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3D Foot Anthropometric Measurements Under Two Weight-Bearing Conditions for Ergonomic Design of Foot-Related Products

Mediciones Antropométricas del Pie en 3D Bajo Dos Condiciones de Soporte de Peso para el Diseño Ergonómico de Productos Relacionados con los Pies

Bingyi Cao[1]; Jian Wang[1]; Wenya Shi[2]; Xi Lu[1] & Kexuan Zhou[2]

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SUMMARY: This study collected 3D models of the left and right feet from 317 Chinese youth (155 females and 162 males) under half weight-bearing and no weight-bearing conditions. Thirteen dimensions and one angle were taken for each sample. By measuring 13 foot dimensions and 1 angle, this study comprehensively investigated the differences in foot shape between genders and the bilateral differences, as well as the foot shape differences under different conditions. The results showed that regardless of the condition, male foot dimensions were significantly larger than those of females. However, female foot shape was not simply a scaled-down version of male foot shape. On the contrary, the average angle of female feet was greater than that of males under both conditions, indicating a higher prevalence of hallux valgus in females. Both males and females exhibited significant correlation in foot dimensions between the left and right feet, with minimal differences. Under the half weight-bearing condition, the average foot length, width, and circumference were significantly larger than the corresponding measurements under the no weight-bearing condition, while the average height and angle were significantly smaller. Therefore, when designing footwear and foot-related medical rehabilitation aids, it is important to consider foot shape and dimensions under different conditions as a reference. The results of this study provide manufacturers of foot-related products with more detailed data support and are of significant value to the field of medical foot morphology research.

KEY WORDS: 3D Foot; Anthropometry; No Weight-Bearing; Half Weight-Bearing; Shape Difference.

INTRODUCTION

In recent years, there has been a growing demand among consumers for footwear and related products that are more suitable and comfortable (Chen *et al*., 2010). As a result, foot measurement and the design of related products have received increasing attention. Wearing ill-fitting shoes has been shown to increase the incidence of foot problems, such as corns, calluses, hallux valgus, palmar or metatarsal pain, and flat feet (Lee & Wang, 2015; Irzmanska, 2016). Incorporating foot measurement information into footwear design can improve the fit and comfort of shoes (McWhorter *et al*., 2003; Ozden *et al*., 2005). The standard method for determining the fit of shoes is to match foot length, width, heel width, ball circumference, instep circumference, heel circumference, and instep height with the footwear product (Witana *et al*., 2004, 2006; Sun *et al*., 2009; Wang *et al*., 2010; Xu *et al*., 2019).

Several studies have shown that there are differences between male and female feet in terms of toe length, foot length, foot width, ball girth, and malleoli height dimensions (Wunderlich & Cavanagh, 2001; Krauss *et al*., 2011). Using 3D scanning techniques, Hong *et al*. (2011) measured the feet of Chinese young adults of both sexes and found that foot breadth, medial ball length, ball angle, and instep height varied significantly across foot types in the same foot length for both sexes. Neutral shoes only fit a limited number of male and female feet and often cause stress and strain in the foot tissues, leading to pain and trauma (Xiong *et al*., 2009).To prevent foot deformities, the gender differences in feet should be taken into consideration when designing shoes (Au & Goonetilleke, 2007; Menz & Bonanno, 2021).

As no two feet are identical, researchers have also

[1] School of Art and Design, Jiangsu Vocational Institute of Architectural Technology, Xueyuan Road, Xuzhou, China.
[2] School of Architecture & Design, China University of Mining and Technology, Daxue Road, Xuzhou, China.
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explored the differences in size between the left and right foot. Related studies found that most foot measurements showed no significant statistical differences between the left and right feet (Bus *et al*., 2009; De Mits *et al*., 2010; Brenton-Rule *et al*., 2019). However, most studies only considered the size differences between the left and right foot in one situation, and did not simultaneously consider the differences under half weight bearing (HWB) and no weight bearing (NWB) conditions. It is widely acknowledged that the foot adapts to the stress placed on it, which results in changes in its form. For example, walking and sitting apply different pressure to the sole of the foot (Yung-Hui & Wei-Hsien, 2005; Niu *et al*., 2020). Previous studies have mainly focused on evaluating foot length, width, height, and circumference under HWB conditions to guide the design of walking insoles and shoes for humans. Few scholars have studied foot sizes under NWB conditions, which is crucial for the development of medical devices such as ankle-foot orthotics and corrective insoles (Barelds *et al*., 2018). Currently, there are few studies that compare and analyze the differences in foot size between HWB and NWB conditions. Moreover, more specific foot measurements, such as ball circumference, instep circumference, and heel circumference, have yet to be explored.

In summary, this study will measure 13 dimensions and 1 angle of each foot model, including length, width, height, circumference, and angle, with a focus on investigating changes in foot shape under different weight-bearing conditions, gender differences, and bilateral differences. The research results will provide detailed data support for the study of foot morphology, as well as the design of footwear products, foot rehabilitation devices, and orthotic products.

MATERIAL AND METHOD

Participants. The study involved a sample of 317 Chinese participants aged between 18 and 30, comprising 155 females and 162 males. The average age of the female participants was 22.08±2.22 years, while the average age of the male participants was 22.33±3.07 years. Participants with a history of foot trauma, congenital or acquired abnormalities, or surgery were excluded from the study. The study was approved by the Ethics Committee of the first author's institution, and all participants provided written informed consent after receiving detailed information about the experiment and their rights.

