

The effects of body mass index on foot shape among U.S. children

Hayoung Jung , Byoung-Keon D. Park , Sheila M. Ebert , Monica L.H. Jones ,
Matthew P. Reed 

Biosciences Group, University of Michigan Transportation Research Institute, 2901 Baxter Rd, Ann Arbor, MI, USA, 48109

ARTICLE INFO

Keywords:

Foot shape
U.S. children
Body mass index (BMI)
Statistical shape model

ABSTRACT

Understanding the three-dimensional shape of children's feet is valuable for designing appropriate footwear and orthotic devices, tracking growth trajectories, and supporting foot health and development. The most important anthropometric change in the U.S. in recent years is the increase in body mass at every age, but the effects of these trends on child foot shapes have not previously been studied. To address this gap, we collected high-resolution, three-dimensional (3d) foot surface data from 490 children ages 3–17 years across body mass index (BMI) from 12.4 to 52.6 kg/m² and developed a statistical foot shape model to analyze the variations in foot morphology related to BMI. After accounting for age effects, a higher BMI was associated with differences in foot dimensions, including broader foot width, greater circumference, and increased thickness, as well as a larger cross-sectional area and volume. Higher BMI was also associated with lower arch height. Specific foot regions, including the medial and lateral sides, arch, and instep, showed more substantial shape differences with varying BMI levels. The observed differences were most pronounced in older children, with 10- and 17-year-olds showing the greatest discrepancy in foot dimensions. Differences in foot shape between median and 95th percentile BMI were much higher than the differences between the 5th percentile and median BMI, particularly concentrated in the hindfoot and anterior ankle area. This study provides the first comprehensive three-dimensional analysis of children's foot shape variations in relation to BMI, compared to previous research that focused primarily on linear dimensions. The findings suggest that the increasing body mass among children may necessitate the redesign of footwear to ensure a good fit. The foot shape model can be used to estimate foot shapes from demographic data, accurately fit low-resolution foot scan data, and aid in the design of footwear and orthotic devices. Future research should aim to collect more data from young children with high BMI, improve the representation of population subgroups, and include consideration of dynamic effects. The children's foot model is publicly available online at <https://HumanShape.org/ChildFoot>.

1. Introduction

Three-dimensional data on children's foot shapes are used for designing footwear and foot-related orthotic devices as well as tracking foot growth trajectories. Children's feet undergo rapid changes during growth and development (Unger and Rosenbaum, 2004). Footwear sizing systems that accurately take into account the shape of children's feet can improve comfort and stability (Mauch et al., 2009). Footwear and orthotic devices designed with children's foot shapes can prevent injuries during various physical activities and support proper development (Fritz and Mauch, 2013). To utilize three-dimensional foot shape data in the study of children's foot shape, researchers have also performed geometric capture accuracy assessment of 3D scanners (Farhan

et al., 2023), repeatability of 3D scans, and dimensional comparison (Hassan et al., 2020).

Research in adults indicates that body mass index (BMI) significantly affects foot shape and arch morphology. Higher BMI is associated with wider, flatter feet and increased footprint asymmetry (Domjanic et al., 2013). Obese and overweight individuals have significantly higher width of the midfoot than the heel region and lower arch angles in plantar foot shape compared to normal and underweight subjects, indicating a higher prevalence of flatfoot (Mallashetty et al., 2019). Additionally, Rosende-Bautista et al. (2021) reported positive correlations between BMI and arch index (Cavanagh and Rodgers, 1987). Similarly, several studies in children have reported that overweight and obese individuals tend to exhibit flatter feet and lower medial

* Corresponding author. Biosciences Group, University of Michigan Transportation Research Institute, 2901 Baxter Rd, Ann Arbor, MI, 48109, USA.

E-mail addresses: niceterran1986@gmail.com (H. Jung), keonpark@umich.edu (B.-K.D. Park), ebertshe@umich.edu (S.M. Ebert), mhaumann@umich.edu (M.L.H. Jones), mreed@umich.edu (M.P. Reed).

