The Influence of Different Playing Surfaces on the Biomechanics of a Tennis Running Forehand Foot Plant

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Research suggests that heightened impacts, altered joint movement patterns, and changes in friction coefficient from the use of artificial surfaces in sport increase the prevalence of overuse injuries. The purposes of this study were to (a) develop procedures to assess a tennis-specific movement, (b) characterize the ground reaction force (GRF) impact phases of the movement, and (c) assess human response during impact with changes in common playing surfaces. In relation to the third purpose it was hypothesized that surfaces with greatest mechanical cushioning would yield lower impact forces (PkFz) and rates of loading. Six shod volunteers performed 8 running forehand trials on each surface condition: baseline, carpet, acrylic, and artificial turf. Force plate (960 Hz) and kinematic data (120 Hz) were collected simultaneously for each trial. Running forehand foot plants are typically characterized by 3 peaks in vertical GRF prior to a foot-off peak. Group mean PkFz was significantly lower and peak braking force was significantly higher on the baseline surface compared with the other three test surfaces ($p < 0.05$). No significant changes in initial kinematics were found to explain unexpected PkFz results. The baseline surface yielded a significantly higher coefficient of friction compared with the other three test surfaces ($p < 0.05$). While the hypothesis is rejected, biomechanical analysis has revealed changes in surface type with regard to GRF variables.

Key Words: impact, cushioning, ground reaction force, kinematics

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Hockey, athletics, and tennis are examples of sports that in the past predominantly took place on natural surfaces but now commonly occur on artificial surfaces (Cox, 2003). The development of artificial surfaces in sport was mainly the result of a need to reduce maintenance costs and the influence of adverse weather conditions on surface playing ability (Kolitzus, 1984; Nigg & Yeadon, 1987). Although artificial surfaces have helped extend the boundaries in some sporting domains such as gymnastics and athletic sprinting events, the force magnitudes and the direction of forces acting on the human body have also been altered (Nigg & Yeadon, 1987). Research has suggested that the increased use of artificial surfaces in place of natural surfaces in sport has led to a higher prevalence of overuse injuries (Nigg, Cole, & Stefanyshyn, 2003; Nigg & Yeadon, 1987). Research is needed to assess changes in loading and movement patterns when participating on different playing surfaces.

Surfaces in tennis are constructed from relatively stiff artificial materials. There is evidence of an increase in overuse injuries in tennis compared with when tennis was predominantly played on natural surfaces. Nigg and Segesser (1988) reported on findings from studies of recreational and professional players that yielded anecdotal evidence of an association between increased levels of lower extremity pain when playing on hard courts as opposed to more forgiving surfaces such as clay. Compared with other regions of the body, a high prevalence of lower extremity injury was also reported, with 85% of all pain from 171 participant questionnaires and physician assessments found to be in the foot (Nigg, Frederick, Hawes, & Luethi, 1986). Nigg and

Denoth (1980) and Nigg et al. (1986), who studied movement patterns on the court, also agree on the prevalence of pain and injury in the lower extremity in tennis players.

Many potential overuse injury causes have been suggested as resulting from increased use of artificial surfaces in sport. Suggested causes include increased levels of impact (Cavanagh & Lafortune, 1980; Frederick, Clarke, & Hamill, 1984; James, Bates, & Osternig, 1978; Light, MacLellan, & Klenerman, 1979; Miller, 1990; Nigg et al., 1986), altered joint movement patterns (Hamill, Bates, & Holt, 1992; Stergiou & Bates, 1997), and differing resistance to sliding between the shoe and surface (Nigg et al., 1986; Stucke, Baudzus, & Baumann, 1984). Quantitative measurement of impacts concerned with the collision between the foot and the ground has typically been reported using ground reaction forces (i.e., Dixon & Stiles, 2003; Nigg et al., 1986).

Motivation behind research concerning the impact peak of vertical ground reaction force relates to the suggested association between impact peak variables (magnitude and loading rate) and the occurrence of overuse injury in runners (Miller, 1990). However, running studies that have measured force variables with changes either in the cushioning afforded by shoes, surfaces, or both have typically reported that peak impact magnitudes are maintained at a similar level across conditions (Bobbert, Yeadon, & Nigg, 1992; Clarke, Frederick, & Cooper, 1982; Dixon, Collop, & Batt, 2000; Nigg & Yeadon, 1987).

Consistent with reports of impact force maintenance, Dixon and Stiles (2003) found no significant difference in vertical impact force or peak in-shoe heel pressures across surfaces typically used in tennis when running at a relaxed pace. They suggested that the mechanical cushioning properties of synthetic surfaces used in tennis were not sufficiently distinct to reveal changes in impact forces and thus demand changes in movement patterns. More dynamic movements than running are included in tennis, for example stopping, turning, and jumping. Lafortune (1997) highlighted the enhanced movement dynamics and task performance encountered in court sports (compared with running) and commented on the lack of sport-specific biomechanical procedures available to the researcher when assessing shoe-surface interaction.

