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Differences in foot shape when wearing wedge-heeled shoes with elevated forefoot height and heel height



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Abstract

Wedge-heeled shoes, which are formed by elevating both the forefoot and heel, have been popular among young women. However, research on the foot shape in wedgeheeled shoes is lacking. This study aimed to access the effects of forefoot height (10, 20, and 30 mm) and heel height (30, 50, 70, and 90 mm) on foot shape and perceived comfort when wearing wedge-heeled shoes. Three-dimensional (3D) foot scanning was performed on 35 females and the 14 foot dimensions were measured. Increased forefoot height generated larger lengths (foot, ball and out ball), smaller girths (ball and instep) and heights (instep and navicular) (p < 0.05). Thus, when the forefoot height increased, the foot became longer, slimmer and flatter. Moreover, elevated heel height resulted in larger dimensions for girths (ball and instep), heights (instep and navicular), and smaller dimensions for lengths (foot, ball and out ball), widths (diagonal and horizontal) and toe 5 angles of the foot (p < 0.01). That means shorter, narrower and more convex foot shapes were observed when heel height increased. Subjective measurements implied that increased forefoot height significantly enhanced perceived comfort, whereas increased heel height diminished comfort. It was found that forefoot elevation could result in less deformation and discomfort which accompanied heel elevation, especially in the low heel-toe drop combinations (10×30 and 20×30 mm). The findings provide valuable references for enhancing shoe fitting and comfort for wedge-heeled shoes by providing dimensional data on the toe, ball, arch and instep regions.

Keywords: Foot dimensions, Women's footwear, Foot shape, 3D foot scanning, Footbed

Introduction

To improve the visual leg-to-body ratio, a great number of women choose to wear shoes with heel elevation, despite studies indicating their negative effects on foot health (Au & Goonetilleke, 2007; McRitchie et al., 2018). As one of the main female footwear characteristics, shoe elevation has become a ubiquitous element in the design of women's footwear. Surveys have reported that 37% to 69% of women wear shoes with stack height on a daily basis (Kannan et al., 2019). It has been proven that passive heel elevation leads to changes in foot shape and greatly increases plantar pressure in the forefoot region,



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causing musculoskeletal symptoms, such as osteoarthritis, hallux valgus, and pain (Buldt & Menz, 2018).

Foot shape is a pivotal factor in human performance related to footwear, as it reveals deformations through foot dimensions. Over the past few decades, researchers have conducted several studies on the analysis of foot shape using two-dimensional (2D) anthropometry, three-dimensional (3D) scanning, and modeling approaches. Threedimensional foot scanners were recommended to collect foot measurements because of their comparatively higher precision, accuracy, and robustness (Lee et al., 2014). It is widely believed that heel elevation causes changes in foot shape that has a relationship with foot function (Jo et al., 2022). Knowledge of foot shape can benefit footwear design (Kim & Do, 2019), thereby mitigating the discomfort and risk of injury due to ill-fitting shoes (Branthwaite & Chockalingam, 2019). Kouchi and Tsutsumi (2000) quantitatively clarified the changes in foot shape caused by heel heights of 0, 40, and 80 mm. Lee and Hong (2005) determined that heel elevation increases medial forefoot pressure and perceived discomfort based on experimental heel heights of 10 (flat), 51 (low), and 76 mm (high). Wan et al. (2017) detected forefoot shape changes in raised fourth and fifth metatarsophalangeal joints caused by heel height elevation. Quantifying the foot shape can be used to inform footwear design by integrating shoe fitting (McRitchie et al., 2018), foot shape (Stanković et al., 2020) or comfort (Matthias et al., 2021) factors.

Additionally, subjective wearing comfort was another important factor in the design and selection of women's footwear. Results from earlier qualitative studies have reported a decrease in comfort with increased heel height (Lee & Hong, 2005; Melvin et al., 2019). Au and Goonetilleke (2007) noted that shoe-fitting preferences were related to the toe, metatarsophalangeal, and arch regions. To minimise foot deformation and discomfort, Witana et al. (2009) emphasised that the footbed shape should be optimised, especially the heel wedge angle. Moreover, Branthwaite et al. (2013) indicated that ill-fitting footwear can be detrimental to foot health, especially in the forefoot area. Wearing comfort influences wearability and impacts physical mobility, performance, and foot-related complaints (Matthias et al., 2021).

