a higher impact when hitting the surface, while on clay the foot is able to roll more smoothly. Using different tread techniques might be useful when switching surfaces, especially a controlled heel strike might be beneficial on hard courts. Therefore, it could be helpful to take smaller steps. The present study also indicates that higher force values occur on clay during acceleration (on the forefoot area). This agrees with the assumption of an eventual need of higher force and pressure to accelerate on the more slippery clay.

The study shows that type of court surface affects plantar pressure distribution during tennis specific movements. A partition of the foot into two defined areas reveals different running styles during tennis specific movements depending on the court surface. Furthermore, a separation of single steps into acceleration and deceleration steps may help revealing high-risk parts and periods during those movements.

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