

Influence of Foot, Leg and Shoe Characteristics on Subjective Comfort

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ABSTRACT

The purpose of this study was to determine the relationships between foot and leg characteristics, shoe characteristics, and the short-term subjective comfort of three different pairs of athletic shoes. Static measurements of foot dimension and leg angles were taken from eighteen subjects. Subjects rated the comfort of three different athletic shoes for standing, walking and running. The shoes were quantified by internal dimensions, hardness, flexibility and torsional stiffness. Average comfort ratings decreased from standing to walking to running. One shoe seemed suited for only a small group of subjects. In contrast, another shoe was generally comfortable for a large group. Skeletal alignment, specifically eversion angle, was related to comfort for one shoe. Therefore, fit of the shoe is not sufficient for comfort. Skeletal alignment, shoe torsional stiffness and cushioning seem to be mechanical variables which may be important for comfort.

INTRODUCTION

Comfort is an important element for the design of sport shoes. However, comfort is not perceived the same way by all subjects. A shoe that some athletes find comfortable may be uncomfortable for others. It has been assumed that for a shoe to be comfortable, the inside of the shoe should closely match the shape of the wearer's foot⁹, but there is a lack of scientific evidence to support this statement. This lack of evidence may be due to difficulty in interpreting comfort assessments. Comfort is a subjective feeling, which is difficult to define and quantify. It has been suggested that it cannot be measured directly^{5,29}, yet everyone can

determine quickly whether or not a shoe is comfortable. Comfort seems to be related to fatigue, injury development and performance. Thus, it is important to identify factors which are important for comfort.

Comfort may be influenced by mechanical, neurophysiological and psychological factors. This paper concentrates on the selected mechanical aspects of shoe material properties, foot shape and shoe fit, and skeletal alignment.

Loading and foot mechanics have been assumed to have an influence on comfort. Shoe construction has a significant influence on pronation and the loading of the foot²⁰. Although it has been argued that cushioning properties of running shoes could create a perceptual underestimation of actual impact severity and therefore lead to running injuries²³⁻²⁶, other studies have found high correlations between cushioning and impact perception, and mechanical variables related to impact^{12,15,29}. Thus, cushioning and impact perception may influence comfort. Furthermore, a change in midsole hardness was not found to influence magnitude and loading rates of external forces; however, it resulted in a redistribution of load¹⁹. Subjects obviously reacted to a change in midsole hardness. The reason for this behavior may be related to comfort.

Shoe construction also affects the in-shoe pressure distribution of the foot during running¹¹. It has been suggested that pressure distribution on the plantar surface of the foot is associated with comfort during walking^{6,7,32}. However, it has also been reported that differences in subjective comfort ratings of three different shoes are not related to any in-shoe plantar distribution result¹³.

Hawes et al.⁹ concluded that unique shoe lasts for North American and Japanese/ Korean populations are required for optimal shoe comfort. However, these studies did not involve the subjective assessment of shoe comfort and its relationship to foot dimension and shape. It is still not clear how foot dimension and shape will affect subjective comfort and what the most important variables are.

The relation between perceptual rating and stimulus

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intensity can easily be biased. Perception is a dynamic process that depends not only on the current stimulus but on recent and expected stimuli as well¹. Thus, psychophysical procedures have been developed to find efficient, reliable and valid measures of subjective experiences. The Borg scale has been used most widely to evaluate perceived exertion²¹. Using a 21-point rating scale, Borg studied the perception of effort during aerobic work². To increase linearity between ratings and workload, the scale has been modified to a 15-point³ and 10-point⁴ graded category scale. Research has been published using similar scales to understand comfort of shoes. A 5-point perception of comfort scale has been used to conclude that the measurement of foot pressures should be useful for identifying causes of discomfort in footwear¹³. A modified Borg 15-point perception scale determined that subjects could detect the difference in cushioning between varying hardness of shoes^{12,17}. A method of relative subjective ranking has been used to find that plantar pressure distribution is related to shoe comfort⁶. However, none of these studies presented data on the reliability of the subjective comfort ratings.