Generally, forefoot shape is an important criterion in footwear design (Krauss et al., 2010). Contrastingly, the heel region is hardly affected by heel elevation or other footwear characteristics (Buldt & Menz, 2018). Hence, in addition to the heel height, the forefoot height of a footbed (also known as forefoot stack height) also should be noted. Furthermore, heel height-related studies were only applicable to high-heeled shoes; therefore, the results cannot be applied to other types of shoes. Although women's shoes with stack height are commonly seen as stilettos with elevated heels, wedge-heeled shoes are also routinely worn in work and other settings. Wedge-heeled shoes are formed by elevating both the forefoot and heel. The wedge-heeled footbed functioned as both the heel and sole with a raised platform. Forefoot height and heel height are defined as the stack height difference between the forefoot and heel regions (Mo et al., 2020; Xiong et al., 2008). Compared with high-heeled shoes, wedge-heeled shoes can provide extra height in the forefoot region and reduce heel-toe drop (the height difference between the forefoot and heel region of the shoe), which affects the comfort and cushioning of the shoe (Mo et al., 2020). For consumers, wedge-heeled shoes are a good compromise for balancing comfort and aesthetics while also enhancing the visual leg-to-body ratio.

To elevate the forefoot region, wedges are frequently constructed by extending and elongating the heel. Most of the previous studies have investigated high-heeled shoes (Branthwaite & Chockalingam, 2019). Information regarding the dimensional differences when wearing wedge-heeled shoes is still lacking. It is uncertain whether the increased forefoot height provided by the wedge-shaped footbeds would have an impact on foot shape. Thus, the research questions (RQs) of the present study are listed as follows:

- RQ 1: How does the foot dimensions change when forefoot height and heel height are elevated in wedge-heeled shoes?
- RQ 2: Does the perceived comfort level decrease while the forefoot and heel heights elevated?

Therefore, this study aimed to determine the effects of forefoot height (10, 20, and 30 mm) and heel height (30, 50, 70, and 90 mm) on foot shape and perceived comfort when wearing wedge-heeled shoes. Objective (14 foot dimensions) and subjective (perceived comfort) measurements were collected for evaluation. The findings can provide valuable anthropometric information on foot shape for footwear designers and manufacturers when designing wedge-heeled shoes within the corresponding heights of footbeds.

Methods

Participants

Thirty-five female adults with a mean age of 22.1 ± 1.5 years were recruited for the current study. The mean body weight and height of the participants were 50.9 ± 6.3 kg and 161.9 ± 3.3 cm, respectively. The inclusion criteria of the participant was the female adult who gets used to wear wedge-heeled shoes in daily. An experienced wearer was referred to the study of Henderson and Piazza (2004) and was defined as an individual who had worn shoes with a minimum heel height of 40 mm more than twice a week for at least 8 h a day. The mentioned criteria was applied to avoid the bias of food morphology caused by the wearing experience lead to the unbalanced standing while scanning. The shoe size of participants ranged from EU 37 to 38. Additionally, the participants reported that they were free of any musculoskeletal disorders or lower extremity pain for at least 1 year. Three-dimensional foot scanning data were collected from May 2021 to November 2021. Written informed consent was obtained from all participants prior to the experiment. The experimental protocols were approved by the Institutional Ethics Committee of the university.

Footbeds

Figure 1a shows 12 footbeds of commercially available wedge-heeled shoes that were used for evaluation. The footbeds were customised in the same wedge style but with different forefoot and heel heights (Fig. 1b). Three forefoot heights (10, 20, and 30 mm) and four heel heights (30, 50, 70, and 90 mm) were used. The forefoot heights used in the study were selected from commercial available wedge-heeled shoes. The levels of heel height were determined in accordance with the guidelines of the AKA64-WMS system. Accordingly, the 30-, 50-, 70-, and 90-mm heel heights were classified as low, medium,



Fig. 1 Twelve wedge-heeled footbeds used in the study (A) and the illustration of wedge-heeled shoes (B)

medium-high, and high, respectively. Each footbed was designed and manufactured exclusively for this investigation to eliminate possible errors caused by the footwear design. The wedge-heeled footbeds used the same 2D bottom pattern shape based on the AKA64 design system. Moreover, the arch curve designs under different heel heights and bottom toe curves in this study were referenced by Luximon (2021). All footbeds have a pointed toe box and a 15° toe spring to position the foot naturally.

Experimental apparatus

A 3D foot scanner (INFOOT USB scanning system, IFU-S01, I-ware Laboratory Co., Ltd., Japan) was used to obtain 3D foot models. The 3D scanner employs eight charged-coupled device cameras and four laser projectors to construct digital foot models with an accuracy of 1.0 mm. The heel height adjustment range was maintained within the allowance of the scanning volume (L400 × B200 × H150 mm). The reliability and validity of the scanner with respect to 3D foot shape collection for ergonomic and medical applications have been confirmed (Lee et al., 2014).

