Center of Pressure Variations in High-Heeled Shoes

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The way in which a person's foot contacts a shoe surface can have short-term and long-term effects on the whole body. Most previous research on footwear has been carried out using commercially available shoes, and as a result the surface of the shoe with which the foot interacts has not been systematically investigated. A recent invention has allowed the design parameters of a shoe to be investigated. The wedge angle and midfoot conditions were varied, and their effects were modeled with psychophysical relationships. The results show that perceived feelings are closely related to the location of the center of pressure.

INTRODUCTION

Wearing shoes with high heel-heights is known to affect the load distribution on the foot relative to that when standing on flat ground (Rodgers and Cavanagh, 1989; Mandato and Nester, 1999; Broch et al., 2004). A 75 mm heel can shift the forefoot load from around 39 % of body weight to around 57% of body weight (Snow and Williams, 1994). Studies have also shown that the center of pressure on the foot moves forward when wearing high-heeled shoes (Shimizu and Andrew, 1999; Snow and Williams, 1994; Gefen et al., 2002; McBride, 1991; and Han et al., 1999). Holtom (1995) showed that increased heel height resulted in higher plantar foot pressures as well. High-heeled shoe purchases tend to be driven by aesthetics, thereby sacrificing comfort and health. Based on surveys such as Lee et al. (2001) and Piller (2002), a few small-scale shoe manufacturers have developed technologies that allow customers to generate mass customized shoes using a set of foot measurements. These shoes tend to fit well on the dorsal side of the foot but are not designed to fit the foot structure or the plantar surface.

Most studies on high-heeled shoes have been performed on commercially available shoes. As a result, there has been little opportunity to investigate the design parameters of the shoe footbed, which contacts the plantar surface of the foot. A footbed simulator (Goonetilleke and Witana, 2010) has allowed the different design parameters of a shoe to be researched (Witana et al., 2009a, b).

The objective of this study was to investigate the effects of footbed parameters on plantar pressure and center of pressure (COP).

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METHODOLOGY

Subjects

The study was approved by the institutional ethics review board. Twelve female participants whose average age was 20 years volunteered for the study. These subjects were free of any foot deformities or ailments, postural instability diseases, knee and spinal injuries or surgeries. Every subject underwent a magnitude estimation screening procedure, to ensure that they were able to give consistent subjective ratings (Witana et al., 2009a). Subjects who passed the screening test were allowed to participate in the experiment. Two marks, on the lateral side corresponding to the point at which the foot touches the ground, and the end of the fifth metatarsal were marked with a pen in order to consistently locate the foot on the footbed simulator.

Equipment

The footbed simulator allowed the quick change of footbed shapes while the F-Scan system (Tekscan, 2010) was used to obtain the plantar foot pressure profiles.

Experimental Design

The independent variables were heel height, wedge angle and type of midfoot support. Two heel heights (50 and 75 mm), three wedge angles (Figure 1) nested under heel height (4°, 10°, 14° at 50 mm; 14°, 18°, 22° at 75 mm) and three different types of mid-foot supports (45-PU, HL-PU, HL-SS) corresponding to different seat lengths (45 mm and anatomical heel length, HL) and two types of materials, PU and SS were the experimental conditions. The toe spring was controlled to be 0°. Each subject was tested in every condition with two replicates.

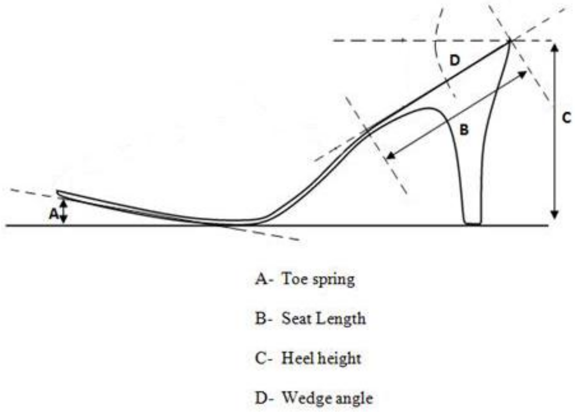

Figure 1: Footwear design variables

Procedure

The experimental task was to quietly stand, on a left and right simulator unit that was set to one of the experimental conditions, for 30 seconds. The different conditions were randomized. Each subject stood on the ground barefooted (called foot-flat) and was told that the perceived feeling for that stance should be set to 100. They were thereafter tested on the simulator unit at each of the experimental settings. The subjects were asked to rate the experimental conditions relative to the level when standing on the ground. The F-scan unit was first calibrated when standing on the simulator unit and the software was set to record the pressure under the foot at 100Hz for 30 s. Each subject stood on a left and right simulator unit for 30 s and rated the perceived feeling relative to that when standing on the ground. The heel to heel distance was controlled at 17 cm due to the equipment limitations.

