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Changes on Foot Dimensions With Elevated Heel Heights: A Pilot Study

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ABSTRACT

Investigating the effect of high heeled shoes on foot dimensions provided a basis for optimizing footwear design and reducing adverse effects on the human musculoskeletal system. The purpose of the study was to determine the effect of elevated heel heights on length-, width-, and height-related foot dimensions. Ten young healthy women participated in a pilot experiment and 3D foot scanning was applied for collecting the 3D anthropometric data. The heel heights selected for evaluation were 30 mm (low), 50 mm (medium), 70 mm (medium high), and 90 mm (high). The one-way ANOVA results indicated that heel heights significantly impacted foot length, ball of foot length, outside ball of foot length, instep height, and navicular height (all $p < 0.01$). With elevated heel heights, the instep height and navicular height became higher, whereas foot length, ball of foot length, and outside ball of foot length were shortened. These changes on foot dimensions allow the designer to determine the foot deformation area, enabling possible design decisions to the heel and shoe upper on high heeled shoes.

Keywords: Foot dimension, Heel height, 3D foot scanning, High heeled shoes

INTRODUCTION

Wearing high heeled shoes (HHS) has been reported to be one of the leading causes of various foot health issues, including hallux valgus, osteoarthritis, ankle sprains, and musculoskeletal disorders (Snow and Williams, 1994). Even so, females are still willing to wear HHS to increase their leg length for better body proportions on beauty.

Digital technology can be used as a strategic tool for new wearable product development to save time and costs. This is especially vital in the shoe industry, particularly for HHS, where striking a balance between comfort and appearance is challenging. With the development of 3D foot scanning technology and computer-aided design/manufacturing systems, many studies have been conducted on the effect of heel height for HHS. Lee and Hong (2005) reported that increasing heel height change foot pressure, impact force, and perceived comfort during walking based on experimental combinations of 10 mm (flat), 51 mm (low), and 76 mm (high) heel heights. Hapsari and Xiong (2016) investigated the wearing experience of HHS and the effect of heel height on human standing balance. The results showed that 70 mm heel height resulted in worse functional mobility. Wan et al. (2017) developed a rapid 3D foot scanning system to obtain 3D foot anthropometric measurements while wearing HHS and discussed the dimensions related to the metatarsal-phalangeal joint and toe box design. Moreover, Milazzo et al. (2020) focused on combining the results from the digital and experimental synergies to design HHS.

Foot dimension was considered a primary measure of foot deformation and related to the fitness and comfort of wearing HHS. Two-dimensional anthropometry, three-dimensional scanning, and digital human modeling have been utilized to analyse the human foot. Foot dimensions are pivotal for footwear design and production, which is easily accessible and directly applicable. Dimensional differences were found strongly correlated with the footwear fit. Footwear design needs to consider not only foot length but also foot width and mid-foot region (Witana et al., 2004). Studies of foot shape changes provided an accurate reference for HHS design (Milazzo et al., 2020; Shariff et al., 2019). Therefore, HHS designers and manufacturers need to consider these foot dimensional changes with elevated heel heights to fit the foot deformation (Luximon et al., 2020).

However, available information about the changes on foot dimensions with elevated heel heights is still lacking. Hence, this pilot study aimed to evaluate the changes on the seven foot dimensions when wearing HHS with different heel heights.

METHODS

Participants

Ten young women (age 23±3.0 years, height 161.7±5.5 cm, weight 53.1±12.5 kg) participated in the study. All the participants had HHS wearing experience (with a minimum heel height of 40 mm two or more times per week and at least 8 hours per day in the past year) by self-reported. Due to the reason of time constraints and a majority of proportion in the female population, the participants with foot sizes from 235 to 240 mm were first evaluated. The data were collected in 2021 at the South China University of Technology, China. All the participants were self-reported to have no experience of any pain or diseases in their foot, ankle, or lower back at least one year prior to the study. Written informed consents were obtained from each study subject before the experiment.

Equipment

The four elevated heel heights (30, 50, 70, and 90 mm) were selected for the evaluation according to the recommendation of the AKA64 design system (Luximon et al., 2020). This set of footbeds encompasses the most regularly worn heel heights in daily use. A 3D foot scanner (INFOOT USB scanning system, IFU-S01, I-ware Laboratory Co., Ltd, Japan), was utilized for collecting digital 3D foot models. The scanner consisted of 8 CCD cameras to capture lasers in order to obtain the entire foot dimensions with a scanning duration of about 10 seconds. The scanning volume was L400 x

B200 × H150 (mm) and the accuracy of the foot scanner is 1.0 mm. The scanner was confirmed as an accurate and reliable instrument for measuring the foot dimensions (Lee et al., 2014).

