Impact absorption of tennis shoe–surface combinations

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Abstract

The aim of this study was to investigate, for typical shoes and surfaces used in tennis, the relative role of the shoe and surface in providing cushioning during running. Five test surfaces ranging from concrete to artificial turf were selected, together with two shoe models. Impact absorbing ability was assessed mechanically using drop test procedures and biomechanically using peak magnitude and rate of loading of impact force and peak in-shoe pressure data at the lateral heel. Differences in biomechanical variables between shoe–surface combinations were identified using a two-way ANOVA ($p < 0.05$). Mechanical test results were found to rank the surfaces in the same order regardless of the shoe model, suggesting that the surface is influential in providing cushioning. However, for all mechanical and biomechanical ($p < 0.05$) variables representing impact absorbing ability, it was found that the difference between shoes was markedly greater than the differences between surfaces. The peak heel pressure data were found to rank the surfaces in the same order as the mechanical tests, while impact force data were not as sensitive to the changes in surface. Correlations between mechanical and biomechanical impact absorption highlighted the importance of testing the shoe–surface combination in mechanical tests, rather than the surface alone. In conclusion, mechanical testing of the shoe–surface combination was found to provide a strong predictor of the impact absorbing ability during running if pressure data were used. In addition, for typical shoe–surface combinations in tennis, the shoe was found to have more potential than the surface to influence impact loading during running. Finally, in-shoe pressure data were found to be more sensitive than force plate data to changes in material cushioning.

Keywords: ground reaction force, peak pressure, court surfaces, injury

Introduction

Participation in sports and exercise takes place on a range of different surfaces, including concrete, asphalt, synthetic materials and natural turf. One factor differing between these surfaces is the amount of cushioning provided to the participant. Although it has been suggested that this factor is influential in the development of overuse injuries such as shin splints, stress fractures, and damage to articular cartilage (James *et al.*, 1978; Andreasson & Olofsson, 1984), little is understood regarding the relative level of impact absorption provided to the participant by typical surfaces (Dixon *et al.*, 1999a). It has generally been assumed that stiffer surfaces provide reduced cushioning, resulting in higher impact forces during running. However, several studies of sports surfaces have reported that this is not the case (Nigg & Yeadon, 1990; Dixon *et al.*, 2000).

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The amount of cushioning, or impact absorption, provided to a player during running is influenced by the structures of the body, and the materials and construction of the shoe and of the surface (Denoth, 1986). Therefore, to increase understanding of the role of the surface in providing cushioning, it is important to increase understanding of the interaction between the player, shoe and surface.

Since the external cushioning provided to the participant is influenced by the shoe and the surface, it is likely that the role of a surface in providing cushioning will be influenced by the shoe worn. This suggestion has been supported in a study demonstrating that the relative surface impact absorbing ability was different when wearing a different model of shoe (Dixon *et al.*, 1999b). However, this previous study did not consider the relative importance of the shoe and surface. For the practical application of results, specification of the relative importance of the shoe and surface in providing cushioning is required, both to help sports surface companies in the development of surfaces and to provide effective guidelines to participants in sport. For example, if impact absorption is considered to be important, it would be beneficial for the consumer to know whether the range of surfaces available for their sport differed in impact absorbing ability and also how important the choice of footwear was in providing absorption of impact on these surfaces.

The impact absorbing ability of playing shoes and surfaces is typically quantified using mechanical test procedures. These tests involve impacting the test shoe or surface under specified impact conditions and measuring the impact variables, including peak deceleration of the impacting device, peak force and material deformation. For testing of surfaces, several sports have adopted the Artificial Athlete Berlin as a standard test procedure, in which peak force measured on the test surface is compared with that on concrete (Kolitzus, 1984). Similar test procedures are used to assess the impact absorbing ability of footwear materials (ASTM and British Standards). Although these methods provide a quantitative measure of the potential of a shoe or surface to reduce impacts in running, biomechanical evidence has demonstrated that correlations between mechanical tests of impact absorption and impact forces occurring during running are low (Nigg & Yeadon, 1987).

