Think high-heels are uncomfortable?

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For many years, medical personnel have alluded to the health hazards of high-heeled shoes. However, fashion tends to override pain, no matter how dire the consequences may be. This led us to ask if high-heel shoes can be comfortable. Our study clearly shows that the design parameters of a shoe significantly influence the perceived feeling of a high-heel shoe wearer. Thirty-two females participated in an experiment where different footbed shapes were investigated at a heel height of 75 mm. The results demonstrate the existence of a footbed shape that is considered to be the most comfortable. The potential reason for the preferences can be related to the contact area between the plantar foot and the footbed surface, the peak plantar pressure distribution and the force distribution among different foot regions.

INTRODUCTION

The first impressions of high-heeled shoes for anyone are discomfort and pain. Even then, wearing high-heel shoes is commonplace and a basic requirement for certain groups of people such as models, actresses, high-ranking officials, and so on. High-heeled shoes give a person some sense of “longer legs” and an elevated “stature”.

The literature related to high-heeled shoes has shown the presence of relatively high loads in the forefoot region when compared to wearing low heel shoes or going barefoot (Broch, Wyller and Steen, 2004; Mandato and Nester, 1999; McBride, Wyss, Cooke, Chir, Murphy, Philips and Olney, 1991; Nyska, McCabe, Linge and Klenerman, 1996; Snow, Williams and Holmes, 1992). The increase in force is accompanied by an increase in pressure under the forefoot, especially with an increase in shoe heel height (Nyska et al., 1996; Rodgers and Cavanagh, 1989). All of these effects are risk factors in relation to foot pain, foot injuries, knee pain, back pain, etc. Given a basic understanding of the conditions that contribute to high loads and high pressures in certain parts of the foot, the question of if high-heeled shoes can be designed to be comfortable seems never to be asked. In this study, we show that high heeled shoes can indeed be comfortable and the design parameters of the footbed govern the level of comfort to a significant extent.

A shoe wearer’s comfort is known to be related to the shape of the footbed of a shoe (Hartsell, Brand, Frantz and Saltzman, 2004; Lee and Hong, 2005; Witana, Goonetilleke, Xiong and Au, 2009). Even though the footbed shape is important in footwear design, designing a last is primarily a process of trial and error or reverse engineering. Organizations around the world have developed guidelines for footbed design based on varying heel wedge angles depending on heel height, the length of heel support (seat length), and certain shank shapes that correspond with the midfoot. Unfortunately, manufacturers tend to adopt their own guidelines due to the lack of scientific evidence for any particular shoe shape. It is thus no surprise that consumers tend to favor particular brands not just because of styling and cost, but because of the comfort level associated with those brands of shoes. The aim of this study is to investigate the effects of differing footbed shapes of high-heeled shoes on the wearer’s perceived feelings of comfort and discomfort.

METHODOLOGY

Participants

Thirty-two females who were regular high-heeled shoe wearers were participants in the experiment. Their ages ranged from 18 to 36 years with an average age of 23.2 years. The range of foot length was from 20.9 cm to 26.0 cm with a mean of 23.4 cm. None of the participants had any foot illnesses or foot abnormalities. Each of the participants was asked to fill in a consent form prior to the experiment. This study was approved by the Hong Kong University of Science and Technology research ethics committee on human subjects.

Procedure

Each of the participants was asked to stand on one footbed shape at a time and rate each shape based on their perceived feeling. A Profile Assessment Device (PAD) (Goonetilleke and Witana, 2007) was used to simulate the footbed shape of a shoe. PAD has built-in adjustments to vary heel height (H), heel wedge angle (θ) and seat length (L) as shown in Figure 1. Once the PAD is set to account for differing parameters, participants are able to stand on it similar to standing on an insole-midsole-outsole combination of a shoe without an upper. The shape of the footbed surface was then captured using the FARO Arm 3D Digitizer (Model B08/ REV 12) from FARO Technologies. The pressure between the foot and the footbed surface was monitored with a FSCAN system from Tekscan® Inc.

