Journal of Sports Sciences, 2002, **20**, 671–679

A study of the discomfort associated with tennis shoes

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Accepted 25 February 2002

Subjective tests based on information gathered using 'discomfort questionnaires' have been used widely in ergonomics. In this study, we used a similar method to examine the discomfort associated with the footwear worn in tennis matches. A sample of 146 tennis players from a population of approximately 4000 completed the questionnaire. We performed a descriptive analysis of the study variables. The associations between discomfort and pain and between discomfort and design errors were evaluated using cross-tabulation and chi-squared tests. We found that 9% of players considered their footwear to be uncomfortable, 23% considered it to be acceptable and 68% regarded it as comfortable. Six design errors were identified and five body areas were reported as experiencing discomfort due to the footwear. Factor analysis identified four factors related to discomfort and six design errors. Subsequent correlation analysis identified several relationships among these factors. There was a strong correlation ($r = 0.187, P = 0.022$) between plantar discomfort and incorrect arch support.

Keywords: comfort, footwear, subjective tests, tennis.

Introduction

Biomechanical studies of sport shoes have in general focused on kinematic (Bates *et al.*, 1978; Stacoff and Kaelin, 1983; Ferrandis *et al.*, 1994) and kinetic (Frederick *et al.*, 1984; Cook *et al.*, 1985; Gheluwe and Deporte, 1992) variables, which affect performance and injury in all sports. Most used force plates or cinematography, as these allow the variables of interest to be recorded objectively and reliably. In epidemiology, the most suitable way of obtaining reliable information about the type, location and frequency of injuries experienced by athletes is to perform a prospective study. However, these are costly both in terms of human and financial resources (Bloomfield *et al.*, 1994). In contrast, retrospective studies of hospital clinics often underestimate the rate and type of injuries (Garrick, 1987) because injured players often do not seek medical help, especially in the case of minor injuries. On the other hand, retrospective studies adopting personal interviews and structured questionnaires (Giannini *et al.*, 1986; Feit and Berenter, 1993) allow researchers to gather a vast amount of data at reasonable human and financial cost.

In addition to performance and injury, Llana *et al.* (1998a) raised the issue of the comfort of sport shoes. Although it is difficult to gather information on comfort in a fast, reliable and valid way, the method used today with many sporting products was first applied over 30 years ago in the field of ergonomics (Shackel *et al.*, 1969).

The ergonomic analysis of user-oriented products, such as sport shoes, is a complex process involving several interrelated factors. For such an analysis, it is necessary to group these factors according to their place in a hypothetical cause-and-effect chain (Page *et al.*, 1994). For tennis shoes, the first level of the chain will group together objective variables that are related to the characteristics of tennis players (sex, age, anthropometric dimensions, standard), the equipment used (hardness of the sole, mid-sole and insole, height) and the features of the tennis court (coefficient of friction, hardness).

The musculoskeletal system is subjected to different mechanical forces as a consequence of a combination of the factors on this first level and the characteristics of a match. Consequently, athletes have constantly to adapt the movements of their body segments, which is

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Journal of Sports Sciences ISSN 0264-0414 print/ISSN 1466-447X online
http://www.tandf.co.uk/journals

known as the 'kinematic adaptation hypothesis' (Nigg *et al.*, 1984; Stucke *et al.*, 1984; Gheluwe and Deporte, 1992). This kinematic adaptation, which can be measured objectively, is the second level in the chain. Directly related to this adaptation, tennis players experience discomfort and fatigue, both physically and mentally. If the mechanical demands are too great, an injury may be sustained. This is the third level of the chain.