RESULTS AND ANALYSIS

The center of pressure (COP) measured from the back of the heel was obtained from the recorded foot pressure. The contact area between the footbed and the foot was calculated from the number of active sensors in the F-Scan sensor (area of one sensor is 0.256 cm^2). Forefoot peak pressure was the highest pressure reading on the front part of the foot without considering the pressure under the toes. The pressure measures and the perceived feeling of comfort were all subjected to an Analysis of variance (ANOVA). Since the wedge angles at the two heel heights were different, two separate ANOVAs were performed corresponding to 50 and 75 mm heel heights.

Wedge angle ($p<0.05$), type of mid-foot ($p<0.05$) and their interactions ($p<0.001$) had a significant effect on perceived feeling of comfort. The interactions were further analysed and the simple effect analysis results showed that at 50 mm, the 10° wedge angle and HL-SS mid-foot condition had the highest level of perceived comfort. At 75 mm, the 18° wedge angle and HL-SS mid-foot condition had a significantly higher perceived comfort rating over the other conditions. Generally, when comparing the types of mid-foot, the HL-SS condition had the highest rating and the 45-PU condition the lowest rating (Figure 2).

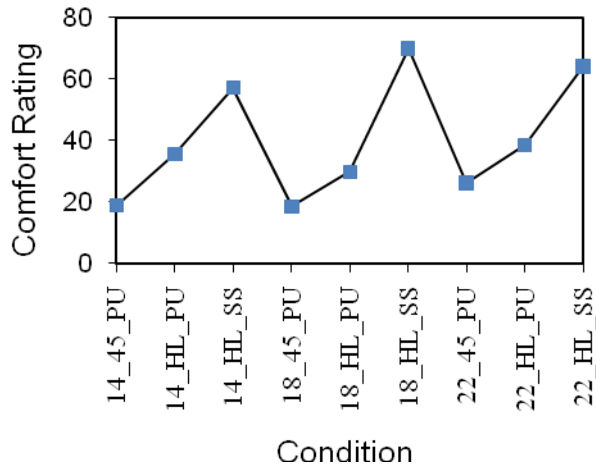

Figure 2. The Comfort rating for the different experimental conditions at 75 mm

An ANOVA on the fore foot peak pressure and plantar foot contact area showed that at both 50 mm and 75 mm heel heights, the mid-foot condition had a significant effect ($p < 0.01$). The *post-hoc* test showed that the HL conditions have a significantly higher contact area and a lower peak pressure than the 45 mm mid-foot support conditions (Figures 3 and 4).

The ANOVA on COP showed that at heel heights of 50 mm and 75 mm, the only significant factor was the type of midfoot ($p<0.001$) with the HL-SS having a significantly lower COP value compared to the other conditions (Figure 5). Another ANOVA was conducted to test the differences between each of the nine conditions and the foot flat condition. For the 50 mm heel height, all HL mid-foot conditions were not different ($p > 0.05$) with the foot flat condition COP. At the higher heel height of 75 mm, only HL-SS was not significantly different with the foot-flat COP (Figure 5).

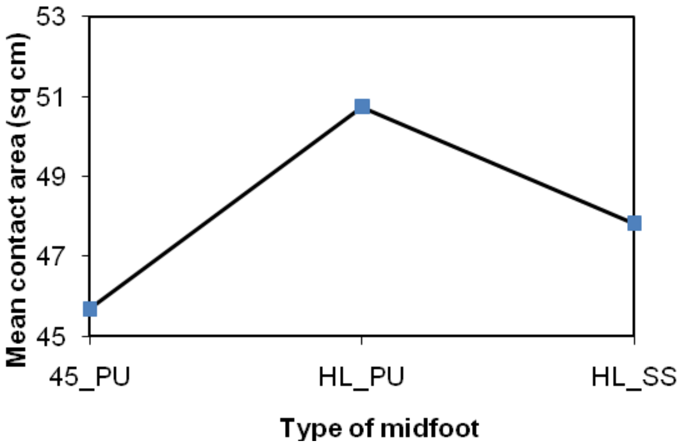

Figure 3. Mean contact area for the three Mid-foot conditions at 75 mm heel height.