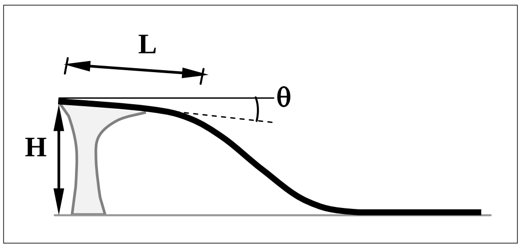

Figure 1. Cross-section of a foodbed; H = heel height, L = seat length, θ = heel wedge angle

The heel height (H) tested was 75 mm. The seat length (L) was determined based on the participants' anatomy. It was set as the distance along the foot from the point at which the rear-foot touched the ground to the fifth metatarsal head. The heel wedge angle (θ) had 7 levels; 12^o, 14^o, 16^o, 18^o, 19^o, 20^o and 22^o.

The dependent variables were perceived feeling when standing on the footbed surface, the plantar foot pressure (peak pressure), the force under the foot and the contacted area between the foot and the footbed. The Fscan pressure assessment system was used to record the plantar peak pressure, force and contact area. The experiment was a within-subject mixed-model design. During testing, both left and right feet were on two different platforms with the same shape. The presentation order of the varied parameters was random.

A subjective screening test of line length estimation was first performed to evaluate the judgment ability of each participant. The method proposed by Kee and Karwowski (2001) was used based on free modulus magnitude estimation (Gescheider, 1985).

Participants were asked to maintain a static posture (i.e., to stand without moving their feet) in balanced standing. A questionnaire was used to obtain the perceived feelings when standing on each footbed. The questions were:

- Do you like the feeling on the right foot (overall)? Give a rating
- Do you like the feeling on the right rear-foot? Give a rating
- Do you like the feeling on the right mid-foot? Give a rating
- Do you like the feeling on the right fore-foot? Give a rating

The free modulus magnitude estimation method (Gescheider, 1985) was used to elicit the participants' ratings. Participants were told that higher ratings corresponded to higher comfort and satisfaction. Each of the participants' questionnaire ratings was normalized based on her maximum and minimum ratings from all the test conditions.

RESULTS

The Statistical Analyses Software (SAS) from SAS Institute Inc. USA was used for all statistical analyses. Figure 2 shows the seven different shapes of participant number 14.

It can be clearly seen that the footbed shapes are different only in the rearfoot and midfoot regions. The maximum dimensional difference between the 12^o wedge angle and the 22^o wedge angle for this participant was approximately 15 mm in the Y-direction (Figure 2).

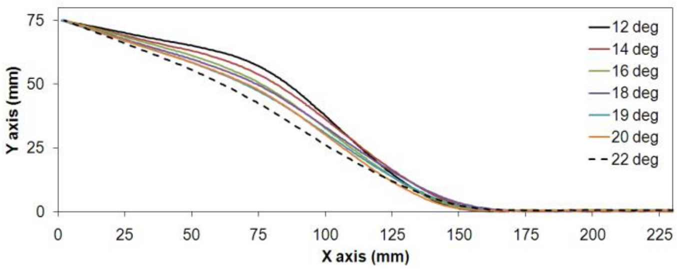

Figure 2. Tested footbed shapes of participant number 14 at 75 mm heel height and 65 mm measured seat length.

The mean normalized perceived ratings for overall, rearfoot, midfoot and forefoot regions were plotted against the heel wedge angles (Figure 3). The plot has an inverted U-shape. This relationship indicates the possibility of an optimal heel wedge angle or a range of angles that can be considered to be comfortable at a heel height of 75 mm.