The quantification of impact absorption during running has generally involved the measurement of ground reaction force data using a force platform (Feehery, 1986; Nigg & Yeadon, 1987; Dixon *et al.* 2000). For shoe testing, the subject runs over the platform wearing the test shoes. For surface testing, the force plate is situated beneath the test surface. Although these procedures are considered appropriate for the quantification of impact absorbing ability of surfaces that are point elastic (Nigg, 1990), there are limitations to using a force plate to measure impact absorption during running. These include the restriction of one set of data per running trial and problems with targeting of the force platform. The recent availability of in-shoe pressure insoles provides an alternative technology for the measurement of impact absorption during running (Milani *et al.*, 1995).

The purpose of this study was to investigate the relative role of the shoe and surface in providing cushioning during running. To provide applied conditions, surfaces used in the sport of tennis were selected for testing. Tennis is played on a large range of surfaces including turf (natural and artificial), acrylic materials, asphalt and concrete, providing a relatively large range of surfaces to be compared. An additional question investigated in the study was whether mechanical testing can be reliably used to predict the relative impact absorbing ability of tennis surfaces during running. Owing to the distinct properties of the test surfaces used in this study, it was hypothesised that biomechanical test data would rank the playing surfaces in the same order as mechanical test results.

Methods

Seven female recreational tennis players (mean mass 61 kg; mean age 21 years) volunteered as subjects for the study. Following a description of the experimental procedure, each subject provided informed consent.

Five test surfaces were used: concrete; cushioned acrylic hardcourt (acrylic); 4 mm thickness polyurethane (PU4); 7 mm thickness polyurethane (PU7); sand-based artificial turf on a shockpad (turf). For each of the surfaces, running trials were performed using two different types of tennis shoe. The two shoe models differed only in their midsole. The upper and sole were similar construction and materials. Shoe 1 contained a basic foam (ethyl vinyl acetate, EVA) cushioning system in the midsole, whilst Shoe 2 also had the company's additional cushioning system ('Hydrosphere Technology', Wilson, UK). The laboratory concrete floor was used to provide a sample concrete surface, with the subject striking the force plate surface during collection of ground reaction force data. The tennis playing surfaces were placed over this concrete, as typically occurs when constructing a tennis court. These surfaces were attached to the concrete with tape and provided a total length of 16 m for running.

Mechanical impact absorbing tests on surfaces

The mechanical impact absorbing ability of the test surfaces was determined using the Berlin Artificial Athlete. This test involves the release of a 20 kg mass from a standard height to impact with a spring. The spring is mounted on a metal foot and introduces compliance to the system to provide an impact time comparable to that typically occurring during the heel impact phase of running. The peak impact force is measured and the surface 'cushioning' is presented as the percentage reduction in force compared with that measured during impact with a concrete surface. This test procedure was adopted because of its routine use by the International Tennis Federation for categorising cushioning ability of surfaces (International Tennis Federation, 1997).

Mechanical impact absorbing tests on shoes

The mechanical impact absorbing ability of the two shoe models and each of the combined shoe–surface combinations was determined using a standard drop test procedure (ASTM, 2001). For this test procedure a 7.8 kg mass is released from a standard height to impact with the heel area of the shoe. Peak deceleration is measured during impact and presented as multiples of the acceleration due to gravity, known as 'peak g'. Each shoe was tested alone and with samples of each of the test surfaces placed below the shoe.

Biomechanical testing

For biomechanical testing, ground reaction force data were collected at 960 Hz using a force platform (AMTI OR6-5) sited below the tennis surface material. In addition, pressure data were recorded at the foot–shoe interface of both feet using an in-shoe pressure insole system sampling at 500 Hz (footscan®, RSScan, Belgium). This system consists of a set of insoles, a data logger worn on the belt of the subject (mass 264 g) and wires connecting the insoles to the data logger. Each insole consists of an array of polymer sensors each of area 7 mm × 5 mm, embedded in a uniform insole of thickness 0.7 mm.