Experiment Procedure

Landmarking and Scanning

To obtain the digital foot model, foot landmarking and scanning of the participant's right foot were performed. The participants' feet were disinfected and dried prior to scanning. The four anatomical points on the right foot surface were identified and pasted with markers including Metatarsal tibia (MT), Metatarsal fibula (MF), Navicular, and Tentative junction point of the foot & leg (TJP) (Shariff et al., 2019). Subsequently, a footbed was placed inside the scanner and the order of each heel height was randomized for each participant.

During the scanning, all participants were asked to stand on a specific heel height of a footbed with both feet and requested to stand still in a natural standing posture. The footbeds were cut from real HHS and applied to simulate wearing a high heel shoe to easily scan the side view of the foot. Only the right foot was aligned and scanned under the equal balance on feet. Each right foot was scanned twice to ensure the quality of the foot model. After every scanning, a foot model with a footbed and the four landmarks were checked with integrity and then stored in STL format.

Foot Measurements Calculation

All scanned data were processed in Polyworks Inspector (version 2020, InnovMetric, Quebec, Canada) to calculate the seven foot dimensions from the 3D foot models. The procedure was referred to the study of Schwarz-Müller et al. (2021). The generated 3D mesh foot model was realigned according to 1) the x-y plane was aligned with the bottom plane of the footbed and, 2) the foot axis was defined as a vector projected on the x-y plane from the pternion to the center point (CP). The CP is located in width of the ball girth cross-section which passes through MT & MF. The alignment rules were referred to in the previous study (Hsieh et al., 2022). Each condition was measured twice by one trained experimenter, and the mean of each foot dimension was calculated for further analysis.

Seven commonly used foot measurements for footwear design were collected and the definitions of foot dimensions obtained in this study were summarized in Table 1.

Statistical Analysis

The data were analyzed using SPSS 26.0 (SPSS Inc., Chicago, IL, United States) with the significance level set at 0.05. Before the test, Kolmogorov-Smirnov and Levene's tests were performed to verify data normality and variance homogeneity. The effects of elevated heel heights were tested by one-way analysis of variance (ANOVA). Then, the Tukey post hoc test was conducted for post hoc comparisons. To determine the effect size and power of the significant effects, partial η^2 and power tests were used.

Table 1. Definitions of seven foot dimensions. (Lee et al., 2014; Redmond et al., 2008; Witana et al., 2006)

Category of foot parameters	Definitions of foot dimensions
Length	1. Foot length (FL): The distance from the pternion to the tip of the longest toe along the Foot axis (X-direction).
	2. Ball of foot length (BFL): The length measured parallel to the foot axis from the end of the heel to the metatarsal tibia.
	3. Outside ball of foot length (OBFL): The length measured parallel to the foot axis from the end of the heel to the metatarsal fibula.
Width	4. Foot width diagonal (FWD): The straight width between the metatarsal tibia and metatarsal fibula.
	5. Heel width (HW): The width of the heel at 16% of foot length forward of the pternion.
Height	6. Instep height (IH): Maximum height of the vertical cross-section at 50% of foot length from the pternion.
	7. Navicular height (NH): The vertical distance from the prominent navicular bone to the standing surface.

Table 2. One-way ANOVA and Tukey post hoc test results on the seven foot dimensions (unit: mm).

	Heel height	Length			Width		Height	
		FL	BFL	OBFL	FWD	HW	IH	NH
Low heel	30 mm	230.615 A	170.339 A	144.964 A	92.747	59.771	59.901 A	35.111 A
Medium heel	50 mm	226.405 B	165.293 A	142.910 AB	90.725	59.990	66.448 A	34.634 A
Medium high heel	70 mm	217.767 C	159.526 B	136.550 B	90.617	59.857	82.105 B	38.532 AB
High heel	90 mm	205.407 D	146.485 C	126.768 C	90.043	59.450	111.585 C	44.155 B
	Sig	***	***	***	NS	NS	***	**

**Significant at $p < 0.01$, ***Significant at $p < 0.001$; NS: non-significant; A, B, C, D: Tukey grouping code.

RESULTS AND DISCUSSION

The results of the one-way ANOVA (Table 2) summarized the overall significant difference between the four heel conditions for all the seven foot measures. Elevated heel heights had a significant impact on foot dimensions in length- (FL, BFL, OBFL) and height-related measures (IH, NH), with all p< 0.01, except for width-related foot parameters (FWD and HW).