Experimental procedures

Prior to the experiment, the demographic data of the participants, such as age, height, weight, foot size, and wearing experience, were recorded. Foot-fitting practice was performed before scanning. The participants were provided with sufficient time to place their feet on different footbeds and were required to stand naturally (without support) while wearing each footbed. An example of a participant while scanning was demonstrated in Fig. 2.

Before data collection, participants' feet were disinfected and dried. Subsequently, a well-trained research assistant placed markers on specific anatomic points on the right foot. Four anatomical positions were used to increase the accuracy of data measurements. The four landmarks were metatarsal tibial (MT), metatarsal fibular (MF), arch point (AP), and junction point (JP). MT and MF were located on the most medial prominence of the first metatarsal-phalangeal joints (MPJ) and the lateral prominence of the fifth MPJ, respectively. AP was at the tubercle of the navicular. JP was on the junction of the leg and foot on the dorsal aspect (crossing point of the



Fig. 2 An example for scanning participant's foot while wearing in a shoe condition

tendon to the fifth toe and the crease between the leg and the foot) (Fig. 3). The anatomical points were also adopted in Hill et al. (2017).

During the scanning process, a footbed was positioned inside the scanner to facilitate a good simulation of foot shape when wearing wedge-heeled shoes. Sequences of the 12 footbeds for each participant were randomly assigned. Only the dominant foot (the right foot) was scanned. The dominant foot is defined as the foot most frequently used for manipulating or mobilising actions. The left foot was positioned on the same shoe to ensure an even distribution of body weight. Each right foot was scanned twice to ensure image quality and scanned in the late morning to avoid foot volume deformation throughout the day (Lee & Wang, 2015). To prevent fatigue, each participant rested for at least 5 min between each footbed. After successful scanning, the digital foot model with a footbed and four landmarks was generated and stored in the STL format for further foot dimension extraction.

Additionally, to evaluate the perceived comfort of wearing, an 11-point Likert scale was used to evaluate the wearing comfort. The subjective measurements were obtained from Matthias et al. (2021). Participants were asked to rate their wearing comfort under the 12 shoe conditions on a scale of 0 (not comfortable at all) to 10 (very comfortable).



Fig. 3 The anatomical points used in the study: metatarsal tibial (MT), metatarsal fibular (MF), arch point (AP), and junction point (JP)

Data extraction and foot dimensions

The foot dimensions used in the study were measured from scanned digital foot models using virtual tools (PolyWorks Software, InnovMetric Software, Quebec, QC, Canada). PolyWorks allows precise measurements along the sagittal (x) and transverse (y) axes and realigned foot axis (Schwarz-Müller et al., 2021; Whitson et al., 2018). The foot axis is defined as the line joining the pternion (Pte, the most posteriorly projecting point of the heel) and the centre point (CP) of the vertical cross-section passing through the MT and MF (Lee & Wang, 2015).

The scanned data were first aligned to avoid the influence of foot orientation differences on the scanning foot data. In particular, the 3D coordinate systems of the generated digital mesh foot models were realigned. The heel centreline of the foot was consistent with the longitudinal axis of the scanned models to draw and measure linear distances, perimeters, and angles as follows:

- Align the X–Y plane with the footbed plane. The X–Y plane is perpendicular to the vertical plane that includes the foot axis and passes through the MT.
- Locate the Pte and CP then re-establish the foot axis.
- Align the foot axis with the longitudinal axis (X-axis) and the 3D coordinate system of Polyworks is overlapped with the actual foot axis.
- Set the Pte as the origin of the coordinate system. Using the foot axis as the X-axis, the foot width in the horizontal direction is used as the Y-axis and the upward direction of the lower leg is used as the Z-axis.

- Construct three cross-sections of the ball girth, instep girth, and short heel girth when the alignment process is completed.
- The foot dimensions were measured using the points, baselines, and cross-sections determined based on each definition.

This procedure was adopted from previous studies by Schwarz-Müller et al. (2021), and Tsung et al. (2003). Each experimental condition was performed twice, and the mean of each foot dimension was calculated for further statistical analysis. Eventually, 14 dimensions were measured from each digital foot model to evaluate the deformation of foot shape when wearing different wedge-heeled shoes. In total, three lengths, three widths, three girths, three heights, and two toe angles were measured. The definitions of the 14 foot dimensions are illustrated in Table 1, including foot length (FL), ball of FL (BFL), outside ball of FL (OBFL), foot width diagonal (FWD), foot width horizontal (FWH), heel width (HW), ball girth (BG), instep girth (IG), short heel girth (SHG), instep height (IH), navicular height (NH), toe height (TH), toe 1 angle (T1A), and toe 5 angle (T5A). The dimensions were derived from the shoe-last template based on the corresponding foot regions (Wang, 2010).