Several studies have analysed the relationships between the factors involved in the first and second levels of this cause-and-effect chain (Clarke *et al.*, 1983a,b; Calder and Smith, 1985; Cook *et al.*, 1985; Nigg and Bahlen, 1988; Simpson *et al.*, 1992; Ferrandis *et al.*, 1994; Forner *et al.*, 1995). These studies looked at the forces, pressures and joint movements that occur when competing in different types of sports shoes. Others have examined the relationships among biomechanical variables, including the impact forces that occur when wearing particular footwear and the players' opinions of the features of that footwear (Grönqvist *et al.*, 1993: Cohen and Cohen, 1994a,b). However, almost all studies that have focused on the relationship between a player's health, fatigue and discomfort and the sport shoes worn have been epidemiological in nature. Few studies have looked at the athlete's pain, discomfort or subjective perception of sport shoes after wearing them (Luethi and Nigg, 1985; Nigg *et al.*, 1986).

The comfort provided by footwear depends on many factors. To determine the final criteria for shoe design, it is necessary to use methods of subjective evaluation. Such methods, which are widely used in the manufacture and design of furniture (Corlett, 1989), are based on 'general' comfort (Shackel *et al.*, 1969) and comfort in tests of particular areas of the body (Corlett and Bishop, 1976). However, such methods have rarely been applied in sport shoe design, despite efforts recently in generating design criteria.

In a population of amateur tennis players, Luethi and Nigg (1985) and Nigg *et al.* (1986) examined the effect of footwear and other environmental factors on discomfort and injuries during tennis practice, using two distinctly different types of sport shoe. They found that nearly 40% of the athletes experienced some kind of problem: 55.1% reported some form of discomfort, 33.3% reported pain and 11.6% reported suffering an injury. Nigg and colleagues considered the frequency and location of injuries to be 'footwear-dependent'. More discomfort was reported by players wearing shoes with a hard mid-sole and a high coefficient of friction (47.0 and 32.6%, respectively); such footwear caused 75% of the discomfort experienced in the toes and knees, 71% of that in the ankles and 75% of that in the heels. The shoes with a soft mid-sole and a lower coefficient of friction were responsible for 75% of the discomfort felt in the internal arch of the foot. It should be noted that Nigg and co-workers used a different method to that used by Shackel *et al.* (1969).

The method used currently in ergonomics (Shackel *et al.*, 1969) gathers information using three questionnaires, which are completed during and after the use of the product being studied, under controlled conditions. The information collected covers general (global) discomfort, discomfort in particular areas of the body and subjective opinions about the design characteristics of the product in question. This method was used in the present study to assess general discomfort, discomfort in particular areas of the body and subjectively perceived errors in footwear design among regular tennis players wearing their usual tennis shoes.

The aims of this study were to examine: (1) the effect of design elements on discomfort in particular body areas, (2) the relative effect of discomfort on these body areas and (3) the relative effect of design errors on general comfort. Objective information was also recorded to determine how it interrelates with the subjectively perceived information.

Materials and methods

Following the method of Shackel *et al.* (1969), we gathered information on general discomfort, discomfort in particular body areas and the subjective opinions of tennis players about their own tennis shoes. General discomfort was measured on a 7-point Likert scale with the anchors 'extremely comfortable' and 'extremely uncomfortable'. To measure discomfort in particular body areas, represented on a diagram of the human body (Fig. 1), we also used a 7-point Likert scale anchored by 'no discomfort' and 'intense pain'. Finally, for the subjective ratings, 14 characteristics of the footwear (Fig. 2) were selected that could be classified using a 3-point Likert scale ('little', 'adequate' and 'high'). The 14 characteristics were: footwear floor-hold, front mid-sole height, rear mid-sole height, mid-sole hardness, front upper vamp hardness, rear upper vamp hardness, rear height, fastening, length, front width, rear width, flexibility, arch support position, arch support height.