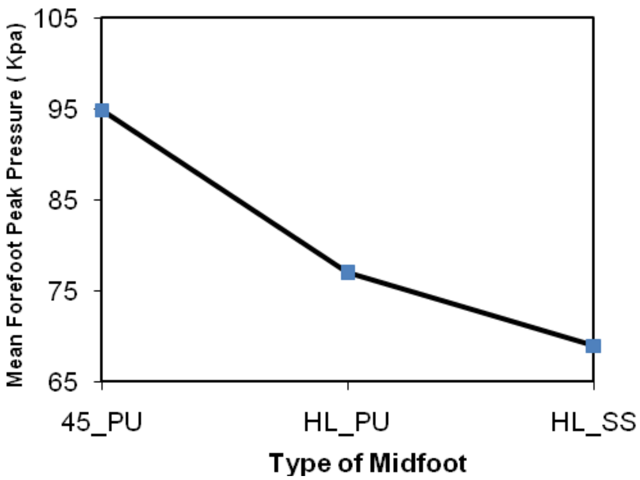

Figure 4. Mean forefoot peak pressure at 75 mm.

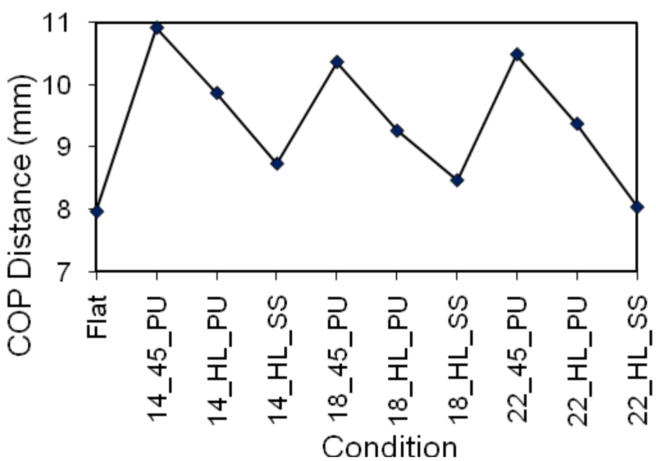

Figure 5. COP variations for the various conditions at 75 mm.

A regression analysis showed the following relationship between perceived feeling of comfort and COP position:

$$\text{Comfort} = 87.2 - 0.798 * \text{COP}; \quad R^2 = 0.704 \qquad (1)$$

DISCUSSION

In the past, researchers have studied shoes available in stores or those made by a shoe manufacturer. The footbed simulator (Goonetilleke and Witana, 2010) allowed a range of footbed parameters to be tested so that the ideal footbed design corresponding to a "neutral" posture may be obtained. COP is an important aspect for body balance and stability. When standing on flat ground, the foot contact area is relatively high and the COP tends to be closer to the heel when standing erect. With most high-heeled shoes the load on the forefoot tends to increase, shifting the COP forward requiring more muscle force to support the upright posture (Joseph and Nightingale, 1956; Lee et al., 2001). The varied conditions tested in this study allowed the shift to be quantified through a regression analysis between comfort rating and COP. The lower COP results in a higher value of comfort. In other words, a shift of COP towards the heel is preferred. The load shift and the COP shift of high-heeled shoes has generally been accepted by high-heel shoe wearers. This study has shown that the design of the footbed can significantly impact the loading on the foot, the COP and thereby comfort.

The comparison with the foot-flat condition also shows a pattern. At lower heel heights, the seat length plays an important role in the COP shift. At higher heel heights, the seat length, and the midfoot condition have to be right in order to be comfortable. In other words, the complete design of the footbed is critical for a high-heel shoe wearer to be comfortable. These results can be explained considering the foot structure. The foot can articulate better than any other part in the body due to its anatomy comprising the various soft tissue and bones. However, the foot cannot bend at areas other than at joints. Hence the footbed has to conform not just to the superficial plantar surface but to the bony structure as well. Thus, the seat length plays an important role to position the heel correctly. The HL distance of the participants ranged from 62 – 67 mm. This distance essentially represents the "length" of the calcaneus. With a seat length of 45 mm, a clear mismatch exists that result in poor contact of the foot with the footbed.

The study does have some weaknesses. Only a quiet standing condition was tested and more research is needed to extend this study with custom fitting shoes having the optimal parameters as predicted from this study.

Acknowledgment

The authors would like to thank the Research Grants Council (GRF 613607) and the Sino Software Research Institute (SSRI11EG02) for funding this study.

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