Statistical analysis

A two-way analysis of variance (ANOVA) was performed for data analysis. The independent variables were the forefoot height (10, 20, and 30 mm) and heel height (30, 50, 70, and 90 mm). The dependent variables were the 14 foot dimensions and perceived comfort measures. Duncan's multiple range test (MRT) was performed for post hoc comparisons of the significant variables. Effect size statistics (partial η^2) and observed power were calculated for the main outcome variables. For each statistical test, a 95% confidence level (p > 0.05) was used to identify the significance. All data were analysed using IBM SPSS Statistics software (version 26, IBM, Armonk, NY, USA).

Results

Effects of forefoot heights on foot dimensions

The various forefoot heights of the wedge-heeled shoes had significant effects on seven of the 14 foot dimensions, as presented in Table 2 (all p < 0.05). When the forefoot height was elevated, foot length ($\eta^2 = 0.175$, power = 1.000), ball of foot length ($\eta^2 = 0.185$, power = 1.000), and outside ball of foot length ($\eta^2 = 0.070$, power = 0.999) measurements increased based on Duncan's MRT results. In contrast, ball girth ($\eta^2 = 0.020$, power = 0.740), instep girth ($\eta^2 = 0.026$, power = 0.856), instep height ($\eta^2 = 0.378$, power = 1.000), and navicular height ($\eta^2 = 0.044$, power = 0.980) significantly decreased when forefoot height increased. Moreover, Table 3 reported that wearing a wedge-heeled shoe with a 30-mm forefoot height yielded the largest foot length (142.40 mm), and the smallest ball girth (224.72 mm), instep girth (225.33 mm), instep height (65.51 mm), and navicular height (25.94 mm). Additionally, no significant differences were found in width- and angle-related dimensions.



Table 1 Definitions of the 14 foot dimensions selected in the study





AP arch point, CP the center point of the vertical cross-section passing through the metatarsal tibial and metatarsal fibular, JP junction of the leg and foot on the dorsal aspect, MF metatarsal fibular, MT metatarsal tibial, Pte pternion

Effects of heel heights on foot dimensions

Table 2 shows that the heel height significantly influenced foot length ($\eta^2 = 0.633$, power = 1.000), ball of foot length ($\eta^2 = 0.621$, power = 1.000), outside ball of foot length ($\eta^2 = 0.434$, power = 1.000), foot width diagonal ($\eta^2 = 0.056$, power = 0.991), foot width horizontal ($\eta^2 = 0.046$, power = 0.972), ball girth ($\eta^2 = 0.123$, power = 1.000), instep girth ($\eta^2 = 0.095$, power = 1.000), instep height ($\eta^2 = 0.791$, power = 1.000), navicular height ($\eta^2 = 0.229$, power = 1.000), and toe 5 angle ($\eta^2 = 0.030$, power = 0.867), with the exception of heel width, short heel girth, toe height, and toe 1 angle. Additionally, the Duncan's MRT results from Table 3 indicated that wearing a high-heeled shoe (90 mm) produced shorter foot length (210.45 mm),

Effect	Forefoot height (F)			Heel height (H)			F×H		
	F	df	p-value	F	df	p-value	F	df	p-value
Lengths									
Foot length	43.39	2	0.00***	234.63	3	0.00***	4.52	6	0.00***
Ball of foot length	46.27	2	0.00***	222.64	3	0.00***	6.47	6	0.00***
Outside ball of foot length	15.66	2	0.00***	104.14	3	0.00***	0.86	6	0.53
Widths									
Foot width diagonal	1.03	2	0.36	8.08	3	0.00***	0.22	6	0.97
Foot width horizontal	1.80	2	0.66	6.58	3	0.00***	0.13	6	0.99
Heel width	0.22	2	0.80	0.07	3	0.98	0.23	6	0.97
Girths									
Ball girth	4.26	2	0.02*	19.46	3	0.00***	1.51	6	0.18
Instep girth	5.53	2	0.01**	14.30	3	0.00***	0.26	6	0.96
Short heel girth	0.09	2	0.92	1.17	3	0.32	0.04	6	1.00
Heights									
Instep height	124.22	2	0.00***	514.94	3	0.00***	17.13	6	0.00***
Navicular height	9.61	2	0.00***	41.37	3	0.00***	1.52	6	0.17
Toe height	0.19	2	0.82	0.07	3	0.98	0.19	6	0.98
Angles									
Toe 1 angle	0.08	2	0.93	1.40	3	0.24	0.06	6	0.99
Toe 5 angle	1.92	2	0.15	4.30	3	0.01**	0.46	6	0.84