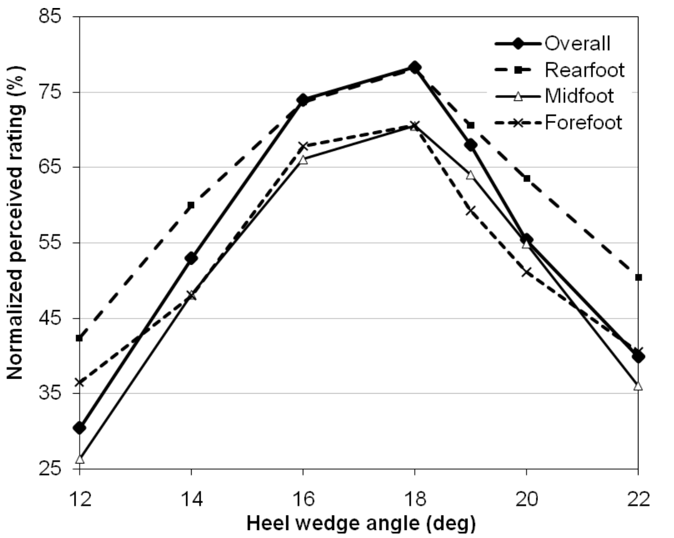

Figure 3. Mean normalized perceived ratings (overall, rearfoot, midfoot and forefoot) in relation to the heel wedge angles.

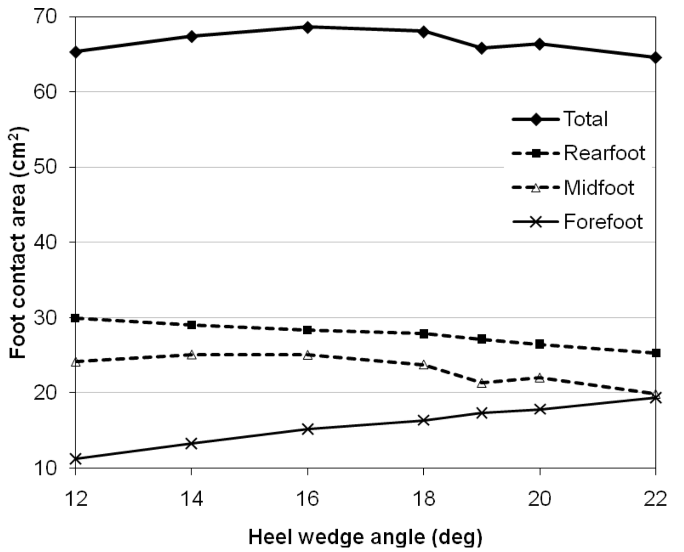

Figure 4. Mean contact area in each foot region when standing on footbed shapes with different heel wedge angles.

Our hypothesis was tested using a repeated-measure Analysis of Variance (ANOVA), followed by a *post-hoc* Student–Newman-Keuls (SNK) test. The repeated-measure ANOVA results showed that the effect of the heel wedge angle was significant at $p < 0.0001$ for all normalized perceived ratings of the overall foot as well as the rearfoot, midfoot and forefoot regions. The SNK test results (Table 1) show that the participants perceived the footbed shapes with heel wedge angles of 18^{o} and 16^{o} as the most comfortable. The footbed shape with a heel wedge angle 18^{o} had the highest subjective rating in the overall and the other foot regions (Figure 3 and Table 1).

Table 1. Post-hoc SNK results on Perceived feeling (overall, rearfoot, midfoot and forefoot) at 75 mm heel height.

Region		Heel wedge angle						
		18^{o}	**16^{o}**	**19^{o}**	**20^{o}**	**14^{o}**	**22^{o}**	**12^{o}**
Overall	Mean	78.3	73.9	68.0	55.4	52.9	39.9	30.4
	SNK							
Rearfoot	Mean	78.1	73.7	70.6	63.5	60.0	50.4	42.4
	SNK							
Midfoot	Mean	70.5	66.1	64.0	54.9	48.1	36.1	26.3
	SNK							
Forefoot	Mean	70.6	67.8	59.3	51.1	48.0	40.5	36.5
	SNK							

To understand the differences among the subjective ratings, several objective measures such as peak pressure, contact area and applied force under the plantar foot were collected. Figure 4 shows the mean contact area (mean of 32 participants) in each foot region.