Coyles, Lake, and Patritti (1998) also advocated the use of "highly dynamic manoeuvres" when assessing shoe-surface interactions. Thus for the assessment of human response to different tennis surfaces, the analysis of a highly dynamic tennis movement is likely to be more revealing than running.

To an extent, maintenance of impact peaks in running studies have been explained by kinematic adjustment, including increased initial knee flexion, reduced heel impact velocity, and reduced initial foot sole angle relative to the horizontal (Bobbert et al., 1992; De Wit and De Clercq, 1997). Support for the potential of initial knee angle to influence impact loading has also been provided from human pendulum studies (Lafortune, Hennig, & Lake, 1996) and modeling studies (Denoth, 1986; Gerritsen, van den Bogert, & Nigg, 1995). Joint kinematics are also influenced by sliding between the shoe and surface (Stucke et al., 1984). While changes in running kinematics have been reported, findings have often been inconsistent, highlighting our incomplete understanding of human adaptation. Studies of kinematic adaptation to changes in the shoe or surface for movements other than running have rarely been reported. Whereas running involves reproduction of a similar movement pattern for each stride, common movements such as stopping and turning are more isolated, task orientated skills. Thus it cannot be assumed that adjustments to changes in surface will be consistent with those observed during running.

In order to compare the impact phases for a movement performed on different surfaces, characterization of the movement is first required. For running, typical vertical and horizontal ground reaction force (GRF) time histories have been extensively reported. Time history profiles for the majority of movements in tennis are unknown. Therefore characterization of the GRF time histories should begin the study of a new movement. Impact peak characterization can be enhanced through identification of kinematic events associated with different aspects of the vertical GRF time history.

The purpose of the present study was threefold: (a) to develop procedures to assess a tennis specific movement; (b) to characterize the GRF impact phases of a tennis specific movement in a laboratory environment; and (c) to assess human response through group analysis during initial impact with changes in playing surface while performing a tennis

specific movement. In relation to the third purpose, it was hypothesized that surfaces with the greatest mechanical cushioning would result in the lowest impact forces and rates of loading when performing a tennis specific movement.

Method

Video observation of tennis and experimenter experience revealed an array of movements from which to select. Initial single participant analyses of two foot plants from a running forehand and a shuffle maneuver were performed. Peak vertical impact force (PkFz) measured using an AMTI force plate (Advanced Mechanical Technology, Inc., Newton, MA) sampling at 960 Hz revealed that the running forehand foot plant was more dynamic, eliciting forces of approximately 4 BW compared with 2 BW from the shuffle foot plant. The running forehand impact phase was characterized using data from a single participant. The running forehand foot plant then underwent analysis using more than one participant to assess impact peak variables, initial kinematics, and joint ranges of movement with changes in surface.

For a right-handed player, a running forehand foot plant involves an outstretched left leg followed by a foot plant made at the end of a dash to the ball (thus not allowing for an open-stance forehand) and which occurs at the same time as ball contact is made with the racket held in the right hand (Figure 1). To enforce the desired movement, participants were shown a picture, video, and live demonstration of the movement in the laboratory. A tennis racket was also held to help with timing and thus enhance the ecological validity of the movement.
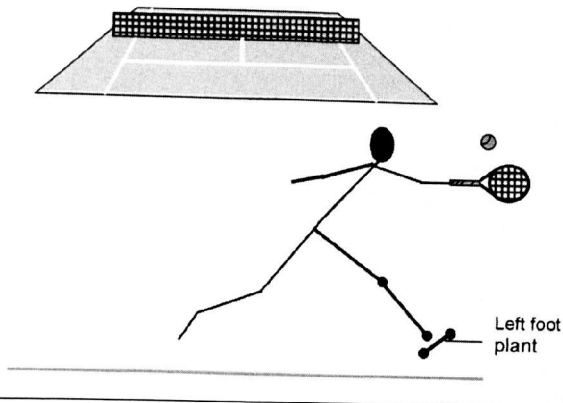

Figure 1 — Running forehand foot plant.

Participants ran over a 9-meter distance (the distance representative of dashing from one side of the court to playing the shot while in the opposite tramlines) at a submaximal but self-selected speed and planted their foot in a marked area (force plate). The foot plant acts as the primary decelerating step to terminate the sprint. Typical tennis recovery steps occurred after the desired foot plant (small deceleration steps in the direction of the movement). Entry times over a 2-meter distance prior to the foot plant were measured using photocells to provide an indication of running speed reliability.