The influence of (a) mechanical characteristics of shoes, (b) foot and leg characteristics, and (c) fit between shoe and foot on comfort assessment has not

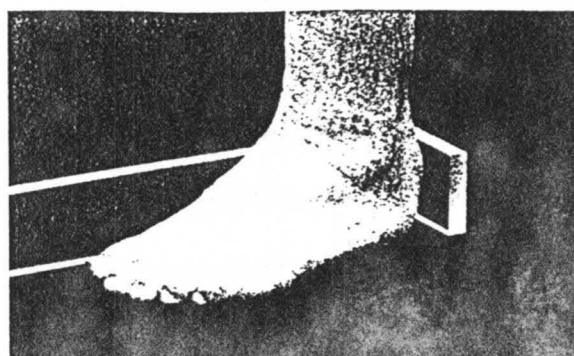


Fig. 1. Photo of the right-handed tool used to establish the origin, longitudinal and medio-lateral axes of the foot: the longitudinal axis was defined parallel to the most medial aspect of the forefoot and rearfoot, the medio-lateral axis perpendicular at the most distal part of the heel.

been studied. They have been studied independently, but a correlation between these characteristics and comfort has not been determined. This is important since it allows us to target specific customer or patient groups with appropriate footwear. Thus, the purpose of this study was to examine the relationship between foot and leg characteristics, shoe characteristics and fit as they relate to short-term comfort of three different shoes. Some of the variables considered were foot dimensions, leg angles, shoe internal dimensions, shoe torsional stiffness, hardness and flexibility, and subjective comfort ratings.

METHODS

The variables quantified in this study included: shape measurements of the left foot and leg; comfort rating for standing, walking, and running in three different athletic shoes; measurements of shape and mechanical characteristics of the shoes.

A sample of 12 male and 6 female subjects was selected, having U.S. men's shoe sizes of 8 1/2 – 9. Their foot measurements were within the normal range of the North American population¹⁰. Each subject judged the shoes used in this study to be an acceptable fit. Any subject who found them too small or large was not included in the study. All subjects gave informed written consent, appeared from visual inspection to have normal gait and did not specify any injuries or pain in the lower limbs at the time of the testing.

Following methods previously developed^{9,10}, foot measurements were taken on the fully weight bearing left foot with the subject standing upright and the right foot resting on a stand 25 cm high. A local co-ordinate system of the foot was established by means of a right-angled tool (Figure 1). The longitudinal axis (z-axis) of the foot was parallel to the widest points on the medial

Table 1. Foot and leg variables calculated from digitized points

Variables	Definition
Height	
H_{Hallux}	Hallux height
H_{F1MH}	Height of first metatarsal head
H_{F5MH}	Height of fifth metatarsal head
H_{Dorsum}	Dorsum height
H_{Farch}	Maximum arch height
H_{Fim}	Lateral malleolus height
H_{Fpc}	Posterior calcaneus height
Length	
$L_{F1T,2T,3T,4T,5T}$	Length from heel to first, ..., fifth digit
L_{F1MH}	Length of heel to first metatarsal head
L_{F5MH}	Length of heel to fifth metatarsal head
$L_{Fdorsum}$	Length of heel to dorsum
Width	
$W_{F1T,2T,3T,4T,5T}$	Width from tip of first, ..., fifth digit to y-axis
W_{Fheel}	Heel breadth
W_{Fpc}	Posterior calcaneus breadth
$W_{Fforefoot}$	Foot breadth measured from first to fifth metatarsal
Angle	
γ	Heel resting position angle
ϕ	Forefoot flexion angle
β	Angle of heel to tibia (eversion)
ξ	Tibial torsion angle during two foot standing