Personal interviews with tennis players from five clubs in Valencia were conducted immediately after matches. The players' personal characteristics (sex, age, body mass, hours of practice) were recorded, together with descriptive information about the shoes (height of top, type of fastening, hell-counters, type of upper vamp, type of insoles, internal arch support, hollow in the mid-sole). Portable instrumentation was used to make the following measurements:

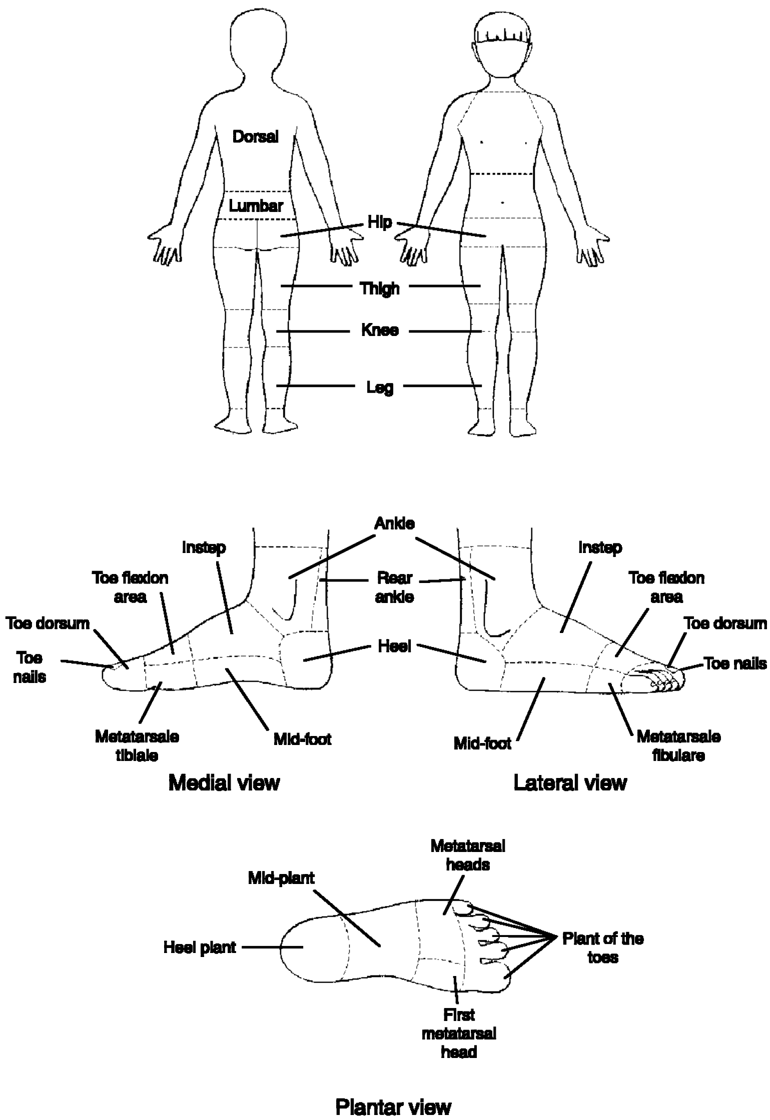

Fig. 1. The human body divided into areas for this study.

- Longitudinal flexibility (torsion) and transverse flexibility (flexion) were determined by machines of our own design using flexion (Fig. 3) and torsion (Fig. 4) axes while applying a 5 kg load. Repeatability was 2° for the torsion machine and 1° for the flexion machine (ISO 5725–1 and ISO 5725–3, section 8).
- Sliding of the footwear on the court surface was quantified using the sliding measurement machine of the Berlin Materials Testing Institute (BAM) (DIN 18032–2). The tests were performed by applying extra weight to the footwear of up to 0.8 kg.
- The hardness of the sole, mid-sole and insole was calculated using a hardness measurement machine (Härteprüfer, ISO 868) and according to the Shore A scale.

To allow for an *a priori* sampling error of 7%, 200 questionnaires were scheduled to be completed (there are approximately 4000 tennis players in Valencia). The target population was 'regular tennis players', individuals who played at least once a week. However, because of laborious data collection, only 146 correctly completed questionnaires were analysed.