For the collection of running data, a speed of 3.83 $\mathrm{ms^{-1}}$ (7 min $\mathrm{mile^{-1}}$) was used. This running speed was monitored using photocells to measure the time taken to cover a 4 m distance. Prior to data collection for each shoe–surface combination, subjects performed practice trials as required for familiarisation with the test condition. For the collection of force plate data, each subject performed four successful running trials for each of the shoe–surface combinations, making a right foot contact with the area of the surface covering the force plate (approximate dimensions 600 mm × 600 mm). A trial was accepted if the running speed was within 5% of the required 3.83 $\mathrm{ms^{-1}}$, and right foot contact with the force plate was achieved without adjustments in running stride. Pressure data were collected simultaneously, with the pressure-measuring insole placed within the running shoe. For each of the four running trials for each test condition, pressure data were collected for two running steps of each foot, resulting in a total of eight sets of pressure data for each foot. To ensure that data were only obtained for steady state running (negligible acceleration), only steps for the middle section of the run (within the photocells) were used for analysis.

For the force plate data, the peak impact force (peak force occurring at heel impact with the surface) and peak rate of loading (greatest rate of change of force during heel impact) were determined for the right foot contact for each running trial. For each subject, the average value over the four trials for each running condition was calculated. The peak pressure at the lateral (outside) area of the heel was used to indicate impact pressure, since this is the area of the foot where initial contact with the ground typically occurs. This area corresponds with H2 in Figure 1, where H1 (medial heel) and H2 were located manually on the first trial analysed for each subject. These masks were placed at equal distance from the rear of

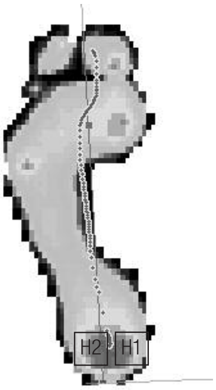

Figure 1 A typical pressure footprint with the areas used for data collection illustrated. Area 'H2' represents the lateral heel and 'H1' the medial heel.

the heel along the longitudinal axis of the foot, and at equal distances from the outer edges of the heel, as determined visually. They were placed to include the area of maximum pressure at the heel, as indicated by the colour scale produced by the software. Once located in a single trial for each subject, the software placed the masks in the same location for subsequent trials analysed in the test session, removing the effects of operator error on repeatability of mask placement. Average peak values for the area H2 were determined over the eight running steps for each running condition, with right and left steps averaged together.

Statistical treatment

For all variables, the mean and standard deviation over the steps analysed were determined for the group of subjects. Statistically significant differences between the values obtained for each of the conditions were detected using a two-way analysis of variance (surface × shoe). This procedure allowed the comparison of peak force and pressure for changes in surface condition and in the shoe worn, and the detection of any interaction effects. The significance level was set at $p = 0.05$.

Results

Figure 2 illustrates the percentage reduction in peak force for each of the tennis surfaces compared with concrete. The turf surface showed the highest mechanical impact absorbing ability, with a 33.5% reduction in peak force compared with concrete. The lowest impact absorbing ability (9.6%) was measured for the 4 mm thick PU.

Figure 3 provides the peak g values for each of the shoe–surface combinations. The shoe condition is for the shoe placed on the steel test plate common to all testing. Based on ability to reduce the peak g value, the rank order of the surfaces is the same for both shoe models. The turf surface has the highest impact absorbing ability (lowest peak g), the 7 mm thick PU