Table 2 Two-way ANOVA on the 14 foot dimensions under wedge-heeled shoes

^{*} p < 0.05, **p < 0.01, ***p < 0.001

Measurements (mm)	Forefoot heig									
	10 mm Mean (SD)		20 mm		30 mm					
			Mean (SD)		Mean (SD)		_			
Foot length	218.77 (11.04)	А	222.29 (9.66)	В	225.35 (8.47)	С				
Ball of foot length	158.52 (11.49)	А	162.08 (8.62)	В	165.04 (7.23)	С				
Outside ball of foot length	137.52 (11.52)	А	139.76 (9.14)	В	142.40 (7.85)	С				
Foot width diagonal	90.22 (3.89)		90.59 (3.88)		90.86 (3.63)					
Foot width horizontal	87.18 (3.69)		87.32 (3.73)		87.57 (3.64)					
Heel width	58.94 (2.87)		59.08 (3.26)		58.85 (2.75)					
Ball girth	228.58 (13.83)	А	226.57 (11.37)	AB	224.72 (9.94)	В				
Instep girth	231.26 (17.76)	А	228.24 (14.92)	AB	225.33 (13.61)	В				
Short heel girth	290.85 (11.67)		291.13 (11.96)		291.44 (11.96)					
Instep height	79.48 (20.89)	А	71.22 (15.73)	В	65.51 (11.79)	С				
Navicular height	39.12 (7.58)	А	37.27 (7.14)	В	35.94 (6.02)	В				
Toe height	19.56 (1.47)		19.63 (1.37)		19.52 (1.60)					
Toe 1 angle	15.35 (5.55)		15.33 (5.35)		15.13 (4.83)					
Toe 5 angle	6.89 (3.68)		7.64 (3.71)		7.58 (3.42)					
Measurements (mm)	Heel height (H)									
	30 mm		50 mm		70 mm		90 mm			
Foot length	230.42 (6.07)	А	227.30 (6.22)	В	220.39 (6.35)	С	210.45 (7.74)	D		
Ball of foot length	169.51 (5.03)	А	166.45 (5.08)	В	160.86 (6.07)	С	150.70 (8.90)	D		
Outside ball of foot length	146.73 (5.74)	А	144.06 (6.34)	В	138.49 (6.42)	С	130.28 (10.64)	D		
Foot width diagonal	91.87 (3.85)	А	90.84 (3.67)	В	90.02 (3.64)	BC	89.50 (3.67)	С		
Foot width horizontal	88.53 (3.64)	А	87.60 (3.45)	AB	86.79 (3.71)	BC	86.50 (3.64)	С		
Heel width	58.88 (2.76)		59.07 (2.83)		58.95 (2.87)		58.94 (3.39)			
Ball girth	223.53 (9.00)	А	223.64 (9.40)	В	225.71 (10.82)	В	233.62 (14.68)	В		
Instep girth	222.72 (11.07)	А	225.74 (13.83)	AB	229.10 (15.59)	В	235.54 (18.47)	С		
Short heel girth	292.55 (11.85)		291.71 (12.00)		290.63 (11.83)		289.66 (11.65)			
Instep height	57.41 (5.23)	А	62.49 (6.15)	В	73.76 (9.88)	С	94.63 (15.60)	D		
Navicular height	34.52 (5.53)	А	34.70 (6.05)	В	37.84 (5.90)	С	42.71 (7.35)	С		
Toe height	19.59 (1.46)		19.53 (1.40)		19.55 (1.51)		19.61 (1.55)			
Toe 1 angle	14.53 (4.82)		15.01 (4.81)		15.72 (5.54)		15.81 (5.70)			
Toe 5 angle	8.41 (3.29)	А	7.28 (3.43)	В	7.03 (3.68)	В	6.76 (3.85)	В		

Tab	le 3	Means	(SD)) and	post-	hoc	Duncan	results	s on f	foot	measurem	ients ((mm)
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All measurements are measured in mm except for angle measurements in degrees. Mean difference pairs with statistical significance: A, B, C, and D

ball of foot length (150.70 mm), and outside ball of foot length (130.28 mm), and greater instep girth (235.54 mm) and instep height (94.63 mm) than wearing other heel heights. Additionally, wearing a 30-mm heel height (low heel) shoe had a smaller ball girth (223.53 mm) and navicular height (34.52 mm), and larger foot width diagonal (91.87 mm) and toe 5 angle (8.41°) than the other three heel heights.