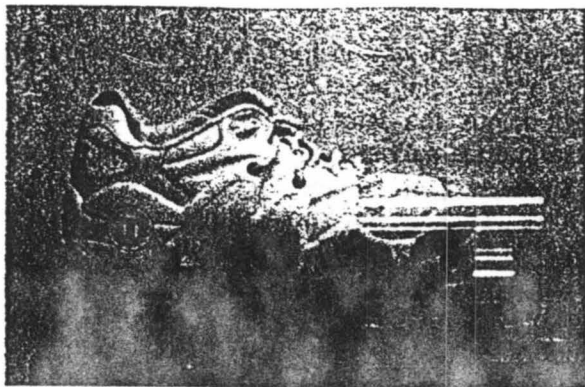


Fig. 2. Photograph of shoe torsional stiffness testing apparatus, consisting of a support to stabilize the heel of the shoe while the forefoot was clamped in a rotating cylinder.

forefoot and heel. All lengths were measured parallel, and widths were measured perpendicular, to this axis. The medio-lateral axis (x-axis) was established to be perpendicular to the z-axis, at the most posterior part of the heel. The y-axis was vertical, with the origin located at the standing surface. Measurements were taken with a Polhemus 3D Fastrak electro-magnetic digitizer with resolution of 0.3 mm. The subjects stood in the magnetic field, and a hand-held receiver was used to digitize three-dimensional co-ordinates of 25 points on the skin surface of each subject's foot and leg. Twenty-seven variables were calculated from the coordinates of the digitized points (Table 1). The detailed protocol of digitization along with accuracy and reliability testing results are published elsewhere¹⁶. In short, lengths, widths, heights and angles of the foot and leg were calculated from the digitized points with respect to the origin of the established co-ordinate system.

Subjects were asked to give the three different pairs of shoes a comfort rating using a modified Borg scale⁴ (1-10) after standing, walking (200 m) and running (600 m). A rating of 10 was defined as very comfort-

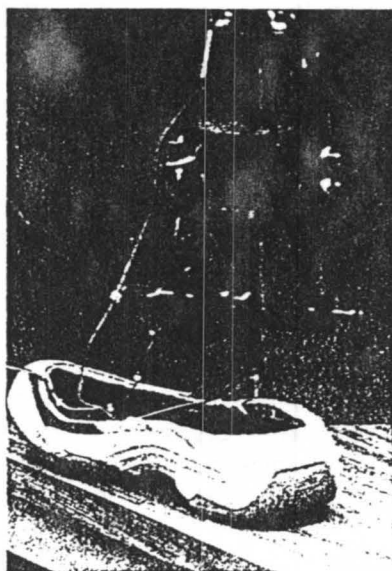


Fig. 3. Photograph of the set-up for the measurement of hardness of each shoe/insert composite, including the shoe with upper removed, and a motor-driven indenter instrumented with a force transducer.

able and a rating of 1 as very uncomfortable. The order in which subjects tried the shoes was random. Each subject ran and walked at a preferred speed. A repeatability study of subjective comfort was conducted consisting of a second rating of the shoes by nine of the subjects at a later date.

Three athletic court shoes of different construction were used in this study. Only one pair of each type was used. The shoes were "broken in" by three volunteers who performed the walking and running trials, then evaluated by the 18 subjects during the experiment. Once all subjects had evaluated them, measurements were performed on the left shoe of each pair. Selected shoe properties were determined, including torsional stiffness, flexibility, hardness of the sole, and internal dimensions. For the measurements of hardness, flexibility and dimensions, the shoe upper was removed.

Torsional stiffness was calculated from measured angular displacements of the forefoot of each shoe for a given applied moment. The toe of the shoe was clamped into a rotating cylinder while the rear of the shoe was fixed (Figure 2). For three trials each, 1.52 and 3.04 Nm moments were applied to the cylinder and the angular inversion and eversion of the forefoot with respect to the rearfoot was measured with a goniometer. The mean and standard deviation of three trials were calculated.