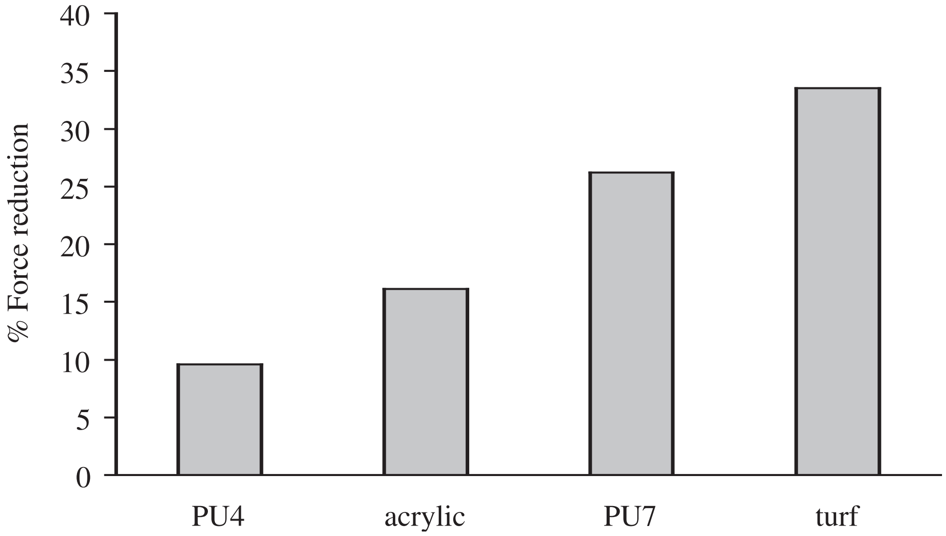

Figure 2 Berlin Artificial Athlete: force reduction for each surface compared with concrete.

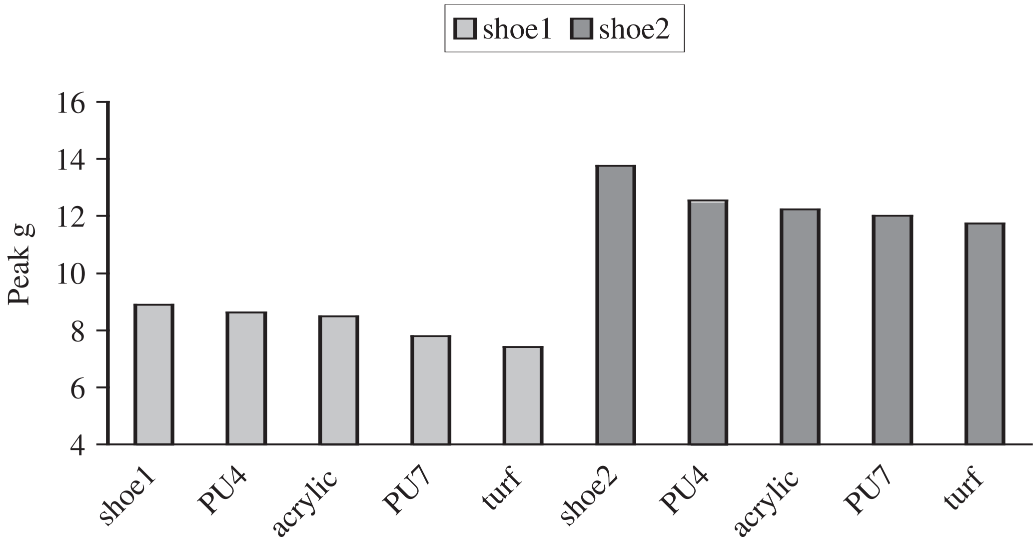

Figure 3 Peak g results for each shoe–surface combination.

surface ranks second. The acrylic surface ranks next, followed by 4 mm thick PU. For both shoe types, the lowest impact absorbing ability is indicated for the shoe-only condition. Consideration of the results for the two shoe models separately indicates relatively small changes in peak g with surface variation (maximum difference approximately 2g). Larger differences in peak g values are seen between the two shoes (approximately 5g), with Shoe 1 providing the most impact absorption.

Biomechanical data are summarised in Table 1. Peak lateral heel pressures are illustrated in Figure 4. No significant differences between playing surfaces were detected in peak lateral heel pressure for either of the shoe models. However, the peak pressures were significantly lower for Shoe 1 than for Shoe 2 ($p < 0.05$). Despite the relatively small differences in peak pressure observed when running on the different surfaces compared with the difference in peak pressure between the shoe types, the rank order of the playing surfaces is the same regardless of the shoe model worn. Based on peak pressure data, the turf surface provides the most impact absorption, and the 7 mm PU surface ranks second. Of the remaining playing surfaces, the acrylic surface is ranked next and the 4 mm PU surface provides the least impact absorption. No significant interaction effects were detected.