Collecting and scanning 3D foot models. In this research, In this research, theparticipants' feet under HWB and NWB conditions were scanned using the MEASURE2.1.2 software and the INFOOT scanner with an accuracy of 0.1 mm. The scanning procedure involved several steps: (Step1) Eight marker dots used for positioning during scanning were placed on the subject's foot at designated locations by the experimenter (Fig. 1A). (Step2) The subject placed the scanned foot into the 3D scanner and maintained full body balance with both feet immobile. 3D data of the subject's feet in HWB and NWB conditions were scanned, respectively, as shown in Figures 1B and C. (Step3) The scanned model was checked for morphological distortions, excessive missing data, etc. If found, the model was rescanned. (Step4) Finally, each scanned model was preprocessed using Geomagic Wrap software (3D Systems, Inc., USA), which involved steps such as noise removal, smoothing, and trimming, as shown in Figure 2. Figure 3 displays the left foot models of a participant under HWB and NWB conditions, respectively. In total, 1268 3D foot models were gathered for subsequent statistical analysis.

Data analysis. The study involved a sample of 317 Chinese participants aged between 18 and 30, comprising 155 females and 162 males. The average age of the female participants was 22.08±2.22 years, while the average age of the male participants was 22.33±3.07 years. Participants with a history of foot trauma, congenital or acquired abnormalities, or surgery were excluded from the study. The study was approved by the Ethics Committee of the first author's institution, and all participants provided written informed consent after receiving detailed information about the experiment and their rights.

Fig. 1. The process of 3D foot scanning, encompassing (A) the placement of marker dots, (B) the scanning of the foot in the HWB condition, and (C) the scanning of the foot in the NWB condition.

Fig. 2. The preprocessing steps of 3D foot, including (A) noise removal, (B) model smoothing, and (C) model trimming.

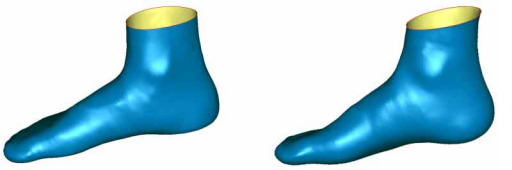

Fig. 3. The left foot models of the same participant under (A) HWB and (B) NWB conditions.

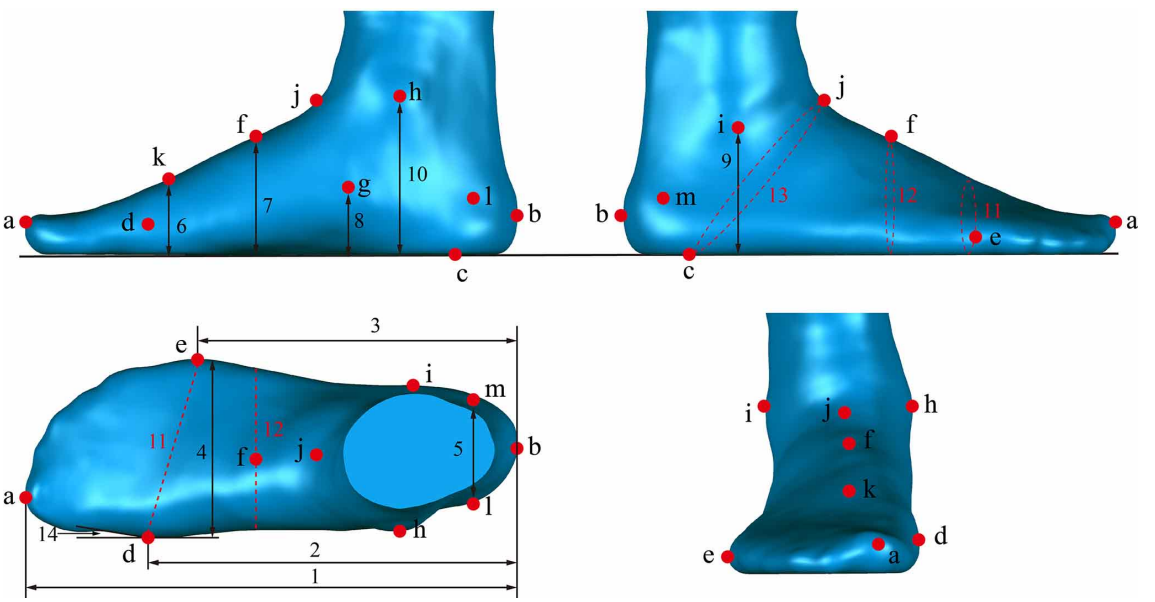

Fig. 4. Characteristic points and dimensions of the foot: (a) Toe point, (b) Heel point; (c) Landing point; (d) Metatarsal tibiale point; (e) Metatarsal fibulare point; (f) Instep point; (g) Navicular point; (h) The most medial point of the medial malleolus; (i) The most lateral point of lateral malleolus; (j) Dorsum point; (k) The highest point of the metatarsal; (l) Medial heel point; (m) Lateral heel point.

Table. I. Definition of 13 dimensions and 1 angel of foot.

		Dimensions	Definition
Lengts	1	Foot Length (FL)	The distance between the toe point and the heel point along the X axis.
	2	Instep length (IL)	The distance between the heel point and the metatarsal tibiale point along the X axis.
	3	Fibulare Instep length (FIL)	The distance between the heel point and the metatarsal fibulare point along the X axis.
Widths	4	Foot width (FW)	Distance between the metatarsal tibiale point and the metatarsal fibulare point and the maximum horizontal width perpendicular to the X axis.
	5	Heel Width (HW)	The distance between the medial heel point and the lateral heel point.
Heights	6	Height of Top of Ball Girth (HBG)	The vertical distance from the highest point of the metatarsal to the supporting surface of the foot.
	7	Height of Instep (HI)	The vertical distance from the instep point to the supporting surface of the foot.
	8	Height of Navicular (HN)	The vertical distance from the navicular point to the supporting surface of the foot.
	9	Lateral malleolus height (LMH)	The vertical distance from the most lateral point of the lateral malleolus to the supporting surface of the foot.
	10	Medial malleolus height (MMH)	The vertical distance from the most medial point the of medial malleolus to the supporting surface of the foot.
Girths	11	Ball girth (BG)	The circumference of the cross section of the metatarsal tibiale point and metatarsal fibulare point.
	12	Instep girth (IG)	The circumference of the cross section of the Instep point.
	13	Heel Girth circumference (HGC)	The circumference of the section of the plane intersects the foot past the landing point and dorsum point.
Angle	14	Toe 1 angle (T1A)	The angle of the line between the toe point and the metatarsal tibiale point with the X axis.