Interaction effect between forefoot and heel heights on foot dimensions

As shown in Table 2, there was a significant interaction between forefoot height and heel height (F × H) in the three foot dimensions: foot length ($\eta^2 = 0.062$, power=0.986), ball of foot length ($\eta^2 = 0.087$, power=0.999), and instep height



Fig. 4 Significant interactions: Comparison of the 12 combinations. F × H: fore heel height × rear heel height. #: post hoc grouping code, *p* < 0.05

Comfort scores		Mean (SD)	Mode (range)	Median	95% Confidence Interval for Mean		p-value
					Lower	Upper	
Forefoot height	10 mm	5.24 (2.33) A ^a	5.00 (2–10)	5.00	4.85	5.62	p<0.001
	20 mm	6.09 (2.10) B	7.00 (1–10)	6.00	5.74	6.44	
	30 mm	5.91 (1.74) B	6.00 (1-10)	6.00	5.62	6.20	
Heel height	30 mm	6.89 (1.91) A	8.00 (3–10)	7.00	6.52	7.26	p<0.001
	50 mm	6.76 (1.66) A	6.00 (4–10)	7.00	6.44	7.08	
	70 mm	5.42 (1.50) B	6.00 (4–8)	6.00	5.13	5.71	
	90 mm	3.91 (1.80) C	4.00 (0-8)	4.00	3.57	4.26	

Table 4 Descriptive statistics, two-way ANOVA and post-hoc results on perceived comfort (N = 35)

^a Duncan MRT grouping code. The same letter denotes non-significant differences

 $(\eta^2 = 0.201, \text{ power} = 1.000)$. Figure 4 shows a comparison in foot dimensions for 12 wedge-heeled shoe conditions under significant measures. The combination of 10 mm × 90 mm resulted in the shortest foot length $(204.44 \pm 6.00 \text{ mm})$ and ball of foot length $(143.82 \pm 10.06 \text{ mm})$ and the highest instep height $(109.26 \pm 12.21 \text{ mm})$, as shown in Fig. 4A–C. In addition, the combination of 10 mm × 30 mm,

20 mm × 30 mm, and 30 mm × 30 mm produced longer foot length (about 230.00 mm) and ball of foot length (about 169.00 mm). A lower instep height was 57.21 ± 4.53 mm and 59.13 ± 4.82 mm observed for the 20 mm × 30 mm and 30 mm × 30 mm combinations (p > 0.05, non-significant), respectively.

Effects of the forefoot and heel heights on perceived comfort

Table 4 summarized the descriptive statistics and the results of two-way ANOVA on perceived comfort. The results revealed that both forefoot and heel height, as well as their interaction, had a significant impact on perceived comfort. Duncan's MRT results showed that a 10-mm forefoot height caused less perceived comfort than the other conditions, as did 90 mm heel height. Specifically, comfort scores significantly increased as the forefoot height increased (p < 0.01, $\eta^2 = 0.052$, power = 0.992), being the lowest (5.24 ± 2.33) in the 10-mm forefoot, and then increasing in the 20 mm (6.09 ± 2.10) and 30 mm (5.91 ± 1.74) heights. Meanwhile, as heel height increased, participants experienced significant more discomfort (p < 0.01, $\eta^2 = 0.370$, power = 1.000). The results showed the highest comfort at 30-mm heel height (6.89 ± 1.91) with no differences with 50-mm heel height (6.76 ± 1.66). The 70-mm heel height showed the comfort scores at (5.42 ± 1.50) . The lowest comfort was at 90-mm heel height (3.91 ± 1.79) . For the interaction effect, the significant difference on perceived comfort (p < 0.001, $\eta^2 = 0.117$, power = 1.000) was found. Comparisons of subjective comfort under each test condition are shown in Fig. 4D. Subjective comfort measures revealed that the most comfortable combinations were 10 mm \times 30 mm, 20 mm \times 30 mm, 20 mm \times 50 mm, and $30 \text{ mm} \times 50 \text{ mm}$ (score: approximately 7.0), whereas the combination of $10 \text{ mm} \times 90 \text{ mm}$ was the least comfortable (score: 2.8).