Single Participant Study

To investigate typical GRF time histories for the selected movement and determine the number of trials to collect for the group analysis, one shod female club-standard tennis player performed 15 running forehand trials on a baseline surface composed of a concrete floor and uncovered force plate. The number of trials to obtain stable GRF data was determined following the procedures of Bates, Osternig, Sawhill, and James (1983) and Bates, Dufek, and Davies (1992). This involved the plotting of cumulative mean deviation from a criterion value (total of 15 trial mean) and identifying a plateau, where the use of increased trials did not notably improve stability. Using these techniques, based on the present single participant data it was decided that the collection of 8 trials for each condition more than satisfied the stability requirements.

Group Study

Six female tennis players of varying standard (world-ranked to recreational) volunteered for testing. They wore the same model of tennis shoe throughout testing (Adidas Big Court III; size range UK 6–8). A brief case history (questionnaire) was obtained from each participant that provided detail on playing frequency, standard, and recent injury. Written informed consent was obtained from each participant. Table 1 displays participant information. Study procedures were reviewed and approved by the Ethics Committee of the School of Sport and Health Sciences, University of Exeter.

Familiarization trials were performed until participants were confident about executing the running forehand movement in the laboratory and had repeatedly achieved the location of the desired

Table 1   Participant Information

Partici-pant	Age (yrs)	Weight (N)	Height (cm)	Weekly playing frequency (hrs)	Standard	Injury in past 3 months that prevented play? And/or Ever had back or lower limb surgery?
1	20	850	173	2	Club	–
2	20	600	164	4	Rating 4.2	–
3	18	670	166	3	Club	–
4	20	740	170	3	Rating 1.4 WR: 1000	–
5	23	530	164	–	Recreational	–
6	22	670	175	2	Recreational	–
Mean (± SD)	20.5 (1.76)	676.67 (110.94)	168.67 (4.72)	2.8	Nonhomogenous	–

Note: A dash refers to no injury or additional information; WR = world ranking; Order of playing standard: WR player; Club player, may include rating (lower number = higher standard); Recreational player.

foot plant on the force plate. At least 5 further trials were performed prior to data collection with each surface change. For each condition, 8 successful running forehand foot plant trials were collected. If participants failed to contact the force plate, dramatically altered their entry speed, or failed to perform a typical movement trial, data were discarded and the trial was repeated.

Three common tennis surfaces were assessed: sand-filled artificial turf, cushioned acrylic hardcourt (12-mm thickness, typically used in professional tournaments), and carpet (6-mm thickness). Using an Artificial Athlete Berlin (mechanical impact test device, DIN 18035-6), these surfaces have been categorized using guidelines provided by the International Tennis Federation (ITF) as having high, moderate, and low cushioning ability, respectively (Dixon & Stiles, 2003). An additional baseline condition consisting of the force plate set flush within a concrete runway was also assessed (representing "zero" cushioning). Complete runway lengths of the acrylic and carpet surface material were placed directly on top of the baseline surface, consistent with tennis court construction specifications. Since it is recommended that artificial turf be laid over a shock pad, the artificial turf was laid over a 5-mm thick acrylic surface. Participants were not provided with any specific surface detail.

A force plate (AMTI) sampling at 960 Hz provided GRF data, with a force magnitude exceeding 10 N signaling initial contact. Synchronized 3-D lower extremity kinematic data were sampled at 120 Hz using an optical system (automatic, optoelectronic system; Peak Performance Technologies, Inc., Englewood, CO). Kinematic data were filtered using a quintic spline (Woltring, 1985).

A combined and adapted version of the joint coordinate systems presented by Soutas-Little, Beavis, Verstraete, and Markus (1987) and Vaughan, Davis, and O'Connor (1992) was used to monitor joint movement at the knee and ankle. The joint coordinate system required the following marker placements: most lateral aspect of the greater trochanter (hip), lateral femoral epicondyle (lateral knee), medial femoral epicondyle (medial knee), proximal and distal bisections in the frontal plane of the posterior distal aspect of the shank (Achilles 1 and 2), bisection in the frontal plane of the anterior distal aspect of the shank (shin), two markers placed on the rear of the shoe to approximate bisection of the calcaneus in the frontal plane (Calcaneus 1 and 2), and on the dorsal aspect of the foot (shoe) at the base of metatarsal 2 (midfoot). A schematic of the marker convention is shown in Figure 2.