Table II. Descriptive statistical analyses and independent samples t-tests for foot measurements in both sexes and sides in the HWB condition (all measurements were recorded in mm, except for T1A , which was measured in degree).

Variable	Males				Females				Independent t-test	
	Mean	SD	Max	Min	Mean	SD	Max	Min	*t*-value	*p*-value*
FL (right)	254.560	9.984	277.5	232.2	232.269	9.027	256.9	210.9	20.822	0.000
FL (left)	254.530	10.237	280.7	230.6	232.094	8.936	256.6	211.6	20.751	0.000
IL (right)	184.419	8.079	200.7	165.0	168.898	6.979	188.2	149.8	18.328	0.000
IL(left)	184.340	8.393	202.7	166.9	168.424	7.054	185.5	148.6	18.307	0.000
FIL (right)	162.281	8.020	180.1	143.1	148.252	6.738	163.9	130.2	16.914	0.000
FIL (left)	162.121	8.284	185.0	143.0	148.232	6.788	165.3	132.1	16.335	0.000
FW (right)	98.788	5.194	110.3	86.5	88.899	3.784	98.0	80.2	19.434	0.000
FW (left)	98.133	4.913	109.8	85.4	89.328	3.993	99.4	78.6	17.547	0.000
HW (right)	66.097	3.287	73.7	57.4	60.639	2.704	67.0	53.9	16.175	0.000
HW (left)	65.848	3.233	73.6	57.6	60.871	2.844	66.5	53.6	14.529	0.000
HBG (right)	43.204	2.833	50.6	37.6	37.635	2.819	46.3	33.5	14.370	0.000
HBG (left)	41.993	3.181	50.5	35.0	38.641	3.024	45.9	32.1	12.489	0.000
HI (right)	64.883	4.173	77.0	53.5	58.631	4.353	68.6	48.7	12.114	0.000
HI (left)	64.244	4.915	76.2	51.5	59.082	4.202	68.8	48.6	10.906	0.000
HN (right)	49.939	5.463	60.9	35.2	44.144	6.344	57.0	30.1	8.727	0.000
HN (left)	49.352	5.740	63.5	34.7	44.264	5.937	57.9	29.8	7.757	0.000
LMH (right)	74.198	5.901	89.9	59.6	67.167	5.032	80.6	52.2	11.430	0.000
LMH (left)	73.762	5.896	88.4	57.7	66.418	5.111	83.5	55.5	11.864	0.000
MMH(right)	86.099	5.300	99.4	72.5	78.290	6.037	94.9	62.3	12.253	0.000
MMH(left)	85.683	5.226	99.7	72.6	77.320	5.055	89.1	64.5	14.472	0.000
BG(right)	242.106	11.403	271.6	212.9	222.354	9.109	242.1	199.5	18.197	0.000
BG(left)	241.751	12.558	276.6	207.2	221.058	9.294	245.3	197.9	15.678	0.000
IG(right)	242.052	11.569	268.3	214.7	222.894	9.827	247.0	199.1	15.914	0.000
IG(left)	244.117	12.246	271.0	213.7	224.337	9.955	245.3	200.1	15.812	0.000
HGC(right)	326.478	12.736	356.5	295.7	295.996	11.403	321.1	267.7	22.417	0.000
HGC(left)	325.646	12.831	354.0	290.5	296.434	11.619	325.1	268.3	21.218	0.000
T1A(right)	6.580	3.948	17.7	0.0	10.034	3.690	16.9	0.0	-8.040	0.000
T1A(left)	8.175	4.072	18.7	0.0	11.423	3.666	19.4	0.0	-7.451	0.000

*p-value < 0.05 is significant.

As shown in Table II, descriptive statistical analyses and independent samples t-tests are carried out for the foot dimensions of males and females in the HWB condition respectively. The results indicate that there are significant differences in foot dimensions between males and females in the HWB condition ($p<0.05$). The average length dimensions (FL, IL, and FIL), the average width dimensions (FW and HW), the average height dimensions (HBG, HI, HN, LMH, and MMH), as well as the average girth dimensions (BG, IC, and HGC), are all larger in males compared to females. However, the average angle (T1A) in males' left and right feet are significantly smaller than those in females.

The foot characteristic dimensions of males and females in the NWB condition were subjected to descriptive statistical analyses and independent samples t-tests, as presented in Table III. The results showed significant differences ($p<0.05$) between male and female foot dimensions in the NWB condition. On average, male left and right feet were larger than female feet in terms of length dimensions (FL, IL, and FIL), width dimensions (FW and HW), height dimensions (HBG, HI, HN, LMH, and MMH), and girth dimensions (BG, IG, and HGC). However, the angle value showed the opposite trend. (Table I).