Table 1 Mean values for peak pressure at the lateral heel area, peak impact force and peak rate of loading for each running condition (standard deviation in parenthesis)

	Peak pressure (N cm^{-2})	Peak impact force (N)	Peak loading rate (N s^{-1})
Shoe 1 + Concrete	35.2 (11.5)	1312 (355.4)	109 235 (74 356)
Shoe 1 + PU4	36.1 (12.3)	1350.1 (274.3)	102 453 (56 002)
Shoe 1 + Acrylic	35.7 (12.2)	1280.5 (317.3)	118 135 (58 442)
Shoe 1 + PU7	35.0 (13.0)	1318.7 (310.7)	112 583 (80 452)
Shoe 1 + Turf	32.8 (9.8)	1330.2 (296.2)	122 355 (70 513)
Shoe 2 + Concrete	44.2 (15.5)	1291.8 (351.8)	123 907 (83 091)
Shoe 2 + PU4	46.2 (14.9)	1367.5 (351.8)	116 338 (62 773)
Shoe 2 + Acrylic	45.9 (14.8)	1310.3 (337.5)	122 868 (61 785)
Shoe 2 + PU7	44.2 (15.6)	1330.0 (412.9)	119 403 (71 565)
Shoe 2 + Turf	42.5 (12.5)	1333.3 (308.5)	123 494 (65 135)

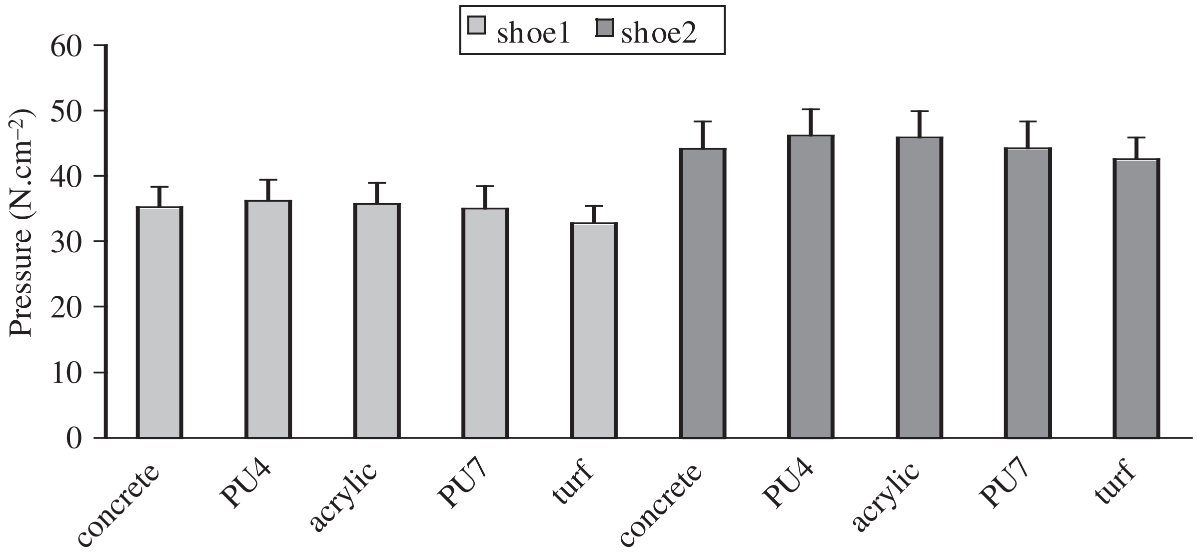

Figure 4 Peak lateral heel pressure for each shoe–surface combination (N.cm^{-2}), with standard error bars illustrated. No significant difference between surfaces. Shoe 1 significantly lower than Shoe 2 ($p < 0.05$).

The peak impact force data highlight different responses to the playing surfaces depending on the shoe worn (Table 1, Figure 5). For example, for Shoe 1 the lowest peak force occurs on the acrylic surface, whilst for Shoe 2 the lowest force is on the concrete surface. No significant differences between surfaces were identified for this variable. In addition, although peak force is generally lower for Shoe 1, the difference between shoes is not statistically significant. For the peak loading rate of impact force there were no