Biomechanical assessment involved analysis of the following kinetic variables: peak vertical impact force (PkFz), time of PkFz (PkFz$_{time}$), peak rate of loading during the impact phase (PkLR), average rate of loading (LR$_{avg}$), peak braking (posterior) force (PkFy), and time of PkFy (PkFy$_{time}$) and impact
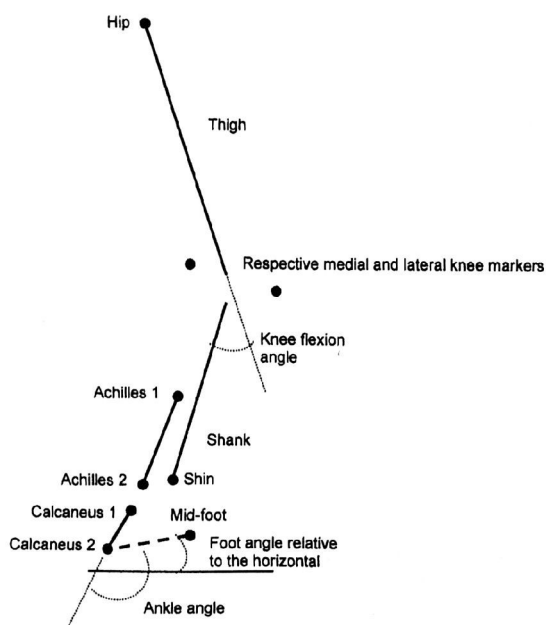
Figure 2 — Joint coordinate system marker conventions and angle definitions.

Figure 3 — Typical running forehand foot plant vertical (Fz) and horizontal (Fy) ground reaction force time histories.

peak for the resultant ground reaction force (PkFres), where all force data were normalized to body weight. Numerical differentiation of vertical GRF with respect to time over the period from initial ground contact to peak impact force was used to calculate rates of vertical force loading. Peak coefficient of friction during the braking phase of the movement was determined by the division of anterior-posterior GRF by the vertical component. Kinematic adjustments were monitored using the following variables: initial foot angle, initial knee flexion angle, and initial vertical heel impact velocity.

Initial kinematics were taken at the frame immediately prior to ground contact. In addition, to fully assess differences between surfaces, the following kinematic variables were measured during stance: peak knee flexion angle, knee angle range of movement from ground strike to peak knee flexion (ROM), peak ankle dorsiflexion angle, peak ankle DF angular velocity, and peak knee flexion velocity. All joint angles were referenced to a relaxed standing position.

An 8-trial subject mean for each surface was calculated for each variable. Descriptive statistics and graphical trend analyses were used to illustrate where changes existed across play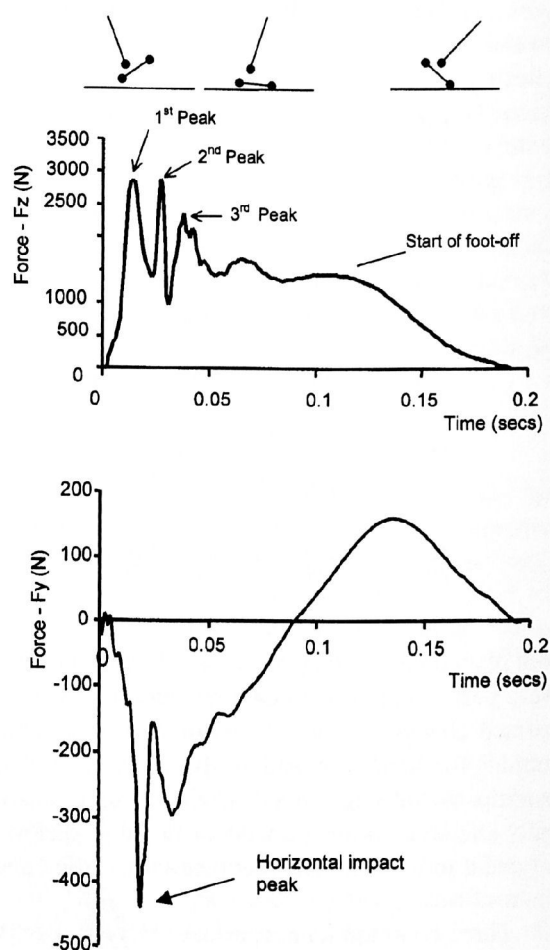ing surfaces. Group mean values for each variable were calculated using participant mean data and were compared using an ANOVA with repeated measures followed by a post-hoc Tukey test ($p < 0.05$).