After removing part of the upper, the hardness of the insert/shoe composite could be determined. A device was used to press an indenter of 0.5 cm² cross-sectional area into the insert/shoe, while force was calculated from force transducer data (Figure 3). The accuracy and reliability of this device have been tested¹⁴. The maximum deflection of the insert/shoe was measured under approximately 400 kPa (20 N applied over 0.5 cm²). Hardness measurements were taken three times each at the center of the heel, approximately 1 cm inside of the medial and lateral arches, at the first

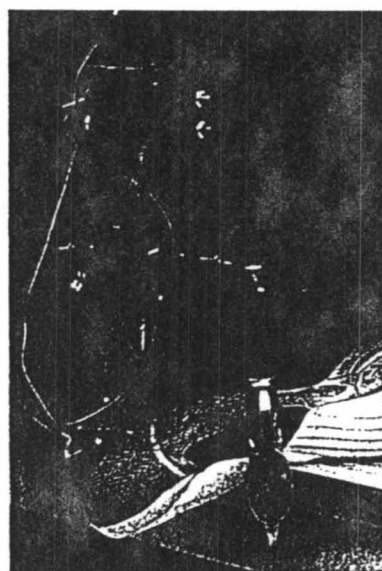


Fig. 4. Photograph of the set-up for the measurement of shoe sole flexibility, including the shoe with upper removed clamped to a table, and a motor-driven indenter instrumented with a force transducer.

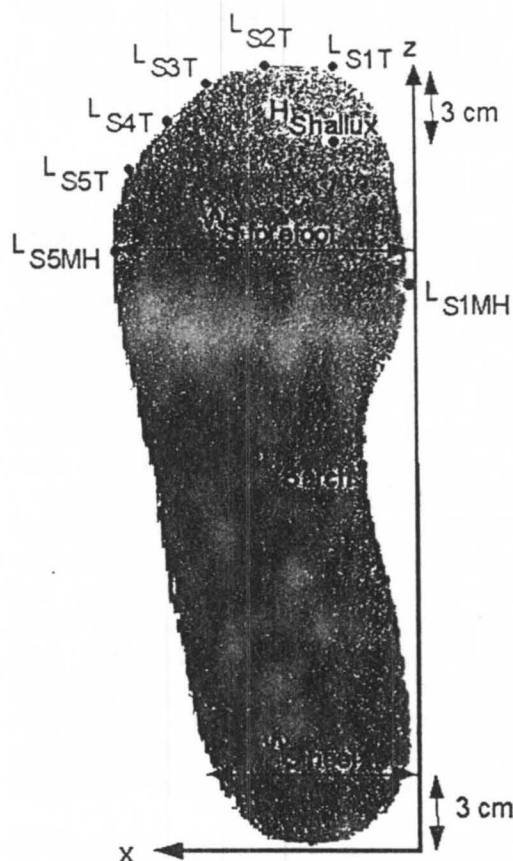


Fig. 5. Locations of points digitized on the left shoe insert, in order to calculate lengths, widths and heights.

metatarsal-phalangeal joint, the fifth metatarsal-phalangeal joint, and the hallux of the shoe. Means and standard deviations were calculated.

Shoe sole flexibility was measured using the same motor/transducer device. The shoe was clamped to a table upside down, with the upper removed (Figure 4). The sole was supported by the table 2 cm posterior to a line between the widest part of the medial and lateral forefoot, which was assumed to be the flexion line. A downward force of 22 N was applied 5 cm anterior to the flexion line and the angle of flexion of the shoe was measured with a goniometer. Three trials were conducted and the means and standard deviations calculated.

The dimensions of the inside of each left shoe were measured in a similar manner as the foot measurements. The reliability of the digitization technique has been reported earlier¹⁶. The longitudinal axis was determined parallel to the two widest points on the medial side of the insert as shown in Figure 5. Arch height (H_{Sarch}) was measured as the highest point on

the arch of the insert with respect to the heel height while the insert was in the shoe. The shoe spring ($H_{Sspring}$) was determined by the difference in the heel height minus the forefoot height, measured at the medial metatarsal head, also while each insert was in the shoe. In other words, a high spring indicates that the thickness of the shoe sole at the heel is much higher than at the forefoot. The toe box height ($H_{Shallux}$) of the shoe was measured 3 cm posterior to the end of the shoe, at the width of the center of the first digit. The location of each digit on the shoe was determined by taking the average distance from the z-axis of each digit for all subjects. Subsequently, the lengths (L_{S1T} , L_{S2T} , L_{S3T} , L_{S4T} , L_{S5T}) were measured at these distances. Heel breadth (W_{Sheel}) was measured as the insert width, 3 cm anterior to the end of the insert. The length from the heel to the most medial and lateral points of the forefoot were determined (L_{S1MH} and L_{S5MH} respectively), and from these points the forefoot width ($W_{Sforefoot}$) was calculated.