The primary data were entered into a database created in Microsoft Access, which were to be treated later in SPSS and Statgraphics Plus. In addition to the descriptive analysis, the following statistical treatment was performed. First, cross-tabulation and chi-squared analysis were performed to determine associations between categorical variables (presence/absence of footwear design elements) and ordinal variables (general discomfort, discomfort experienced in particular

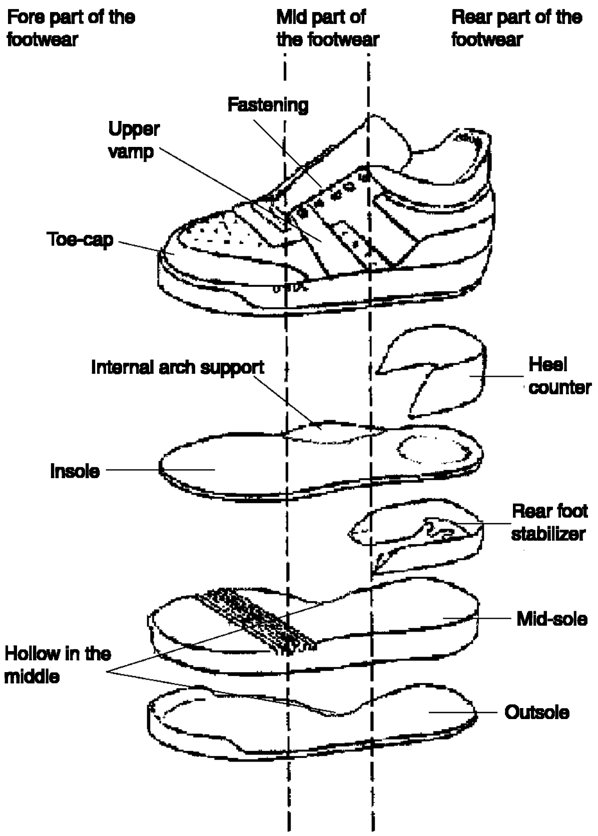

Fig. 2. The design elements of the footwear.

Fig. 3. Machine to determine longitudinal flexibility (torsion).

body areas, design errors) converted to categorical ones; significance was set at $P < 0.05$. The importance of (1) the discomfort felt in particular body areas and (2) design errors was assessed using attributable percentages (Sommer's *D* in 2 * 2 tables). These attributable percentages represent the percentages of players who experience general discomfort and particular discomfort and those who recognize design errors.

Fig. 4. Machine to determine transverse flexibility (flexion).

Analysis of variance was used to assess the dependence between the numerical and categorical variables (factors), setting significance at 0.05 and determining differences between factor levels using the LSD *post-hoc* test. Factor analyses of discomfort in particular body areas and design errors were used to identify group and independent variables. The analysis of main components was done using varimax rotation, taking values above 1 and considering those with a component higher than 0.52. Although this technique is based on parametric variables, it has been used widely in studies of subjective perceptions of specific products, for example footwear (Ishihara *et al.*, 1997), and in ergonomics in general (Jindo and Hirasago, 1997). Finally, Spearman correlation analysis was performed on factors leading to particular discomfort and design errors.

Results

Characteristics of the participants

The 146 tennis players (128 men, 18 women) were aged 26.1 ± 8.2 years (mean ± *s*). The body mass index was significantly different between males (23.2 ± 4.5) and females (19.9 ± 2.2) ($P < 0.05$).The players took part in 3.1 ± 2.1 h of tennis per week.

Characteristics of the footwear

The upper vamp material of 84% of the shoes was made of leather and 16% of synthetic materials. All shoes were fastened using laces and 79.9% had an internal arch support. Heel–counters were found in the rear or on the medial aspect in 83.2% of shoes and on the lateral aspect in 75.7%. Only 4.9% of the players were using insoles other than the original ones. Twenty–five percent of the shoes had a hollow in the mid–sole at the level of the mid–foot (a gap between the front and rear of the shoe).