Results

A single participant's sample vertical and anterior-posterior force time histories are presented in Figure 3. Labels 1st Peak, 2nd Peak, and 3rd Peak were assigned to represent the series of peaks observed. The first peak occurred at around 8% of total stance time, corresponding to approximately 20 ms. Analysis of more participants revealed that a different number of vertical peaks can occur, ranging from typical accentuated running impact peaks followed by push-off to the occurrence of one or two further peaks after the initial impact peak toward
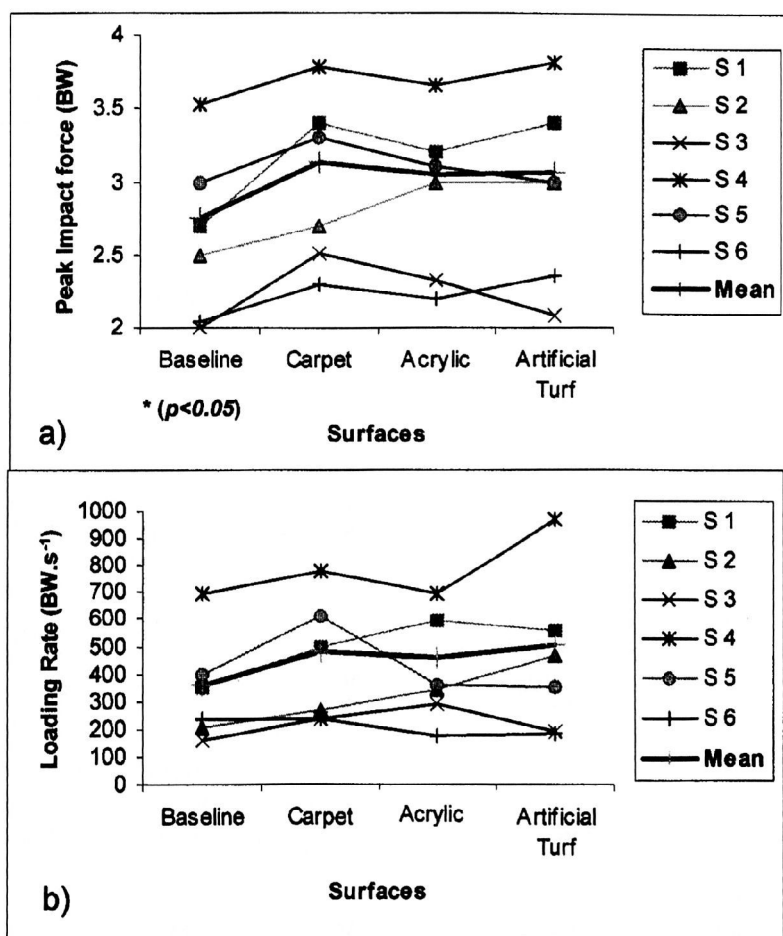
Figure 4 — (a) Individual and group mean peak impact force values for each surface (BW). (b) Individual and group mean peak loading rates for each surface ($BW \cdot s^{-1}$).

"foot-off." The term foot-off is preferred to push-off since, due to the nature of the running forehand foot plant, propulsion into another step is minimal. The first impact peak was used as an indicator of surface cushioning.

Individual participant data are presented together with a bold line representing the group mean value (Figure 4), for which data are also presented in Table 2. Peak impact force for the baseline surface (2.59 BW, ± 0.61) was significantly lower than the magnitudes yielded from carpet, acrylic, or artificial turf ($p < 0.05$). An effect size of 0.87 and statistical power of 0.86 for an alpha level of 0.05 was calculated based on the peak impact force results. The peak impact magnitudes for the remaining three surfaces were similar to each other and comparable to the base-line value. Individual participant results support the group peak impact force finding (Figure 4a). There were no significant differences for group mean peak impact time of occurrence between surfaces ($p > 0.05$). Although for some participants the peak rates of loading show a trend between surfaces to mimic individual peak impact trends (Figure 4b), group peak rate of loading data did not reveal any significant differences between surfaces ($p > 0.05$). Consistent with vertical impact force, resultant impact force was significantly lower for the baseline surface than for the tennis specific surfaces ($p < 0.05$).

Anterior-posterior GRF time histories illustrate a marked braking (posterior) force occurring within the first 50 ms of the ground contact phase (Figure

Table 2   Group Mean (±SD) Ground Reaction Force and Kinematic Variables With Changes in Surface