Average comfort ratings were calculated for each shoe and each condition. The repeatability of the comfort ratings was tested using the Pearson product-moment correlation coefficient. Groups were formed which consisted of subjects who preferred each shoe (highest rating) for each condition (standing, walking and running). This resulted in a total of nine groups (3 shoes, 3 conditions). One-way analysis of variance was calculated to determine which foot and leg variables were significantly different between people who preferred different shoes for a given condition.

For all the dimension measurements taken on the shoe, a measure of fit was calculated. These variables were calculated as the size of the shoe minus the size of the foot for each subject (indicated by " Δ "). For the other subject measurements, for which there was not a corresponding measurement on the shoe, only the foot or leg dimension was studied. Correlations of foot measurements or fit variables, and leg angles, with comfort were determined using Pearson's product moment correlations, and by visual analysis for trends. For the visual analysis, shoe, foot and leg dimensions were plotted against the subjective comfort ratings and the graphs were analyzed for trends which seem to indicate an optimum range or value for the measurement variable in order to have maximum comfort.

RESULTS

In general, Shoe 1 was the longest and widest shoe and had the highest spring. Shoe 2 had the highest toe box and arch, while Shoe 3 had the lowest spring, arch height and toe box (Table 2).

Shoe 1 had the highest torsional stiffness for inver-

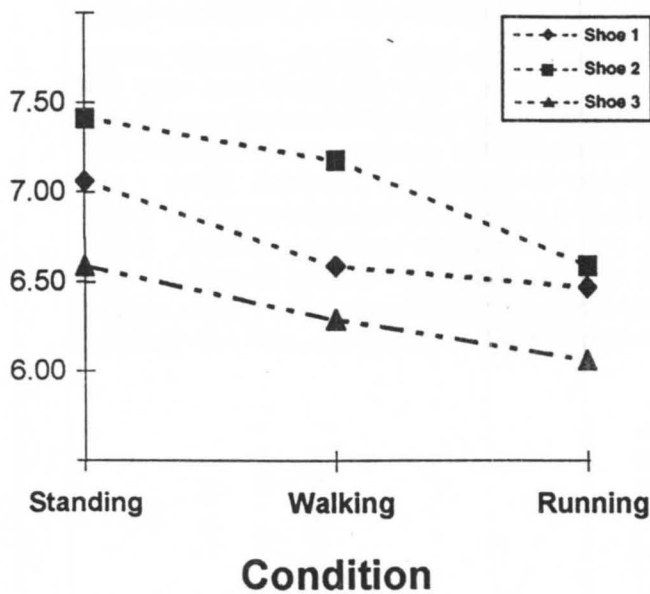


Fig. 6. Average comfort ratings for each shoe, for standing, walking and running conditions.

sion, the lowest eversion stiffness and the lowest forefoot flexibility. Shoe 2 was the most flexible and also generally the hardest shoe. Shoe 3 was, in general, the softest shoe (Table 2).

For the standing condition, the comfort rating of shoes 1 and 2 were not very repeatable. However, there is a better correlation between the first and second comfort ratings for walking and running (Table 3).

On average, Shoe 2 was the most comfortable, and shoe 3 was the least comfortable. The comfort rating decreased from standing to walking to running, although it did not decrease in a similar way for each

Table 2. Summary of shoe characteristics

Characteristics

Shoe 1	Longest
	Widest
	Highest spring
	Highest torsional stiffness, inversion
Shoe 2	Lowest torsional stiffness, eversion
	Highest toe box
	Highest arch
	Highest torsional stiffness, eversion
Shoe 3	Highest forefoot flexibility
	Hardest
	Lowest toe box
	Lowest arch height
	Lowest spring
	Shortest
	Lowest torsional stiffness, inversion
	Softest

Table 3. Pearson product moment correlation coefficient (r) for repeated subjective comfort ratings.