The mean contact area in the rearfoot region decreased and the mean contact area in the forefoot region increased with increasing heel wedge angle (Figure 4). Interestingly, the plot shows an inverted U-shape for the mean contact area in the midfoot region in relation to the heel wedge angle with a maximum contact area at the 16^{o} heel wedge angle. The total contact area and the heel wedge angle also follow an inverted U-shape relationship. The maximum total contact area is at the heel wedge angles of 16^{o} and 18^{o} (Figure 4).

Figure 5 shows the percentage of body weight (mean of 32 participants) acting on each foot region when standing with different heel wedge angles. The plot clearly shows that as the heel wedge angle increases, the percentage of body weight acting on the rearfoot decreases while the percentage of body weight acting on the forefoot increases.

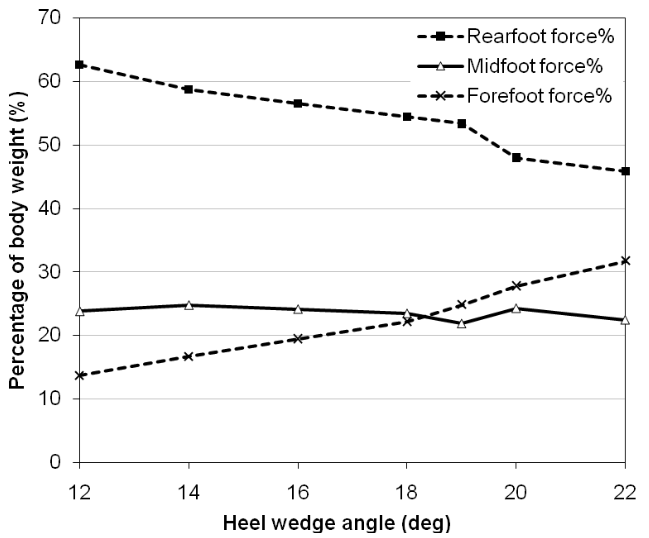

Figure 5. Percentage of body weight acting on each foot region when standing.

The percentage of body weight acting on the midfoot region remains somewhat constant as the heel wedge angle increases (Figure 5). This plot indicates the transfer of load from the rearfoot to the forefoot as the heel wedge angle increases.

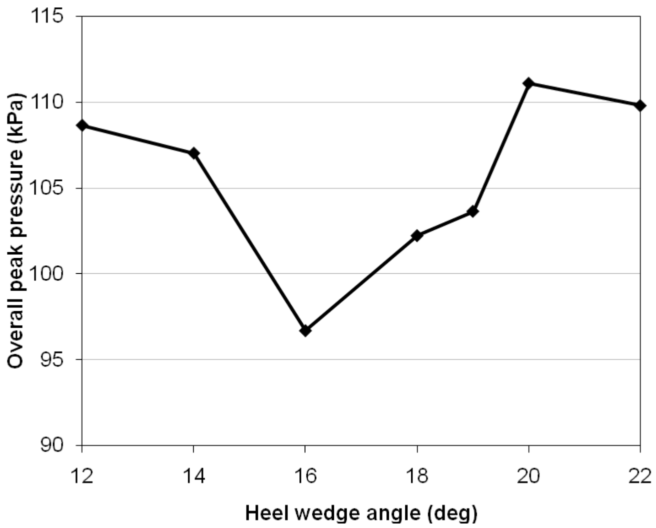

Figure 6. Mean peak pressure acting on foot during standing.

The mean of all participants' peak pressures (overall) are plotted in relation to the heel wedge angle in Figure 6. The plot shows a U-shape relationship with the minimum peak pressure at the 16^o heel wedge angle (Figure 6).