Table IV presents the results of paired samples t-tests for male and female left-right foot measurements under HWB conditions. The analysis results show significant correlations between the measurements of the left and right feet, with correlation coefficients ranging from 73.4 % to 94.5 % for male and from 72.7 % to 95.5 % for female. Despite the strong correlation between the left and right feet samples under HWB conditions, no part of the human body is completely symmetrical and identical. There are significant differences ($p<0.05$) in the mean dimensions of FW, HW, HBG, HI, IG, HGC, and the mean angle T1A between male left and right feet. Similarly, there are significant differences ($p<0.05$) in the mean dimensions of FW, HW, HBG, LMH, MMH, BG, IG, and the mean angle T1A between female left and right feet.

Table III. Descriptive statistical analyses and independent samples t-tests for foot measurements in both sexes and sides in the NWB condition among young Chinese adults (all measurements were recorded in mm, except for T1A, which was measured in degree).

Variable	Males				Females				Independent *t*-test	
	Mean	SD	Max	Min	Mean	SD	Max	Min	*t*-value	*p*-value*
FL(right)	247.288	9.665	275.0	225.1	225.286	8.753	248.0	203.5	21.214	0.000
FL(left)	247.020	10.239	276.7	222.7	224.365	8.892	247.8	201.9	20.994	0.000
IL(right)	179.518	7.418	195.1	163.5	162.851	6.924	180.1	144.2	20.656	0.000
IL(left)	178.410	7.466	193.1	161.7	161.895	6.963	176.0	140.0	20.346	0.000
FIL(right)	160.988	7.954	179.1	143.0	146.961	6.380	159.0	130.0	18.082	0.000
FIL(left)	159.999	8.194	181.9	141.0	146.375	7.328	161.9	129.8	14.910	0.000
FW(right)	92.073	4.978	103.4	79.2	82.973	4.025	93.9	73.5	17.932	0.000
FW (left)	91.295	4.711	103.5	79.1	83.553	4.106	94.2	73.6	15.569	0.000
HW(right)	61.739	3.060	69.1	54.4	56.732	2.779	64.3	49.5	15.230	0.000
HW(left)	61.495	3.131	69.5	53.9	56.775	2.802	64.2	49.7	14.121	0.000
HBG(right)	50.102	3.204	58.1	43.7	44.815	4.350	56.8	36.3	12.277	0.000
HBG(left)	49.729	4.086	60.2	41.6	45.972	4.345	59.6	37.6	7.934	0.000
HI(right)	74.159	4.289	87.3	62.6	67.061	4.696	80.8	55.2	14.062	0.000
HI(left)	73.707	4.934	86.5	61.7	67.838	4.084	77.9	58.8	11.557	0.000
HN(right)	57.854	5.751	68.3	44.3	51.373	5.697	64.5	37.7	9.332	0.000
HN(left)	57.375	6.269	71.5	41.1	52.716	5.485	64.8	39.7	7.752	0.000
LMH(right)	78.594	7.370	98.1	61.9	70.656	6.265	87.3	55.5	10.310	0.000
LMH(left)	77.356	6.871	95.6	63.5	70.337	7.283	87.8	55.8	8.830	0.000
MMH(right)	92.652	7.359	109.5	73.9	85.647	5.758	98.4	73.0	10.810	0.000
MMH(left)	91.646	7.239	106.5	74.8	84.648	5.315	99.1	73.9	8.436	0.000
BG(right)	234.315	11.453	262.8	205.2	213.677	9.200	236.5	191.0	17.724	0.000
BG(left)	232.247	11.217	260.2	202.9	213.378	8.962	237.0	191.1	16.581	0.000
IG(right)	238.082	11.448	266.8	210.4	218.785	9.560	241.5	197.4	16.011	0.000
IG (left)	239.877	12.025	270.0	211.2	219.146	9.422	245.7	196.3	17.424	0.000
HGC(right)	318.875	14.898	356.4	279.2	288.633	13.583	323.0	253.0	17.998	0.000
HGC(left)	317.492	16.476	364.0	279.4	290.052	15.533	332.9	253.1	16.011	0.000
T1A(right)	8.552	3.857	19.6	0.0	11.697	3.911	21.4	0.0	-7.207	0.000
T1A(left)	9.426	3.740	18.7	0.0	13.034	3.440	21.8	0.0	-8.928	0.000

*p-value < 0.05 is significant.

Table V shows the results of paired samples t-tests for male and female left-right foot measurements under NWB conditions. The results indicate significant correlations between the measurements of the left and right feet for both males and females, with correlation coefficients ranging from 74.4 % to 95.9 % for male and from 70.2 % to 92.8 % for female. There are significant differences ($p<0.05$) in the mean dimensions of FW, HW, IG, HGC, and the mean angle T1A between male left and right feet. Similarly, there are significant differences ($p<0.05$) in the mean dimensions of FW, HBG, HI, HN, MMH, and the mean angle T1A between female left and right feet.

The data presented in Table VI indicate significant differences in the right foot dimensions between the HWB and NWB conditions ($p < 0.05$), regardless of gender. Specifically, compared to the NWB condition, males and females exhibit larger average length, width, and girth dimensions of the right foot in the HWB condition, whereas the average height dimensions of the right foot are larger for males and females in the NWB condition. In the HWB condition, the average length dimensions (FL, IL, and FIL) of the male right foot are respectively 7.271 mm, 4.901 mm, and 2.292 mm greater than those in the NWB condition. For the female right foot, the average length dimensions are respectively 6.983 mm, 6.047 mm, and 1.291mm greater than those in the NWB condition. Additionally, in the HWB condition, the average width dimensions (FW and HW) of the male right foot are respectively 6.716 mm and 4.358 mm greater than those in the NWB condition, whereas the average width dimensions of the female right foot are respectively 5.926 mm and 3.907 mm greater than those in the NWB condition. The average girth dimensions (BG, IG, and HGC) of the male right foot in the HWB condition are respectively 7.790 mm, 3.969 mm, and 7.603 mm greater than those in the NWB condition, while the average girth

dimensions of the female right foot in the HWB condition are respectively 8.677 mm, 4.109 mm, and 7.362 mm greater than those in the NWB condition.