The hardness of the soles, mid–soles and insoles was found to be different ($P < 0.001$), with mean values of 63.1 ± 4.3, 40.6 ± 3.7 and 33.2 ± 6.6, respectively (Shore A scale). The use of a hollow in the mid–sole at mid–foot level reduced the longitudinal flexibility (torsion) of the shoes ($P < 0.05$), with values of $24.5 \pm 1.5°$ for shoes without a hollow and $21.6 \pm 1.9°$ for shoes with a hollow. The results for transverse flexibility approached significance, with a similar trend to that of torsion: $44.4 \pm 4.9°$ for shoes without a hollow and $37.9 \pm 4.6°$ for shoes with a hollow.

There was a 40% difference in sliding on concrete and clay surfaces ($P < 0.001$), with mean values of 0.918 ± 0.148 m and 1.314 ± 0.243 m, respectively.

Discomfort

The *a priori* sampling error associated with the data (146 interviews) was 7.96%, considering that the probability of the event was 0.5 in the least favourable case (see Appendix). However, once the data were collected, the most frequent discomfort occurred in 17% of the players, thus the *a posteriori* sampling error dropped to 5.98%. These percentages refer to the sampling errors for the regular tennis playing population in Valencia, but could possibly be extrapolated to other regular players, since the shoes worn are similar.

Most tennis players stated that their footwear was comfortable (67.4% thought their shoes were 'extremely comfortable', 'very comfortable' or 'rather comfortable'), while only a minority considered their shoes to be uncomfortable (9.1% considered their shoes to be 'extremely uncomfortable', 'very uncomfortable' or 'somewhat uncomfortable'). The remaining 23.6% considered their shoes acceptable, neither comfortable nor uncomfortable.

In an analysis of the relationship between general discomfort and the discomfort experienced in particular body areas, five areas were considered to have an influence on general discomfort, all of them areas of the foot (Table 1): mid–foot plant, heel, Achilles tendon (rear ankle in Fig. 1), medial aspect of the first metatarsal and lateral aspect of the fifth metatarsal. Similarly, general discomfort was perceived subjectively to be affected by six footwear design errors (Table 2): soft toe–cap, hard mid–sole, poor hold, soft midsole, rigid toe–cap and low mid–sole at rear foot.

In an analysis of footwear design and discomfort in particular body areas after practice, there were several significant relationships. With the aim of simplification, we performed a factor analysis. Such an analysis seeks 'summary variables' (independent factors that group interrelated variables) that contain most of the inform-

Table 1. Frequency of discomfort in certain areas of the body

Body area	Frequency (% of occurrence)	Importance (Sommer's D)	Significance (P)
Mid–foot plant	11.1	54.7	0.00001
Heel	9.0	23.3	0.009
Achilles tendon	7.6	43.4	0.003
Inner side of first metatarsal	7.6	33.6	0.023
Outer side of fifth metatarsal	6.3	48.1	0.003

Table 2. Frequency of footwear design errors

Design error	Frequency (% of occurrence)	Importance (Sommer's D)	Significance (P)
Soft toe–cap	36.6	19.3	0.019
Hard mid–sole	25.2	26.4	0.007
Poor hold	22.2	22.4	0.021
Soft mid–sole	21.9	20.4	0.045
Rigid toe–cap	10.5	36.5	0.014
Low mid–sole at rear	10.0	31.6	0.022

ation provided by the original variables and that are independent of each other.

For discomfort in particular body areas, four of the factors identified contained 64.7% of the original information; for footwear design, six factors contained 62.8% of the original information. These factors, which were given a name and a code (in the case of 'M4', no name was assigned because it concerned vastly different anatomical areas), are shown in Tables 3 and 4.

After correlating both groups of factors, we found the following statistically significant associations:

- Factor E1 (mid-sole too high) correlated with M1 (shock absorption; $r = -0.250$, $P = 0.023$), M3 (functional adequacy of footwear to foot; $r = 0.186$, $P = 0.023$) and M4 ($r = 0.155$, $P = 0.049$).
- Factor E2 (hard and not very flexible) correlated with M4 ($r = -0.234$, $P = 0.006$).
- Factor E3 (incorrect arch support) correlated with M2 (plantar discomfort; $r = -0.187$, $P = 0.022$).