Variables	Baseline	Carpet	Acrylic	Artificial turf	Significance level from RMANOVA
PkFz (BW)	2.59 (0.61)	2.93 (0.52) *$p < 0.01$	2.86 (0.49) *$p < 0.05$	2.88 (0.61) *$p < 0.05$	0.005 *
Time of PkFz (sec)	0.024 (0.003)	0.023 (0.004)	0.022 (0.004)	0.024 (0.006)	0.588
PkLR (BW·s^{-1})	360.89 (209.04)	477.81 (230.00)	455.70 (177.35)	507.05 (291.46)	0.217
Time of PkLR (sec)	0.019 (0.007)	0.018 (0.005)	0.019 (0.006)	0.020 (0.006)	0.318
LR$_{ave}$ (BW·s^{-1})	109.57 (19.54)	132.08 (30.15)	135.10 (31.66) *$p < 0.05$	132.08 (42.94)	0.039 *
PkFy (BW)	1.05 (0.13)	0.79 (0.14) *$p < 0.05$	0.70 (0.20) *$p < 0.01$	0.78 (0.17) *$p < 0.05$	0.006 *
Time of PkFy (sec)	0.035 (0.006)	0.031 (0.004)	0.035 (0.005)	0.035 (0.008)	0.072
PkFres (BW)	2.67 (0.63)	3.00 (0.57) *$p < 0.05$	2.87 (0.56)	2.91 (0.61)	0.016 *
Time of PkFres (sec)	0.024 (0.004)	0.023 (0.004)	0.022 (0.003)	0.023 (0.004)	0.398
Peak friction coefficient	0.53 (0.08)	0.34 (0.13)	0.29 (0.06) *$p < 0.05$	0.35 (0.08)	0.005 *
Initial Kinematic Variables					
Initial foot angle (deg)	38.36 (6.34)	36.16 (9.94)	39.56 (10.15)	35.57 (10.19)	0.210
Initial knee angle (deg)	11.87 (5.57)	7.49 (4.92)	11.80 (7.26)	13.16 (9.30)	0.271
Heel impact velocity (m·s^{-1})	2.38 (0.24)	2.51 (0.37)	2.49 (0.41)	2.57 (0.50)	0.816
Stance Kinematic Variables					
Peak knee angle (deg)	57.94 (12.48)	49.92 (13.56)	57.2 (9.79)	53.33 (11.93)	0.164
Knee angle ROM (deg)	45.98 (14.15)	40.58 (15.05)	45.16 (14.42)	43.16 (10.29)	0.696
Peak knee flex. velocity (rad·s^{-1})	14.918 (1.92)	13.754 (1.60)	14.338 (2.01)	13.336 (2.25)	0.114
Peak DF angle (deg)	25.24 (6.18)	21.13 (7.55)	23.56 (7.84)	20.99 (6.87)	0.970
Peak PF ang. velocity (rad·s^{-1})	11.234 (5.42)	12.820 (4.82)	16.212 (7.08)	12.393 (2.82)	0.452
Peak DF ang. velocity (rad·s^{-1})	11.120 (1.08)	11.384 (1.31)	11.130 (2.24)	10.476 (3.42)	0.854
Entry speeds (m·s^{-1})	3.94 (0.32)	4.02 (0.63)	4.11 (1.27)	3.57 (0.84)	0.402

Note: *Statistical differences compared with baseline surface unless otherwise stated, $p < 0.05$, $p < 0.01$.

3). This force was significantly higher for the baseline surface than for the three tennis playing surfaces ($p < 0.05$), while the timing of peak braking force did not differ significantly ($p > 0.05$).

Mean initial foot angle and knee angle showed minimal and inconsistent variation between surfaces. Although heel impact velocity was found to be smaller for the baseline surface compared with other test surfaces (Figure 5), this result was not statistically significant ($p > 0.05$). Consideration of single participant data illustrates a trend for peak dorsiflexion angle to be highest for the baseline surface compared with the other surfaces, supported by results from 5 participants (Figure 6). However, group statistical analysis revealed no significant differences for this variable ($p > 0.05$). No significant differences were detected in entry speeds ($p > 0.05$).

Discussion

The present study developed procedures to analyze a tennis-specific movement in the laboratory. Characterization of the impact phase of the running forehand foot plant advances our understanding of a sport-specific movement other than running.

Rather than one early vertical peak typical of heel-toe running gait (Cavanagh & Lafortune, 1980), the running forehand foot plant generally yielded two or more early peaks. Each peak occurred during the first 50 ms of stance. This time period has been defined as the impact phase (Hardin, van den Bogert, & Hamill, 2004). In the present study, the first of these peaks was used to compare the cushioning provided by the different test surfaces.

The running forehand anterior-posterior GRF time history also differed markedly from that typically observed during running, with a horizontal impact peak identified during the first 50 ms of ground contact. The values of 0.7 to 1 BW for the peak posterior force during the running forehand foot plant are approximately double the magnitude reported for peak braking force for running at a similar speed (Cavanagh & Lafortune, 1980). In addition, this peak braking force occurred much earlier (33 ms) than the peak braking force during running and is within the 50-ms time period that defines the impact phase.