Discussion

Foot measurements with elevated forefoot height and heel height

Dimensionally, raising forefoot height produces longer foot length, ball of foot length, and outside ball of foot length, smaller ball girth and instep girth, and lower instep height and navicular height. foot length is an essential parameter when choosing an appropriate footwear size. One possible explanation for the induced longer foot length, ball of foot length, and outside ball of foot length is that when wearing wedge-heeled shoes, the foot shape tends to flatten upward. Furthermore, ball girth, instep girth, and instep height became smaller, while the width parameters were not changed significantly, indicating that the increased forefoot heights made the cross-sectional girth of the forefoot and midfoot shape shorter and flatter. Previous studies have shown that the change in foot dimensions is related to a shift in plantar pressure, where plantar pressure in the heel and midfoot region shifts to the medial forefoot with heel elevation (Hong et al. 2005, Melvin et al., 2019). This was reflected in the foot measurements as an increase in the total foot contact area and forefoot width. However, this study found that there was no significant change in foot width diagonal and foot width horizontal when the forefoot height increased; a lower navicular height was also found indicating a flatter medial arch.

Thus, increasing the forefoot height of wedge-heeled shoes seems likely to alleviate the deformation of the forefoot and arch in a static standing position. Additionally, dimensional changes increase during the walking process (Boppana & Anderson, 2021). The effect of walking in wedges may differ from the static measurements in this study. The observed flatter medial foot arch may be associated with poor performance in postural instability (Anzai et al., 2014) and leg fatigue (Ghasemi & Anbarian, 2020).

In terms of heel height effect, shorter foot length, ball of foot length, and outside ball of foot length, narrower foot width diagonal and foot width horizontal, and smaller toe 5 angle were found when wearing wedge-heeled shoes; in contrast, larger ball girth and instep girth, as well as higher instep height and navicular height were obtained. Meanwhile, from the Duncan post hoc test results, we noted that a heel height of 90 mm caused greater foot deformation than the other conditions. An increased heel height caused the foot length to become shorter. These findings are consistent with those of Wan et al. (2017) and Makiko and Tsutsumi (2000). Additionally, shorter dimensions were observed for ball of foot length and outside ball of foot length. This may be attributed to the foot position of plantar flexion with elevated heels. Hill et al. (2017) demonstrated that reduced foot width is a dimensional effect of excessive supination. The smaller foot width diagonal and foot width horizontal observed in this study suggest that supination also occurred as the heel height started rising in wedge-heeled shoes. Moreover, the ball girth and instep girth increased, but the short heel girth did not change significantly. This shows that the elevated heel height gives a more convex cross-sectional shape in the forefoot and midfoot regions, except for the heel region. For higher navicular height, Lee and Hong (2005) previously indicated that the cavus-type of the higher arch would be seen in women wearing elevated heels. Changes in arch caused by heel elevation in wedge-heeled shoes showed the same results. One possible reason for the observation of higher navicular height is the increased foot loading caused by the peak pressure and impact force, which can lead to decreased wearing comfort and plantar fasciitis (Hill et al., 2017; Stanković et al., 2020). Furthermore, the toe 5 angle was found to be the smallest on an elevated rear heel of 90 mm ($6.76^{\circ} \pm 3.85^{\circ}$). The smaller toe 5 angles might imply that (1) the foot rotates anticlockwise in the vertical view, and (2) the fifth toe migrates toward the lateral side with heel elevation, which is consistent with the findings of Wan et al. (2017).

Interaction effect and subjective measurements

For the interaction effect (as shown in Fig. 4), the combination (forefoot × heel height) of 10×90 mm resulted in more foot deformation and greatly reduced perceived comfort. The combinations that had the highest mean perceived feeling ratings were 10×30 mm and 20×30 mm combinations, which also produced a longer foot length, ball of foot length, and lower instep height. To calculate the values of 'heel height'— 'forefoot height', which is named heel-toe drop, similar perceived comfort was observed in the same height difference (e.g., 20, 40, and 60 mm). The smaller difference in heel-top drop, the significantly better wearing comfort was found (p < 0.05). Meanwhile, the difference between forefoot height and heel height can show the actual degree of

comfort. The findings were in line with Mo et al. (2020) reported that a small heel-toe drop resulted in less variation in foot dimensions, which is optimal for wearing comfort. Besides, although there was no difference in foot dimensions and perceived comfort level for the combinations with the same heel-toe drop (10×30 v.s. 30×50 , 10×50 v.s. 30×70 and 10×70 v.s. 30×90 mm) based on the post hoc analysis, it can be inferred from Fig. 4D that comparing the same heel-toe drop conditions, the perceived comfort may be decreased by the forefoot height was increasing. Overall, for wedge-heeled shoe combinations, 10×30 mm and 20×30 mm can be considered as better combinations for designing wedge-heeled shoes.