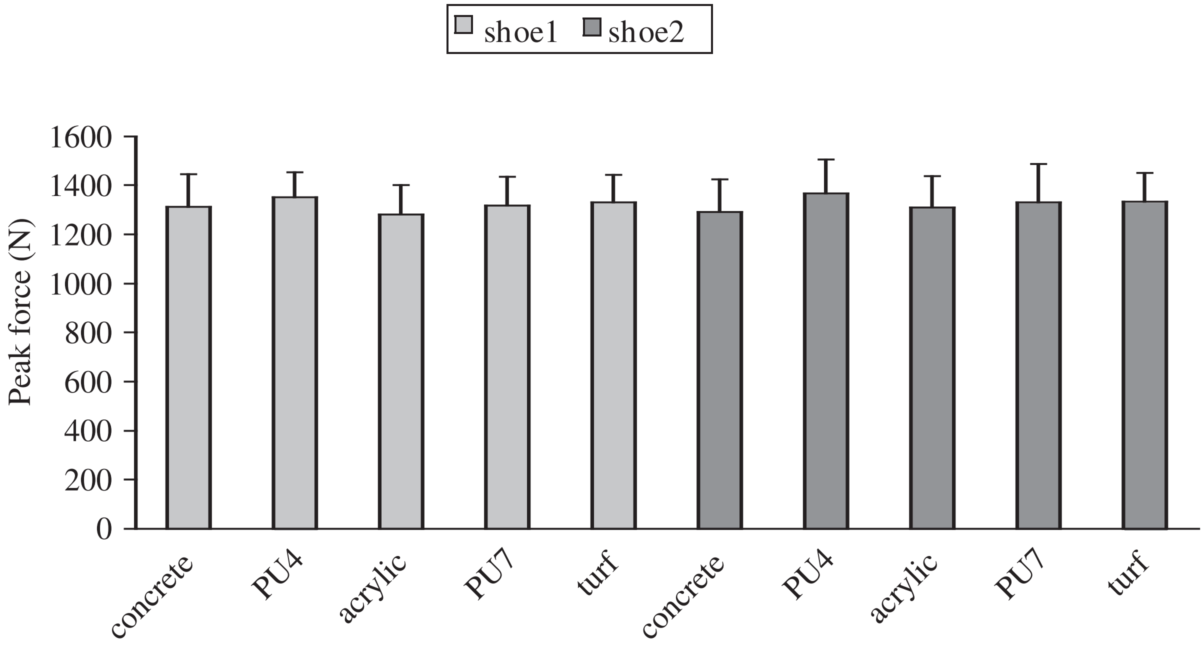

Figure 5 Peak impact force for each shoe–surface combination (N), with standard error bars illustrated. No significant difference between surfaces. No significant difference between shoes.