On the other hand, in the HWB condition, the average height dimensions (HBG, HI, HN, LMH, and MMH) of the male right foot are respectively 6.897 mm, 9.277 mm, 7.915 mm, 4.396 mm, and 6.553 mm smaller than those in the NWB condition. For the female right foot, the average height dimensions are respectively 7.180 mm, 8.430 mm, 7.229 mm, 3.489 mm, and 7.357 mm smaller than those in the NWB condition. In the HWB condition, the average angles (T1A) of the male and female right foot are also smaller than those in the NWB condition.

The results from Table VII indicate significant differences in left foot dimensions between HWB and NWB conditions ($p < 0.05$). Specifically, in the HWB condition, both males and females have larger average length, width, and girth dimensions of the left foot, while in the NWB condition, males and females have larger average height dimensions of the left foot.

More specifically, compared to the NWB condition, in the HWB condition, the average length dimensions (FL, IL, and FIL) of the male left foot are respectively larger by 7.509 mm, 5.930 mm, and 2.122 mm, and the average length dimensions of the female left foot are respectively larger by 7.728 mm, 6.529 mm, and 1.857 mm. In the HWB

Table IV. Bilateral differences of foot measurements within the sexes in the HWB condition using paired samples t-test (all measurements were recorded in mm, except for T1A, which was measured in degree).

Variable	Males (right-left)					Females (right-left)				
	MD*	SEM*	*t*-value	*p*-value*	Cor*	MD	SEM	*t*-value	*p*-value*	Cor*
FL	0.060	0.264	0.113	0.910	0.945	0.175	0.251	0.696	0.488	0.939
IL	0.079	0.377	0.210	0.834	0.831	0.474	0.285	1.664	0.098	0.872
FIL	0.160	0.368	0.434	0.665	0.835	0.020	0.285	0.071	0.943	0.863
FW	0.655	0.192	3.411	0.001	0.885	-0.428	0.156	-2.744	0.007	0.876
HW	0.249	0.123	2.018	0.045	0.884	-0.232	0.108	-2.151	0.033	0.884
HBG	1.212	0.172	7.057	0.000	0.742	-1.007	0.181	-5.562	0.000	0.705
HI	0.639	0.320	1.995	0.048	0.709	-0.451	0.297	-1.519	0.131	0.727
HN	0.587	0.425	1.380	0.170	0.734	-0.120	0.404	-0.297	0.767	0.766
LMH	0.435	0.380	1.147	0.253	0.764	0.749	0.351	2.137	0.034	0.730
MMH	0.416	0.297	1.398	0.164	0.742	0.970	0.375	2.584	0.011	0.758
BG	0.355	0.538	0.659	0.511	0.841	1.296	0.340	3.809	0.000	0.894
IG	-2.065	0.410	-5.041	0.000	0.906	-1.443	0.378	-3.817	0.000	0.887
HGC	0.832	0.421	1.979	0.034	0.912	-0.439	0.279	-1.570	0.118	0.955
T1A	-1.596	0.401	-3.977	0.000	0.789	-1.388	0.255	-5.454	0.000	0.729

*MD: Mean Difference; SEM: Standard Error of Mean; Cor: Correlation, p-value < 0.05 is significant.

Table V. Bilateral differences of foot measurements within the sexes in the NWB condition using paired samples t-test (all measurements were recorded in mm, except for T1A, which was measured in degree).

Variable	Males (right-left)					Females (right-left)				
	MD*	SEM*	*t*-value	*p*-value*	Cor*	MD	SEM	*t*-value	*p*-value*	Cor*
FL	0.268	0.298	0.901	0.369	0.929	0.921	0.269	1.424	0.254	0.928
IL	1.108	0.228	1.856	0.101	0.924	0.956	0.255	1.744	0.078	0.895
FIL	0.990	0.295	1.352	0.211	0.892	0.586	0.369	1.587	0.114	0.784
FW	0.778	0.192	4.053	0.000	0.874	-0.580	0.213	-2.718	0.007	0.787
HW	0.244	0.124	1.977	0.050	0.871	-0.044	0.138	-0.316	0.752	0.809
HBG	0.373	0.235	1.587	0.115	0.788	-1.157	0.242	-4.790	0.000	0.761
HI	0.452	0.264	1.715	0.088	0.744	-0.777	0.240	-3.234	0.001	0.777
HN	0.478	0.308	1.552	0.123	0.790	-1.343	0.248	-5.425	0.000	0.849
LMH	1.238	0.459	2.697	0.008	0.765	0.319	0.548	0.583	0.561	0.702
MMH	1.006	0.654	1.537	0.126	0.750	0.999	0.465	2.149	0.033	0.756
BG	2.068	0.257	8.050	0.000	0.959	0.299	0.321	0.932	0.353	0.904
IG	-1.795	0.366	-4.899	0.000	0.922	-0.361	0.439	-0.822	0.412	0.834
HGC	1.383	0.568	2.434	0.016	0.899	-1.419	0.881	-1.610	0.109	0.724
T1A	-0.873	0.301	-2.907	0.004	0.793	-1.336	0.280	-4.775	0.000	0.757

*MD: Mean Difference; SEM: Standard Error of Mean; Cor: Correlation, p-value < 0.05 is significant.

condition, the average width dimensions (FW and HW) of the male left foot are larger by 6.838 mm and 4.353 mm, respectively, while the average width dimensions of the female left foot are larger by 5.774 mm and 4.095 mm, respectively, compared to the NWB condition. The average girth dimensions (BG, IG, and HGC) of the male left foot in the HWB condition are larger by 9.504 mm, 4.240 mm, and 8.154 mm, respectively, while the average girth dimensions of the female left foot in the HWB condition are larger by 7.680 mm, 5.191 mm, and 6.383 mm, respectively, compared to the NWB condition.