As heel heights elevated from 30 mm (low heel) to 90 mm (high heel), the IH [$F_{(3, 36)} = 104.871$, $p < 0.001$, $\eta^2 = 0.897$, $1-\beta = 1.000$] and NH [$F_{(3, 36)} = 4.565$, $p < 0.01$, $\eta^2 = 0.276$, $1-\beta = 0.849$] became larger, whereas FL [$F_{(3, 36)} = 113.525$, $p < 0.001$, $\eta^2 = 0.904$, $1-\beta = 1.000$], BFL [$F_{(3, 36)} = 50.315$, $p < 0.001$, $\eta^2 = 0.807$, $1-\beta = 1.000$], and OBFL

[$F_{(3, 36)} = 19.088$, $p < 0.001$, $\eta^2 = 0.614$, $1-\beta = 1.000$] were shortened. The Tukey post hoc results indicated that no significant foot dimensional difference was obtained between the 30 mm and 50 mm heel height, except for FL. The IH and NH were significantly increased as the heel height elevated from 50 mm to 90 mm. Moreover, there was a substantial variation in foot dimensions between the 70 mm and 90 mm heel heights, except for NH.

The longest length parameters were observed on low heel height (30 mm), with 230.615 mm for FL, 170.339 mm for BFL, and 144.964 mm for OFBL. The smallest length parameters were discovered when wearing the 90 mm heel height. FL, BFL, and OBFL at the 90 mm heel height is much shorter about 25.208 mm in FL, 23.854 mm in BFL, and 18.196 mm in OBFL compared with the 30 mm heel height.

Changes on length-related dimensions might be owing to a shift of the plantar pressure towards the forefoot region (especially the metatarsal area). This interpretation was consistent with the findings of other studies in HHS, in which plantar pressure was highest under the metatarsal heads and medial forefoot with elevated heel heights (Branthwaite et al., 2013; Melvin et al., 2019; Snow et al., 1992; Lee and Hong, 2005). Moreover, change on length-related foot dimensions might lead to the lack of footwear fit which results in slippage from the heel, as well as abrasion and ulceration in the heel area to increase the incidence of foot trips and falls (Davis et al., 2016).

The width-related dimensions did not change significantly, observed small differences in width-related dimensions (maximum difference of 2.704 mm in FWD, 0.321 mm in HW) in this study. The results were agreed with the work of Wan et al., (2017).

For the height-related foot dimensions, the IH was found to be the highest on heels elevated at 90 mm (111.585 ± 9.988 mm), followed by heels elevated at 70 mm (82.105±7.672 mm), 50 mm (66.448±5.755 mm), and 30 mm (59.901±3.219 mm). The largest NH was found on a 90 mm elevated heel (44.155±8.230 mm). Excessive IH may affect human standing balance and functional mobility. The heel elevation causes more effort from lower limb muscles (especially calf muscles) and leads to decreased functional mobility (Hapsari and Xiong, 2016). NH has a very direct physical meaning; a high foot arch causes an imbalance in the body and reduces its cushioning effect against gravity and ground reaction forces (Xiong et al., 2010).

Furthermore, changes on IH and NH can have a significant impact on the midfoot shape, which is critical for shoe upper design. The dorsal side of the foot will be under much pressure if the upper of HHS is too low. Once the top of the HHS is excessively high, the foot moves back and forth continuously and resulted in exerting pressure on the toes (Xiong and Goonetilleke, 2006). Therefore, the IH and NH of the midfoot shape were needed to take into consideration the compensation in the shoe upper design when designing HHS for young women.

Generally, the results of this preliminary study suggest that foot dimensions change proportionally with different heel elevations, as statistically significant mean differences were found in five of the seven foot measurements. With the elevated heel heights, FL, OBFL, and BFL extended less, IH and NH heights became higher. The heel area and shoe upper of HHS needed to be redesigned based on the changes of the foot dimensions, especially under the 70 mm and 90 mm heel height.

There are several limitations of this pilot study. Only young and healthy female subjects were studied and the sample size is relatively small. The definition of foot dimensions utilized in this study has an impact on the study's findings and application to footwear design.

CONCLUSION

The heel heights have a significant influence on the length and height-related foot dimensions and resulting in foot deformations. The effect was especially noteworthy, starting from 70 mm heel height. Observed changes on foot dimensions provide dimensional references for HHS design and footwear production for young women. The findings of this study could provide helpful information for designers regarding the foot deformations of young women under different heel heights.

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