Discomfort and design of the footwear

Of the different design elements analysed, the stabilizing heel counters were associated with a reduction in discomfort in four body areas, mainly in the foot plant area (Table 5): head of the first metatarsal, toe plant, heel plant, mid-foot plant and fore thigh. The material the upper vamp was made from was associated with an increase in discomfort in the toe flexion area and in the heels (Table 6). The hollow in the mid-sole was associated with an increase in discomfort in the head of the first metatarsal (Table 7).

Discussion

Using flexibility measurement machines, we found that a hollow in the mid-sole of footwear at mid-foot level leads to less torsion. This was unexpected, since such a system was devised to favour the physiological torsion movement of the fore foot in relation to the rear foot (Stacoff *et al.*, 1989, 1991). Furthermore, the

Table 3. Independent factors for discomfort in certain areas of the body

Factor and code	Description (discomfort in body areas)
Shock absorption (M1)	Heel, lumbar back and, to a lesser extent, heel plant, internal side of first metatarsal and mid-foot plant
Plantar pain (M2)	Metatarsal heads, mid-foot plant and inner side of first metatarsal
Functional adequacy of footwear to foot (M3)	Ankle and rear of leg
(M4)	Toe flexion area and dorsal back

Table 4. Independent factors for footwear design errors

Factor and code	Description (type of footwear design errors)
Mid-sole too high (E1)	Mid-sole too high
Hard and poorly flexible (E2)	Toe-cap too rigid, poor flexibility and mid-sole too hard
Incorrect arch support (E3)	Too high or incorrectly placed arch support
Incorrect last (E4)	Too large and big footwear, incorrect lacing system and rear foot too rigid
Rearfoot too wide (E5)	Rear foot too wide
Cross-training (E6)	Excessive hold to court surface and rear foot upper material too high

Table 5. Internal heel-counters in rear foot

Body area	Frequency (%)	Importance (%)	Significance (P)
First metatarsal head	16.8	−19.8	0.017
Toe plants	14.7	−17.4	0.028
Heel plant	14.7	−17.4	0.028
Mid-foot plant	11.2	−16.5	0.019
Fore thigh	6.3	−12.5	0.022

Table 6. Synthetic upper material

Body area	Frequency (%)	Importance (%)	Significance (P)
Toe flexion area	10	13.2	0.026
Heel	9.2	16.1	0.016

Table 7. Hollow in the mid-sole at midfoot level

Body area	Frequency (%)	Importance (%)	Significance (P)
First metatarsal head	16.5	14.8	0.039

discomfort experienced in the first metatarsal was associated with footwear with a hollow. Both these results support the view that the hollow simply plays an aesthetic role and does not fulfil its theoretical functional purpose, at least in the footwear currently being marketed.

Although we identified several design errors and discomfort in several areas of the body (Tables 1 and 2), their frequency was reported to be low (6–37%), as was their perceived importance (19–55%). This explains the small proportion of tennis players who regarded their footwear as being uncomfortable. Nevertheless, significant design errors were detected (subjectively perceived) that cause discomfort in different areas of the body. The grouping of design errors and discomfort in various body areas resulted in four and six independent factors, respectively (Tables 3 and 4). Correlation analysis identified the associations among them. Factors E1 (mid-sole too high) and E3 (incorrect arch support) were previously identified by Nigg *et al.* (1986). This lends support to the method used, since similar results have been obtained using more 'traditional' biomechanical methods.

Of the correlations identified, the following were the most important. First, a high mid-sole was associated with a reduction in the discomfort attributable to shock absorption problems. It could be that with a higher sole and mid-sole, the loading on the musculoskeletal system is reduced during mechanical braking after landing on the court surface (Frederick *et al.*, 1984; Cook *et al.*, 1985). This obviously benefits players, especially when playing on less absorbent surfaces, such as concrete or asphalt. However, a high midsole also has its drawbacks (see below).