On the other hand, in the HWB condition, the average height dimensions (HBG, HI, HN, LMH, and MMH) of the male left foot are respectively smaller by 7.736 mm, 9.463 mm, 8.023 mm, 3.594 mm, and 5.963 mm, and 5.963 mm, and the average height dimensions of the female left foot are respectively smaller by 7.331 mm, 8.576 mm, 8.542 mm, 3.919 mm, and 7.328 mm, compared to the NWB condition. The average angles (T1A) of the male and female left foot in the HWB condition are also smaller compared to the NWB condition.

Table VI. Bilateral differences of right foot measurements between the HWB and NWB condition using paired samples t-test (all measurements were recorded in mm, except for T1A, which was measured in degree).

Variable	Males (HWB-NWB)				Females (HWB-NWB)			
	MD*	SEM*	*t*-value	*p*-value	MD*	SEM*	*t*-value	*p*-value*
FL	7.271	0.244	29.806	0.000	6.983	0.192	36.275	0.000
IL	4.901	0.175	27.954	0.000	6.047	0.206	29.349	0.000
FIL	2.292	0.320	7.157	0.000	1.291	0.259	7.160	0.000
FW	6.716	0.115	58.283	0.000	5.926	0.138	43.081	0.000
HW	4.358	0.106	41.171	0.000	3.907	0.148	26.423	0.000
HBG	-6.897	0.195	-35.314	0.000	-7.180	0.311	-19.821	0.000
HI	-9.277	0.235	-39.539	0.000	-8.430	0.373	-21.370	0.000
HN	-7.915	0.461	-16.128	0.000	-7.229	0.329	-21.958	0.000
LMH	-4.396	0.661	-6.653	0.000	-3.489	0.454	-7.693	0.000
MMH	-6.553	0.609	-10.758	0.000	-7.357	0.543	-11.699	0.000
BG	7.790	0.191	40.701	0.000	8.677	0.150	49.141	0.000
IG	3.969	0.168	23.648	0.000	4.109	0.379	9.877	0.000
HGC	7.603	0.719	12.495	0.000	7.362	0.528	13.938	0.000
T1A	-1.973	0.219	-9.029	0.000	-1.663	0.372	-4.467	0.000

*MD: Mean Difference; SEM: Standard Error of Mean; Cor: Correlation, p-value < 0.05 is significant.

Table VII. Bilateral differences of left foot measurements between the HWB and NWB condition using paired samples t-test (all measurements were recorded in mm, except for T1A, which was measured in degree).

Variable	Males (HWB-NWB)				Females (HWB-NWB)			
	MD*	SEM*	*t*-value	*p*-value*	MD*	SEM	*t*-value	*p*-value*
FL	7.509	0.312	24.071	0.000	7.728	0.287	26.904	0.000
IL	5.930	0.393	15.081	0.000	6.529	0.314	20.807	0.000
FIL	2.122	0.413	5.140	0.000	1.857	0.384	3.364	0.001
FW	6.838	0.225	30.417	0.000	5.774	0.200	28.835	0.000
HW	4.353	0.156	27.833	0.000	4.095	0.143	28.541	0.000
HBG	-7.736	0.289	-26.779	0.000	-7.331	0.321	-25.986	0.000
HI	-9.463	0.371	-25.536	0.000	-8.756	0.357	-27.176	0.000
HN	-8.023	0.653	-13.015	0.000	-8.452	0.450	-18.775	0.000
LMH	-3.594	0.604	-5.950	0.000	-3.919	0.609	-6.438	0.000
MMH	-5.963	0.620	-9.610	0.000	-7.328	0.556	-14.978	0.000
BG	9.504	0.516	18.416	0.000	7.680	0.384	23.378	0.000
IG	4.240	0.487	8.713	0.000	5.191	0.588	9.438	0.000
HGC	8.154	0.760	8.914	0.000	6.383	0.898	7.104	0.000
T1A	-1.251	0.355	-3.525	0.001	-1.611	0.394	-4.092	0.000

*MD: Mean Difference; SEM: Standard Error of Mean; Cor: Correlation, p-value < 0.05 is significant.

DISCUSSION

According to the analysis results from Tables IV and V, it is evident that under both HWB and NWB conditions, the average length, width, height, and circumference measurements of male feet are significantly larger than those of females. Specifically, the maximum differences in length between male left foot and female left foot, male right foot and female right foot are denoted as FL. The maximum differences in width are denoted as FW, in height as MMH, and in girth as HGC. Conversely, under HWB and NWB conditions, the average T1A angle of female left and right feet is significantly greater than that of males. This result indicates a higher proportion of deformities or hallux valgus in the first metatarsal toe area among females, making them more prone to developing bunions. Hence, individuals in such cases may necessitate personalized shoe insoles or medical devices to mitigate imbalanced pressure on the soles of their feet. It is crucial to acknowledge that there exist structural and biomechanical disparities between female and male feet and ankles. Female feet are not mere replicas of male feet on a smaller scale (Krauss *et al*., 2011). Therefore, when designing footwear, these factors should be given due consideration.