Shoe	Standing	Walking	Running
1	0.41	0.70	0.64
2	0.36	0.86	0.65
3	0.86	0.84	0.89

Table 4. Significantly different foot/leg measurements for groups rating each shoe most comfortable ($p \leq 0.05$).

Foot/leg Variable	Standing	Walking	Running
H_{Hallux} [mm]			
Shoe 1			21.56 (1.38)
Shoe 2			18.44 (0.65)
Shoe 3			19.34 (2.39)
H_{Dorsum} [mm]			
Shoe 1		77.48 (12.04)	
Shoe 2		82.42 (3.38)	
Shoe 3		74.34 (2.57)	
L_{Dorsum} [mm]			
Shoe 1		103.51 (3.90)	
Shoe 2		102.52 (5.89)	
Shoe 3		112.51 (3.28)	
W_{Fpc} [mm]			
Shoe 1	33.6 (2.12)		
Shoe 2	28.1 (1.87)		
Shoe 3	31.2 (1.42)		
W_{Forefoot} [mm]			
Shoe 1			100.38 (1.97)
Shoe 2			92.88 (3.91)
Shoe 3			98.23 (4.30)

shoe. For walking, the average ratings of shoes 1 and 3 were relatively close, however for running, the comfort of shoe 1 was almost as high as shoe 2 (Figure 6).

For the groups of subjects who rated each shoe most comfortable, the foot/leg dimensions which were significantly different between the groups were the hallux height, dorsum height, dorsum length, posterior calcaneus width, and forefoot width (Table 4). Shoe 1 was rated most comfortable by groups that had on average the largest hallux height, posterior calcaneus width, and forefoot breadth. Shoe 2 was rated highest by groups that had on average large dorsum heights and small hallux heights, posterior calcaneus widths and heel breadths.

Significant correlations ($|r| > 0.5$, $p < 0.05$) between foot and leg measurements and the subjective comfort ratings of the shoes could indicate important factors for comfort. A positive correlation with subjective comfort means comfort of a given shoe increases as the foot dimension increases. The highest correlations were found for posterior calcaneus width in shoe 1 ($r = 0.70$), and heel eversion for shoe 2 ($r = -0.63$). Shoe 1 had, in total, 6 significant correlations, whereas shoes 2 and

3 had only 3 and 1 correlation, respectively (Table 5).

From the visual analysis of all variables plotted against comfort ratings, several variables seemed to have a trend towards a range or value for maximum comfort. This was especially the case for shoe 1 more than the other two pairs. Figures 7, 8 and 9 are representative of some of the trends that were determined graphically. The lines shown on these figures are intended to help illustrate the trend, and were not calculated statistically. The fit of the length and width of shoe 1 at the toes was consistently related to comfort. For example, the best width of the third digit from the longitudinal axis was about 65 mm for standing in shoe 1 (Figure 7). The best fit of shoe 1 at the fifth digit was very small for standing, walking and running (Figure 8). A tight fit at the forefoot was also desirable for this shoe, indicated by a negative optimum difference between shoe and foot (Figure 9). In total, shoe 1 demonstrated 38 of these types of trends for all 3 conditions, whereas shoes 2 and 3 exhibited considerably fewer trends (2 and 22, respectively).

DISCUSSION

This study attempted to detect possible relationships between foot and leg characteristics, shoe characteristics and the short-term comfort of shoes for a healthy population. The correlation coefficients for repeated comfort ratings for walking and running ranged from 0.64 to 0.89. Although other footwear studies addressing comfort have not presented results on reliability, one study found a within-subject coefficient of variability of 20% for perception ratings of impact¹⁵. Considering the subjects were rating impact, a variable much more easily quantifiable than comfort, the correlation coefficients for repeated comfort ratings for walking and running in this study are acceptable.