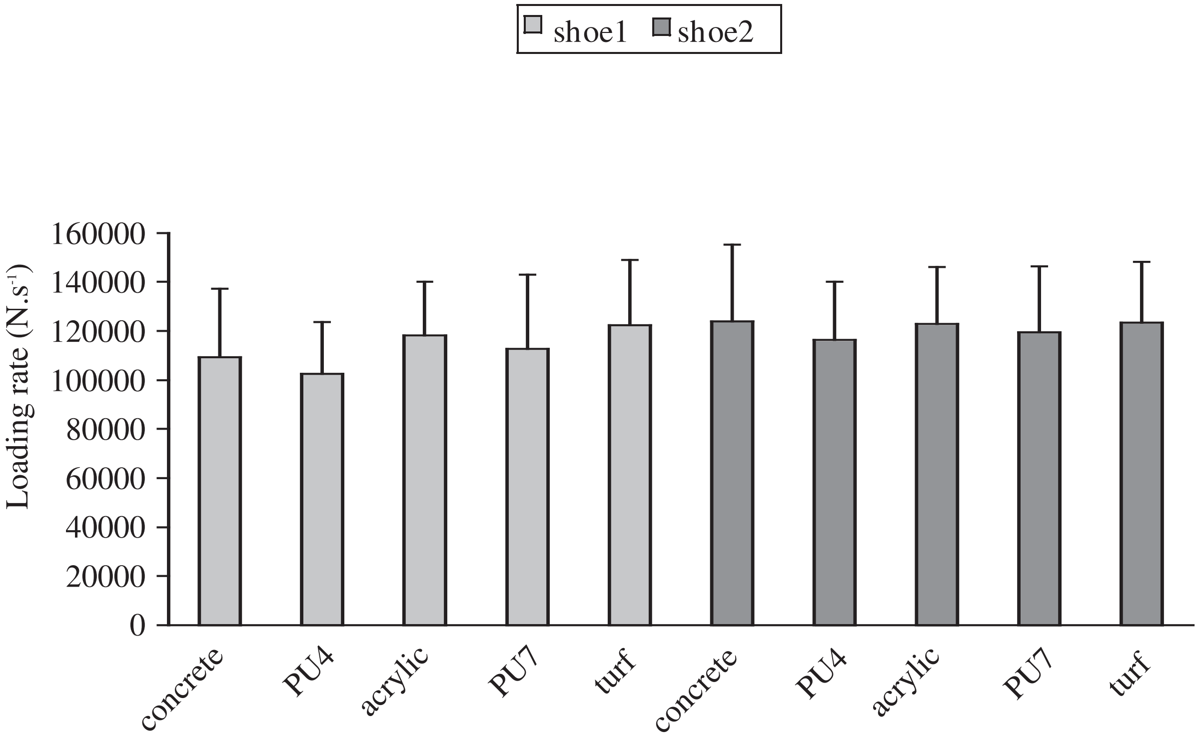

Figure 6 Peak loading rate for each shoe–surface combination (N.s^{-1}), with standard error bars illustrated. No significant difference between surfaces. Shoe 1 significantly lower than Shoe 2.

significant differences identified between surfaces (Figure 6). However, the comparison of shoes indicated that running in Shoe 1 resulted in a significantly lower peak rate of loading than running in Shoe 2 ($p < 0.05$).

Discussion

The ranking of the test surfaces for each of the shoe models suggests that surface is influential in determining the impact absorption provided by the combined shoe–surface combination. Both of the mechanical test procedures (Berlin Artificial Athlete and the drop test) rank the surfaces in the same order based on impact absorbing ability. Placing the surface with highest impact absorbing ability first, the rank order is: turf, PU7, acrylic, PU4, concrete. In the drop test, this order remains the same regardless of the shoe material placed between the test apparatus and the surface, indicating that the surface is most influential in determining the combined level of impact absorption. However, although the surface does appear to be influential, the difference between shoes is markedly greater than the differences observed when the surface is changed. Thus, although the surfaces tested in the present study have some potential to influence the level of impact absorption provided by the shoe–surface combination, the shoe appears to have more potential.

The suggestion that the shoe is more influential than playing surface is supported by the peak heel pressure data and the peak loading rate of impact force data when running on the test surfaces in the two different shoes. As with the mechanical test data, the variation of the shoe has a much greater influence on the level of impact absorption than the change in surface. For each separate shoe, the differences between surfaces in peak heel pressure and in loading rate of impact force are small and non-significant. The differences between shoes are larger and statistically significant ($p < 0.05$). Thus, both the mechanical testing and the biomechanical data highlight the dominant role of the shoe in providing cushioning for the shoe–surface combinations used in the present study.

The difference in ranking of surfaces based on ground reaction force data compared with mechanical test results is consistent with the findings of previous studies. For example, Nigg and Yeadon (1990) reported that, despite differences in impact absorbing ability indicated by mechanical tests, similar peak impact forces occurred when running on their test surfaces. Similarly, Dixon *et al.* (2000) found that there were no differences detected in peak impact force for subjects running on a range of surfaces with differing mechanical characteristics. As previously suggested by these authors, the lack of significant difference in peak impact force, despite mechanical differences between the surfaces, may be the result of human adaptations, such as changes in joint angles or muscle activation, acting to vary the lower extremity stiffness.

Although the differences in peak heel pressures between surfaces are small and non-significant, consistent trends in surface effect are demonstrated, with the rank order of the surfaces being the same regardless of the shoe worn. This order of surfaces is also consistent with the order indicated by the mechanical tests. The pressure data therefore support the initial hypothesis that biomechanical data rank the playing surfaces in the same order as the mechanical test results. However, despite the consistent trends, the lack of statistically significant differences indicates that further analysis is required before mechanical tests can be recommended for prediction of relative impact absorption during running.