Chen *et al*. (2010) noted that generally there is no significant difference between an individual's left and right

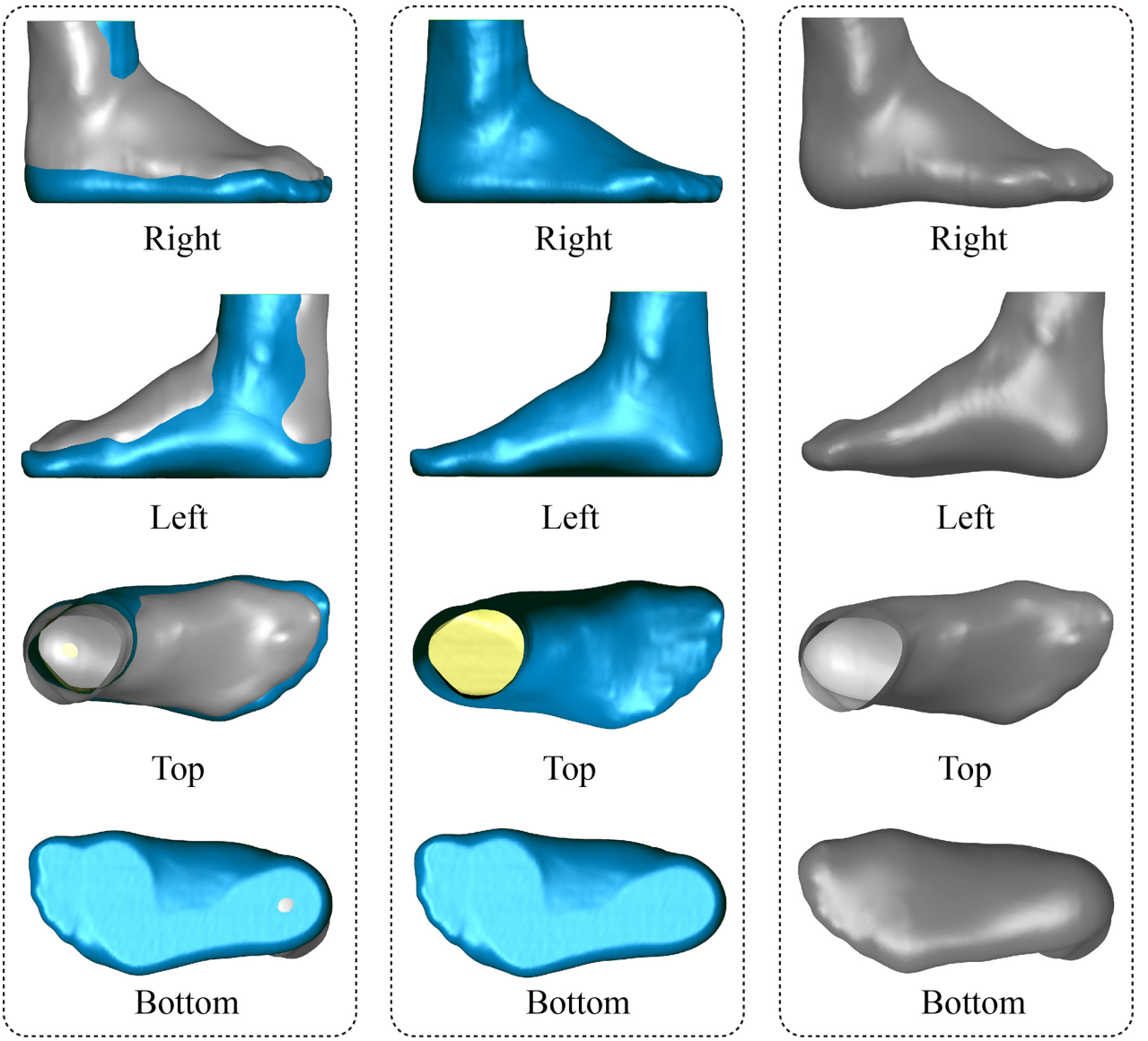

Fig. 5. Comparison the same foot in the HWB and NWB conditions.