DISCUSSION

The questionnaire ratings had an inverted U-shaped relationship with the heel wedge angle (Figure 3). Among all the different footbed shapes tested at a heel height of 75 mm, the heel wedge angle of 18^o had the highest overall perceived feeling rating with a mean value of 78.3 (Figure 3 and Table 1). On the questionnaire, participants indicated whether or not they liked the shape (in terms of Yes/No/Neutral) of each of the tested footbed shapes along with their perceived ratings. Figure 7 shows the box plot of the normalized perceived ratings (overall) in relation to whether or not the participant liked the shape or if they were neutral about the shape. The participants liked the footbed shape when the heel wedge angle was 18^o and 16^o (Figure 3 and Figure 7). The same conclusion can be drawn from the SNK analysis of the overall ratings in which the wedge angles of 18^o and 16^o were grouped together (Table 1).

The footbed shapes at wedge angles of 18^o and 16^o had the highest contact areas between the plantar foot and the footbed, and the lowest overall peak pressure (Figure 4 and Figure 6). These findings are consistent with those of Hong et al. (2005), Hartsell et al. (2004), and Goske et al. (2006) that larger contact areas reduce the plantar pressure resulting in improved comfort. On the contrary, Godfrey et al. (1967) and Hodge et al. (1999) reported that higher plantar pressure is related to pain and discomfort.

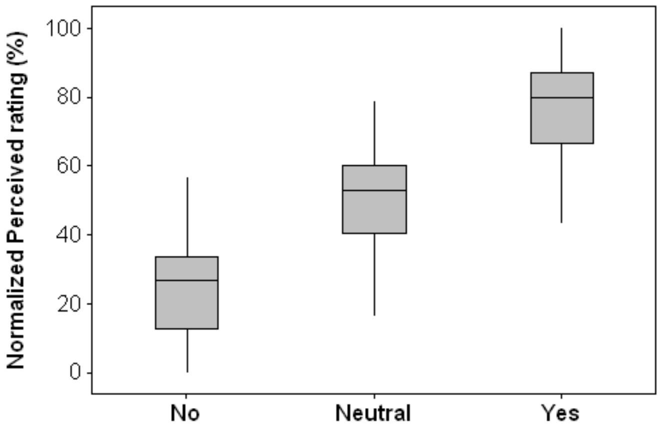

Figure 7. Box plot of normalized perceived ratings (overall) in relation to participants' likeness (Yes, No & Neutral).

It is also interesting to note that at a heel wedge angle of 18^o, the percentage of body weight acting on the midfoot region and the forefoot region are approximately equal. With further increases in the heel wedge angle, the percentage of body weight acting on the forefoot region is higher than that on the midfoot region. Snow and Williams (1994) reported that static forefoot loading increases with increasing heel height. Even though this is true, our findings suggest that there is room to manipulate the amount of forefoot loading by varying the footbed shape and hence obtaining the optimum load distribution at any given heel height. The normalized perceived rating increased from around 30 to 78 as the wedge angle increased from 12^o to 18^o, clearly indicating that high-heeled shoes can be made comfortable if the footbed is properly designed.

Although our results were conclusive, our study was not without its weaknesses: only bipedal static standing was evaluated. This is no doubt a good start toward understanding the effect of the different footbed shapes. Further research is needed to quantify comfort of footbed shapes under dynamic conditions (i.e. walking or running) and to identify comfortable footbed shapes for various heel heights.

CONCLUSION

This study highlights the importance of footbed shape in the design of a comfortable high-heeled shoe. Various footbed shapes were studied to determine the shape that gives a satisfactory level of footwear fit and comfort. The subjective ratings were supported by results of the measurements of the contact area between the plantar foot and the footbed surface, the peak pressure in the plantar pressure distribution and the force distribution in different foot regions.

Acknowledgements

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