Secondly, there was a correlation between a high mid-sole and the functional adequacy of the footwear to the foot. A too high mid-sole was associated with an increase in discomfort to the ankle and rear of the leg. This was possibly due to the lateral instability caused by a high sole and mid-sole. It has been reported that the higher the sole and mid-sole, the more unstable is footwear at the ankle–subtalar joint complex. Consequently, prono-supination angles occur that impose high mechanical demands on the structures supporting this joint complex. This is in line with the results of previous studies (Stacoff *et al.*, 1985; Stüssi and Stacoff, 1993), which found that footwear for such sports as tennis should not have too high a sole and mid-sole, since ankle sprains are the most common form of injury (Llana *et al.*, 1998b).

Thirdly, we found that footwear with too rigid a toe-cap, poor flexibility and too hard a mid-sole reduced discomfort in the toe flexion area. Such discomfort is usually caused by friction with the upper vamp material. Consequently, it would appear that 'rigid' and 'hard' footwear does not allow flexion in this area, so that sores are avoided.

Finally, an incorrect arch support (height or placement) was found to increase plantar discomfort, possibly due to the incorrect transmission or distribution of plantar pressures during locomotion. Considering how important the longitudinal arch is in the distribution of plantar pressures during locomotion, a badly designed arch support must have a negative effect (Gheluwe *et al.*, 1994). To confirm this, a study with instrumented insoles will be necessary. This was beyond the scope of the present study.

Of the design elements of the footwear, internal stabilizing heel counters were found to reduce discomfort in several body areas, especially that involved in the foot plant (Table 5), due to their effect on the biomechanics of the stance phase during sport practice. On the one hand, they contribute to a better control of rear foot pronation (Stacoff and Kaelin, 1983; Ferrandis *et al.*, 1994). This limits hyperpronation, which diminishes the mechanical demands on the ankle–subtalar joint complex and avoids excessive medial plantar pressures. On the other hand, heel counters improve the shock absorbency of the soft tissue of the heel, thus reducing the severity of impacts in this region and, consequently, in other areas of the body (Wosk and Voloshin, 1981, 1982; Voloshin and Wosk, 1982; Voloshin *et al.*, 1985;

Jorgensen and Bojsen-Moller, 1989; Ferrandis *et al.*, 1994). These results support the role of heel counters in sports such as tennis, not only because of their positive impact on injuries (Lllana *et al.*, 1998b) and performance (Llana *et al.*, 1998c,d), but also because of their positive effect on comfort.

Conclusions

In this study, we applied the method proposed by Shackel *et al.* (1969), for the evaluation of products designed for use by humans, to tennis shoes to determine the relationships between discomfort and footwear design characteristics. Most players studied considered their footwear to be comfortable. Nevertheless, many design errors were perceived subjectively to increase discomfort. An important correlation was noted between an incorrect arch support and plantar discomfort. Also, a high mid-sole reduces the severity of impacts but increases discomfort in the ankle and rear foot.

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Appendix

According to the Valencia Tennis Federation, 4000 people play tennis regularly in Valencia – that is, at least once a week. The sampling error for 146 tennis players was calculated as follows:

$$E = K \cdot \sqrt{(p \cdot q)/n} \cdot \sqrt{(N - n)/(N - 1)}$$

where E is sampling error for 1% (multiply by 100 to obtain 100%); K is a confidence constant, here 1.96; p is the probability of an event; q $(= 1 - p)$ is the probability of the opposite event; N is the size of the population (here 4000); and n is the sample size (here 146).

Thus, the *a priori* sampling error was $0.0796 \cdot 100 = 7.96\%$, when $p = 0.5$ and $q = 0.5$. Once the study had been completed, however, the most frequent discomfort was experienced by 17% of the players ($p = 0.17$ and $q = 0.83$). Consequently, the sampling error fell to $0.0598 \cdot 100 = 5.98\%$.