The average comfort ratings changed for each shoe and each condition, reinforcing the fact the comfort of a given shoe depends not only on the individual and shoe characteristics, but also on the activity. The average comfort rating decreased from walking to running. Although this study did not attempt to determine the relation between short-term and long-term comfort, this result suggests that more consideration should be given in buying a shoe intended for running, as opposed to a shoe intended for day-to-day wear. For example, when choosing a shoe for running, the wearer should run in the shoe before making a purchase, if possible.

Some shoes may be generally comfortable for most people, whereas other shoes are comfortable only for specific groups. Shoe 2 had the highest toe box, arch and flexibility, and was the hardest. It was, on average,

the most comfortable shoe, and its comfort ratings ranged from 4 to 8. But this shoe had very few foot/shoe variables with statistical correlations or visual trends with respect to comfort. The fit seemed to be less critical for the comfort of this shoe. Shoe 1 was the longest and widest, with the highest spring. It also had the highest inversion torsional stiffness, lowest eversion stiffness and lowest forefoot flexibility. It was in general not as comfortable as shoe 2, but its comfort ratings ranged from 2 to 9. Shoe 1 also had the most

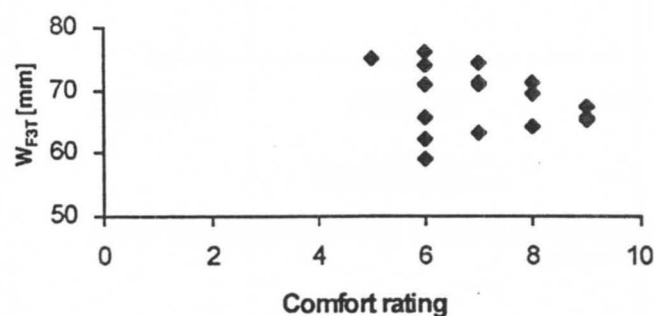


Fig. 7. Width of the third toe from the longitudinal axis vs. comfort rating, for each subject after standing in shoe 1.

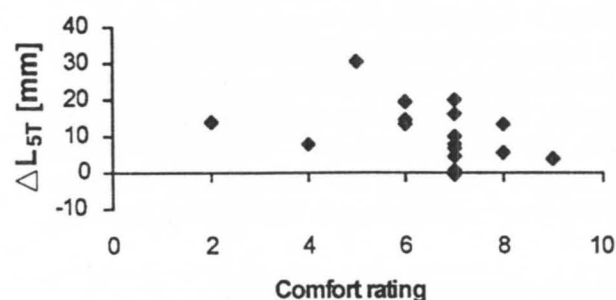


Fig. 8. Difference between length of the shoe and length of the foot at the fifth toe vs. comfort rating, for each subject after running in shoe 1.

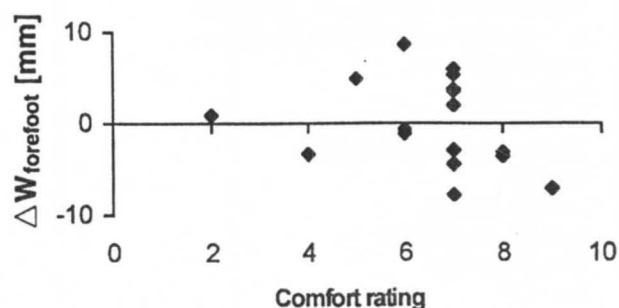


Fig. 9. Difference between the shoe and foot forefoot width vs. comfort rating, for each subject after running in shoe 1.

Table 5. Pearson correlation coefficients between foot/leg dimensions and subjective comfort rating ($|r| > 0.5$, $p < 0.05$).

Foot/Leg Variable	Shoe 1			Shoe 2			Shoe 3		
	standing	walking	running	standing	walking	running	standing	walking	running
H _{F5MH}	-0.57								
L _{F1T}			0.51						
L _{F2T}				0.51					
L _{F3T}				0.53					
W _{Florefoot}		0.51					-0.56		
W _{Fpc}	0.70		0.55						
γ		-0.55							
β					-0.63				

in choosing a comfortable shoe. One of the significant correlations found in this study is that comfort increases with decreasing eversion angle ($r = -0.638$) for shoe 1. It was noted that the plantar surface of this shoe

number of foot/shoe variables which had significant correlations or trends for maximum comfort. In other words, shoe 1 was more comfortable for a specific group of people.