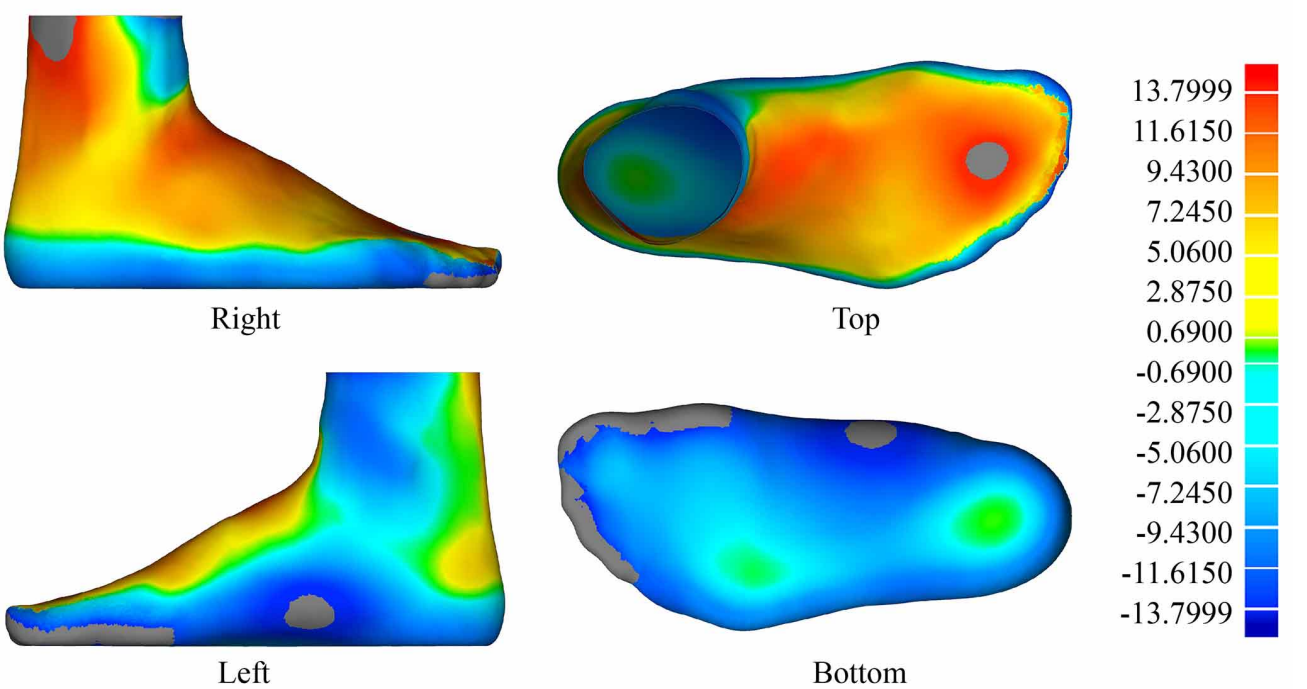

Fig. 6. Deviation analysis of the same foot in HWB and NWB conditions.

feet. However, our research analysis has revealed small differences in certain dimensions of the foot. Under both HWB and NWB conditions, the average differences in length dimensions (FL, IL, and FIL) between the left and right feet of males and females are all less than 1.108 mm. Similarly, the differences in width dimensions (HW and FW) are less than 0.778 mm, while the differences in height dimensions (HBG, HI, HN, LMH, and MMH) are less than 1.238 mm. In terms of circumference dimensions (BG, IG, and HGC), the differences are less than 2.068 mm, and the difference in angle T1A is less than 1.596 mm.

The shape and size of the foot undergo changes with variations in weight-bearing. Studying the differences in foot shape and size under different loading conditions is crucial for improving the design of insoles and foot orthoses and for clinical research in foot morphology. Xiong *et al.* (2009) indicated that the foot length of Hong Kong adults decreased by more than 3 mm from HWB to NWB conditions. Tsung *et al.* (2003) compared the foot sizes under HWB and NWB conditions and found that the circumference dimensions BG, IC, and HG decrease with reduced load. The findings of this study are consistent with the results mentioned above. Figure 5 illustrates the comparison of foot shape in a male right foot under HWB and NWB conditions, while Figure 6 presents the analysis of shape deviation in the same foot under HWB and NWB conditions. From Figures 5 and 6, it can be observed that there are significant differences in foot shape between the two conditions. The foot length dimensions (FL, IL, and FIL), width dimensions (FW and HW), and girth dimensions (BG, IG, and HGC) under HWB conditions are noticeably larger than the corresponding dimensions under NWB conditions, particularly with a heel discrepancy of approximately 9 millimeters. Conversely, the foot height dimensions (HBG, HI, HN, LMH, and MMH) under HWB condition are smaller than those under NWB condition, especially with a deviation of approximately 7 mm in foot instep. Therefore, when designing footwear-related products and foot orthoses, manufacturers need to consider the foot shape and size parameters under different load-bearing conditions.

CONCLUSIONS

This study systematically investigates the gender differences and bilateral differences in foot shape among Chinese youth under HWB and NWB conditions, as well as the foot shape differences under different weight-bearing conditions. The research findings can be applied to guide the ergonomic design of footwear products and foot orthotics for medical rehabilitation. Future research will explore the foot shape differences among Chinese individuals below 18 years old and above 30 years old, aiming to establish a comprehensive database of foot shape and size information for the Chinese population.

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CAO, B.; WANG, J.; SHI, W.; LU, X. & ZHOU, K. Mediciones antropométricas del pie en 3D bajo dos condiciones de soporte de peso para el diseño ergonómico de productos relacionados con los pies. *Int. J. Morphol., 41(4)*:1209-1218, 2023.

RESUMEN: Este estudio recolectó modelos 3D de los pies izquierdo y derecho de 317 jóvenes chinos (155 mujeres y 162 hombres) en condiciones de carga media de peso y sin carga de peso. Para cada muestra se tomaron trece dimensiones y un ángulo. Al medir 13 dimensiones del pie y 1 ángulo, se investigó exhaustivamente las diferencias en la forma del pie entre ambos sexos y sus diferencias bilaterales, así como las diferencias en la forma del pie en diferentes condiciones. Los resultados mostraron que, independientemente de la condición, las dimensiones del pie de los hombres, estos eran significativamente más grandes que los de las mujeres. Sin embargo, la forma del pie femenino no era simplemente una versión reducida de la forma del pie masculino. Por el contrario, el ángulo promedio de los pies de las mujeres fue mayor que el de los hombres en ambas condiciones, lo que indica una mayor prevalencia de hallux valgus en las mujeres. Tanto hombres como mujeres exhibieron una correlación significativa en las dimensiones del pie, entre el pie izquierdo y el derecho, con diferencias mínimas. Bajo la condición de medio soporte de peso, la longitud, el ancho y la circunferencia promedio del pie fueron significativamente mayores que las medidas correspondientes bajo la condición sin soporte de peso, mientras que la altura y el ángulo promedio fueron significativamente más pequeños. Por lo tanto, al diseñar calzado y dispositivos médicos de rehabilitación relacionados con los pies, es importante tener en consideración la forma y las dimensiones del pie en diferentes condiciones como referencia. Los resultados de este estudio, brindan a los fabricantes de productos relacionados con los pies un soporte de datos más detallado y son de gran valor para el campo de la investigación médica de la morfología del pie.

PALABRAS CLAVE: Pie 3D; Antropometría; Sin soporte de peso; Medio soporte de peso; Diferencia de forma.

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Corresponding author:
Jian Wang
School of Art and Design
Jiangsu Vocational Institute of Architectural Technology
Xueyuan Road
Xuzhou 221116
CHINA

E-mail: shejizhu@hotmail.com