It has been demonstrated that changes in surface can be detected using GRF data. In contrast to the expected reduction in vertical peak impact force with increased mechanical cushioning, it was
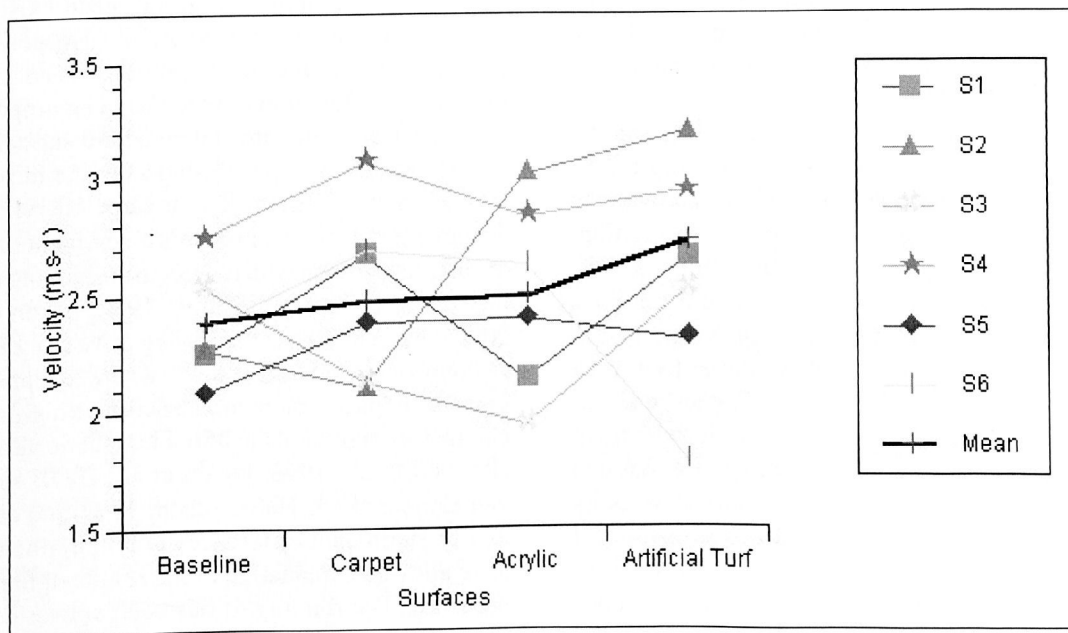

Figure 5 — Individual and group mean heel impact velocity ($m \cdot s^{-1}$).
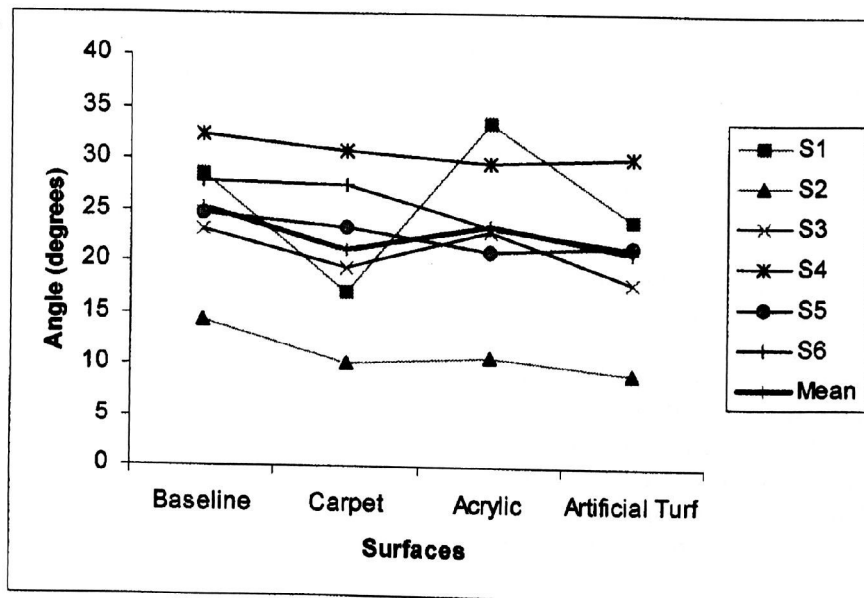
Figure 6 — Individual and group mean peak ankle dorsiflexion (degrees).

found that the surface with the lowest mechanical cushioning resulted in the lowest vertical force magnitude during a tennis specific movement. The study hypothesis that the surfaces with greatest mechanical cushioning would result in the lowest impact forces and rates of loading when measured during the performance of a tennis specific movement is therefore rejected.