Regarding subjective measurements, an elevation in forefoot height increases perceived comfort; conversely, a higher heel height is associated with a lower comfort level. The effect of heel height agrees with the findings of Lee and Hong (2005) and Melvin et al. (2019). The subjective comfort results may be related to pressure relief in the forefoot and better shoe fitting. Witana et al. (2009) investigated footbed shapes for enhanced footwear comfort and found that the corresponding heel wedge angle and heel seat length play an important role in optimum sensation. The increased forefoot height in the wedge-heeled footbed in this study may have pressure-relieving effects on the forefoot area associated with muscle fatigue, enhanced shoe fitting, and improved perceived wearing comfort within the static standing condition.

Implications to footwear design and wearing fitness

The current findings suggest that the shoe lasts and the design of wedge-heeled shoes should carefully reflect changes in foot shape and how they affect the fit and comfort of wearers. Wedge-heeled shoe manufacturers should develop lasts and products based on the dimensional differences and comfort in wedge-heeled shoes caused by forefoot and heel heights, not the general effects of elevated heels. First, changes in length-related parameters suggest that slight compensation may be required for ill-fitting wedge-heeled shoes. Consistent with the studies by Wan et al. (2017) and Branthwaite et al. (2013), in the forefoot region, the toe box design in wedge-heeled shoes may also need to be slightly compensated for. The length parameters should maintain some leeway and should be 9–15 mm longer than the foot when properly fitted. Second, the change in ball girth indicates that the foot circumference allowance in the metatarsal area needs to be considered by the designers (e.g. circumferences of the shoe last-corresponding girths of the foot). Third, the instep is one of the most important regions for shoe fitting (Xiong et al., 2008). Boppana and Anderson (2021) reported that instep height and instep girth correspond to the dorsal foot shape of the midfoot. Likewise, the mismatch of instep height and instep girth of wedge-heeled shoes may adversely affect fit and comfort in the midfoot region. Furthermore, women with higher arches had a higher prevalence of footwear-related pain (Hill et al., 2017). The current study suggests that an elevated forefoot may mitigate a high arch. Commercial shoes or boots with a wedge-shaped footbed would provide good arch support for comfort when the forefoot is elevated. However, the shape of the heel region generally does not change even for different styles of shoes (Buldt & Menz, 2018). According to our findings, forefoot and heel elevations of wedgeheeled shoes did not affect the shape of the heel region. In these aspects, shoe lasts and

footwear can be designed to more closely resemble foot shape to help customise the fit around the toe, ball, midfoot, and arch regions.

Limitations and future study

This study recruited participants with limited shoe sizes (EU 37-38), which may not represent all users. An investigation of participants using other shoe sizes is required. Moreover, owing to the demographic characteristics of the participants, the results of this study are valid only for young, healthy females. It is also worth noting that the 3D foot models were captured using footbeds without uppers. Thus, the effect of the wedge-heeled shoe on the other footwear design elements could be examined in future studies. In addition, only the static standing condition was considered at different forefoot/heel heights. Further research is needed on foot shape, plantar pressure and wearer performance while walking or running in the same coordinated space under dynamic scanning. Moreover, a control group (foot shape information in a flat state) can be used for further comparison and analysis. These would contribute to identifying these differences in the production of type-specific lasts and footwear designs in addition to the recommendations made in this study.

Conclusions

This study aimed to investigate various numerical size difference in foot shape when wearing wedge-heeled shoes. Differences in foot morphology that change with forefoot height and heel height were analysed by comparing foot dimensions. Three forefoot and four heel heights were evaluated. It was found that elevation of the forefoot and heel affected different dimensional changes in foot shape; the low heel-toe drop was considered to be the most comfortable height characteristic in wedge-heeled shoes. When wearing a wedgeheeled shoe, the foot became longer, flatter, and slimmer owing to elevated forefoot height. The elevation of heel height deformed the foot shape and dimensions of the young women; they became shorter, narrower, and more convex with higher instep and arch, as well as smaller toe 5 angles. Dimensional differences imply that forefoot height may help alleviate the deformation associated with heel elevation. Subjective measurements showed that the improvement in perceived comfort through an increase in forefoot height was significant, whereas discomfort was induced by elevated heels. This research focused on the height characteristics of wedge-heeled footbeds and provided useful information for foot anthropometric measurements of wedge-heeled shoe conditions. The findings of this study can be considered to improve the design of wedge-heeled shoes and the overall perceived comfort.

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The study protocol was approved by the ethics committee of the institution (reference number: 10306HE023).

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IRB statement

The experimental protocols were approved by the Institutional Ethics Committee of Taoyuan General Hospital, Ministry of Health and Welfare (IRB Approval No. TYGH112010) regarding ethical issues including consent to participate.

Authors' contributions

AZ participated in ideation, collecting data, drafting, and revision of the manuscript. YCL participated in ideation, drafting, and revision of the manuscript and managed submission process as the corresponding author. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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