For shoe 1, fit was a more important factor than for the other shoes. Shoe 1, being generally the biggest shoe, was rated most comfortable by subjects that had high halluxes and wide forefeet (Table 4). It was also more comfortable for people with higher toe lengths (Table 5). The fit of the length and width of shoe 1 at the toes, and width at the forefoot was related to comfort. However, shoes 2 and 3 did not demonstrate these patterns. This may be because shoes 2 and 3 were smaller and in general a better fit. Therefore, the effect of the fit of the shoes was not as noticeable and other variables became important. It seems that a good fit may be the most critical factor for comfort, followed by some of the other variables discussed. For all the trends shown (Figures 7, 8, 9), it is important to note that each variable is necessary but not sufficient for maximum comfort. Several other variables play a confounding role.

Skeletal alignment may also need to be considered

was lower at the medial forefoot than at the lateral forefoot. Many subjects commented that the shoe felt like it was causing them to evert. It may be that subjects with a low eversion angle, who tend to have more weight on the lateral side of their foot, felt less pressure on the lateral side due to the construction of shoe 1.

In order to determine which shoe characteristics may be more important for comfort, the first step should be to look at the variables which are considerably different for the most and the least comfortable shoe (Table 6). Torsional stiffness is different between shoes 2 and 3, and is also different for shoe inversion versus eversion. There seems to be an optimal amount of torsional stiffness, however it is not possible to say what that is yet. Torsional stiffness of shoes is known to affect foot and lower leg kinematics^{30,31,33}, and it may be that shoe stiffness, comfort, and risk of injury are related. It also seems that cushioning plays an important role, as there are considerable differences between the overall cushioning of the most and least comfortable shoes. It has been argued whether or not cushioning is important for injury^{8,19,28}. It will be important in the future to understand these relationships as both shoe comfort and injury prevention are critical factors in shoe design.

Table 6. Summary of differences between most and least comfortable shoes.

Comfort		Shoe 2 best	Shoe 3 worst	Shoe 1 medium
Torsional Stiffness	inversion	medium	soft	stiff
	eversion	stiff	medium	soft
Flexibility		soft	medium	stiff
Cushioning	general	hard	soft	hard
	heel	hard	medium	soft
Dimensions	length	long	small	long
	width	small	small	wide
	height	high	low	high

CONCLUSIONS

The distribution of comfort rating for sport shoes can be quite different. Some shoes were generally comfortable for most subjects, while other shoes were comfortable for only a specific group of subjects. The reason for these differences may be explained by a number of interdependent factors including the subject characteristics, shoe characteristics, and possibly the individual's response to a given shoe:

- The comfort of a given shoe depended on the activity being performed.
- An important factor for shoe comfort was the fit of

the shoe. The most critical foot dimensions included hallux height, dorsum height and length, forefoot and posterior calcaneus width, and toe lengths. If a shoe provided a good fit, other factors became more important, such as alignment of the lower leg.

- Subject characteristics such as skeletal alignment influence comfort. For example, heel eversion angle was related to comfort for some shoes. Certain shoe characteristics, such as forefoot eversion, may change skeletal alignment, hence affecting comfort.
- Mechanical shoe variables were necessary but not sufficient factors for comfort. In other words, some mechanical variables, such as torsional stiffness and cushioning, were related to comfort. However other factors, such as a good fit, were still required for the shoe to be comfortable.

The relationship between subject and shoe characteristics, and sport shoe comfort is only partially understood. It is suggested that torsional stiffness and cushioning of a shoe are important variables for comfort and should be studied further. Other subject characteristics such as foot sensitivity to pressure and vibration²², and dynamic foot function may also affect the comfort of sport shoes. The goal of further research is to find whether groups of people with certain anthropometric, dynamic foot function and sensitivity characteristics react to specific shoe characteristics in a consistent way, and what those groupings of characteristics are.

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