Correlations were performed to investigate the possibility of using mechanical test results to predict reliably the impact absorbing performance of surfaces during running. Correlation of Berlin Artificial Athlete results with peak pressures in running provided non-significant correlation coefficients of –0.714 and –0.318 for Shoe 1 and Shoe 2, respectively. This indicates that, although the rank order of surfaces is consistent between the mechanical and biomechanical testing, the results of the Berlin Artificial Athlete cannot be used to predict reliably the level of impact absorption provided during running.

For the drop test results of shoe–surface combinations and the peak heel pressures obtained in running, a significant ($p < 0.05$) correlation coefficient of 0.92 was obtained. This indicates that the results of the drop test on defined shoe–surface combinations provide a reliable prediction of the relative impact absorbing ability of each condition during running. These correlation results highlight the importance of performing mechanical testing on the combined shoe–surface combination, since testing of the surface alone (as with the Berlin Artificial Athlete) does not take into consideration the potential influence of the shoe.

The finding that the surfaces are ranked in the same order using peak pressures as they are using mechanical test procedures is contrary to findings when force plate data alone have been used, both in the present and previous studies (Nigg & Yeadon, 1990; Dixon *et al.* 2000). Whilst it is acknowledged that only a sample of heel area has been utilised, the results of the present study suggest that in-shoe pressure may be a more sensitive measure of impact absorbing ability than ground reaction force. It is only recently that pressure systems have been available that can sustain the high loads associated with sports movements without being damaged, and that can sample data at a sufficiently high rate. That researchers should continue to use these new systems to compare the impact absorbing ability of shoes and surfaces is supported by the results of the present study.

The International Tennis Federation at present recommends the categorisation of impact absorbing ability of playing surfaces using:

0–5% reduction = 'very low' cushioning
5–10% = 'low'
10–20% = 'moderate'
and greater than 20% = 'high' cushioning

Based on the categorisation guidelines provided by the ITF, the turf surface and the 7 mm PU surface are categorised as giving high impact absorption, the acrylic surface as giving moderate and the 4 mm PU surface as giving low impact absorption. Based on the results for the surfaces used in the present study, the Berlin Artificial Athlete is able to provide a measure of the relative impact absorbing ability of surfaces, as indicated by the consistent ranking of surfaces compared with that based on peak pressures. However, since the peak pressure differences between surfaces when running are small and non-significant, this study provides only weak support for the description of surfaces as providing specific levels (such as 'very low', 'low', 'moderate' and 'high') of impact absorption during running. The relatively large impact absorption provided by one shoe model suggests that, by comparison, all the test surfaces have relatively low impact absorbing ability. Comparison of the levels of force reduction for the test surfaces in this study, with those for other sports, also supports this suggestion. For example, the International Amateur Athletic Association requires a minimum force reduction in the Berlin Artificial Athlete test of 35% for running tracks, a greater level than that of any of the tennis surfaces tested in the present study. It is therefore suggested that the large range of impact absorbing ability indicated by the recommended ITF categorisations may not be appropriate. In addition, the inclusion of the shoe in providing recommended categorisations may be appropriate. Further study of specific shoe–surface combinations is required to investigate this possibility.

The results of the present study highlight two specific areas requiring further investigation. It is acknowledged that the present study has considered impact absorbing ability only during running and that tennis involves many more movements that may result in relatively high loads being experienced by the human body. Further biomechanical study of player–shoe–surface interaction during typical tennis movements is therefore required. In addition, the present study has considered only shoe–surface combinations typical for tennis. For other sports, for example running or soccer, the relative contribution of the shoe and surface may differ. Thus further study of shoe–surface combinations should be performed to increase understanding of the interaction between the participant and the materials of shoes and surfaces.

Conclusion

Based on the results of the present study, it is concluded that mechanical testing of the shoe–surface combination provides a strong predictor of the impact absorbing ability during running. It is also concluded that, for typical shoe–surface combinations in tennis, the shoe has more potential than the surface to influence impact loading during running (and in mechanical tests). Finally, in-shoe pressure data appear more sensitive than force plate data to changes in material cushioning.

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