Individual peak impact force results for the baseline surface may only be explained to a limited extent using kinematic adjustments, previously suggested to contribute to increased cushioning. Increased initial knee flexion (cushioning flexion) as demonstrated by Participants 2 and 3 provides greater collision deformation (Lafortune et al., 1996). A lower initial foot angle (flatter foot) may indicate increased shoe-surface contact area for Participants 3 and 5, suggested to be an adjustment contributing to increased cushioning (De Wit and De Clercq, 1997). A lower heel impact velocity (Participants 4 and 5) demonstrates a method of minimizing the collision acceleration component, as suggested by Denoth (1986). A high peak knee flexion velocity occurs on the baseline surface for Participant 5 compared with the other surfaces, perhaps demonstrating a high need for this participant

to utilize intrinsic cushioning from the mechanics of rapid knee flexion (rapid muscular extension under tension) as observed by De Wit, De Clercq, and Aerts (2000) when running barefoot versus shod. While variation about the group mean exists, the amount of variation and thus individual response to a particular surface (i.e., the baseline) does not appear to be of a sufficient magnitude to overcompensate for an expected high impact on a hard surface.

The similar group peak impact forces measured for the three tennis surfaces of carpet, acrylic, and artificial turf supports previous assessment of shoe or surface interface with respect to cushioning (Bobbert et al., 1992; Clarke et al., 1982; Dixon et al., 2000; Dixon & Stiles, 2003; Nigg & Yeadon, 1987). In contrast to previous studies, where explanations of group impact peak maintenance have highlighted changes in sagittal plane initial kinematic variables (Bobbert et al., 1992; Dixon et al., 2000; Hamill, van Emmerick, & Heiderscheit, 1999), no consistent or significant differences in initial kinematics have allowed explanation of the results of the present study. For running, it has been suggested that kinematic adjustments may be aimed at reducing the risk of injury (Derrick, 2004) or allowing one to maintain optimal performance (Hardin et al., 2004).

For the skill assessed in the present study, the small and inconsistent differences in impact kinematics across surfaces and participants render it impossible to state specific adjustments. However, the similar impact forces across the tennis surfaces despite their markedly different structure suggests that some kind of adjustment occurs.

The resultant impact force follows the vertical impact force results, with a significantly lower impact peak on the baseline compared with the tennis specific surfaces. As with running, the resultant ground reaction force of the running forehand foot plant is primarily contributed to by the vertical compared to horizontal magnitude of force. However, in contrast to the findings for peak vertical and resultant impact forces, the isolated analysis of the horizontal force component has identified a significantly higher peak braking force for the baseline surface. This peak force component occurs later, at an average of 33 ms following initial ground contact, than the peak vertical and resultant impact forces, which each occur at an average of 23 ms. The braking force will be influenced by both the horizontal deformation and level of friction of the shoe-surface combination. A significantly greater coefficient of friction has been measured during the braking phase for the baseline surface. This suggests that an increased resistance to sliding contributes to the greater horizontal force component for the baseline compared with the tennis-playing surfaces.

Despite the markedly different design characteristics of the three tennis surfaces, no significant differences in peak horizontal force or coefficient of friction were identified between these conditions. Mechanical measurements of resistance to sliding on sand-filled artificial turf and acrylic have detected distinct differences between these surfaces (Dixon & Cooke, 2004), with the turf surface showing the least resistance. Despite this mechanical difference, external loading patterns are not significantly different when the foot plant has been performed on these surfaces. This implies that, consistent with suggestions from Stucke et al. (1984), players are making adjustments to account for the different mechanical properties. The use of typical tennis shoe-surface combinations in the present study makes it difficult to identify whether adjustments result from cushioning or from friction differences between conditions. Separate systematic adjustment of these surface parameters is required to examine this further.

In conclusion, GRF characteristics of a tennis specific movement facilitated the comparison of loading variables across different surface conditions. A lower peak vertical impact force for the baseline surface versus the more cushioned tennis surfaces was unexpected. It is suggested that, compared with running, the more dynamic skill used in this study may have resulted in an overcompensation when performing on the relatively stiff force plate surface. This compensation has not been satisfactorily explained by group changes in kinematics, suggesting that factors not measured in this study have an influence on impact force. For the three tennis-playing surfaces, only small and nonsignificant differences were identified in vertical and horizontal loading at impact. While this supports findings in the literature regarding the maintenance of similar impact forces for different shoe-surface conditions in running, the present study has failed to detect consistent kinematic adjustments that account for the observed impact force results.

The task-oriented skill used in this study may result in greater between-subject variability in the selected strategy for coping with different surface conditions compared with adjustments observed for running. It is suggested that a study making systematic changes in cushioning or friction provided by the surface may improve our understanding of player adjustment to surface conditions and help to identify desirable shoe-surface combinations.

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