<https://doi.org/10.1016/j.apergo.2026.104741>

Received 31 May 2025; Received in revised form 20 January 2026; Accepted 22 January 2026

Available online 27 January 2026

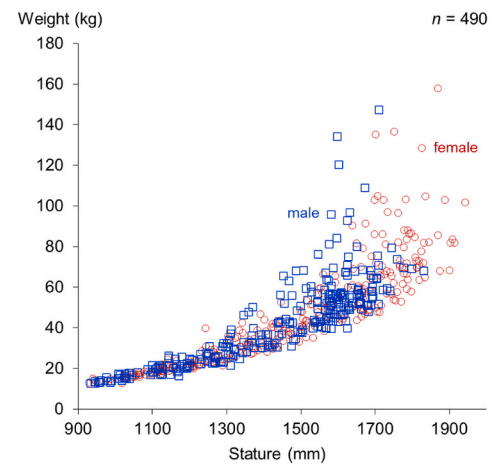
0003-6870/© 2026 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Table 1
Stature, BMI, foot dimensions of participants by age groups (mean, SD).

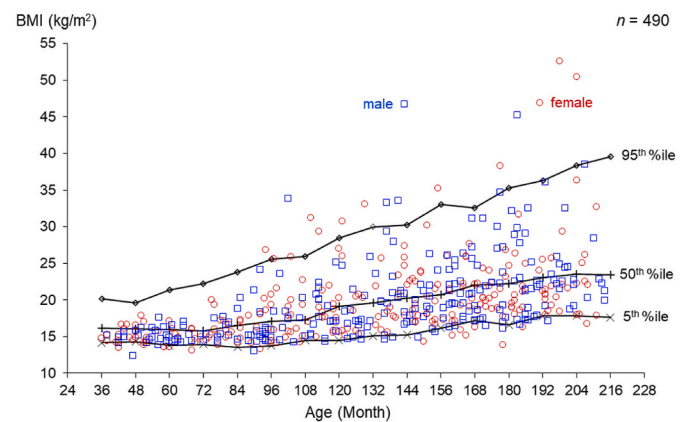
Age group	N	Stature (mm)	BMI (kg/m ²)	Foot length (mm)	Foot breadth (mm)
3–4	18	995.1 (44.5)	14.9 (1.1)	157.7 (9.6)	62.5 (4.4)
4–5	25	1074.2 (50.2)	15.3 (1.2)	169.0 (9.7)	69.6 (4.5)
5–6	24	1132.7 (52.6)	15.1 (1.1)	177.1 (11.7)	71.0 (4.2)
6–7	24	1190.4 (46.4)	16.0 (1.6)	188.3 (11.8)	73.0 (4.3)
7–8	37	1256.3 (62.5)	16.6 (2.9)	198.1 (13.5)	76.1 (4.2)
8–9	33	1337.4 (73.1)	18.4 (4.3)	209.3 (13.5)	80.8 (5.9)
9–10	34	1387.1 (63.0)	18.8 (3.9)	219.5 (17.2)	82.1 (5.0)
10–11	32	1462.0 (74.7)	19.3 (4.8)	229.0 (14.7)	84.8 (5.5)
11–12	37	1536.9 (77.0)	21.8 (6.4)	236.1 (21.0)	88.2 (6.8)
12–13	41	1566.6 (71.2)	20.1 (4.0)	238.9 (11.2)	87.8 (6.6)
13–14	44	1637.4 (87.6)	21.1 (3.9)	248.3 (16.7)	91.2 (5.4)
14–15	46	1670.3 (105.6)	21.5 (4.9)	247.4 (18.4)	91.9 (8.0)
15–16	42	1693.2 (102.9)	23.4 (6.8)	252.3 (18.7)	92.9 (7.5)
16–17	34	1705.5 (101.2)	23.5 (6.5)	252.7 (22.4)	93.6 (7.2)
17–18	19	1696.7 (91.9)	25.4 (8.6)	247.8 (16.1)	91.8 (6.5)

longitudinal arches, suggesting that excessive body weight may distort foot shape and contribute to deterioration of both longitudinal and transverse arches (Mauch et al., 2008; Villarroya et al., 2008; Puszczalska-Lizis and Ciosek, 2017). Follow-up studies further showed that arch-related measures decrease significantly with increasing BMI, with notable changes occurring when BMI reaches 21 kg/m² (Yan et al., 2023). However, other studies have suggested that the influence of BMI on foot shape in younger children may be less pronounced. Gijon-Nonogueron et al. (2016) reported that flat foot posture and shape are commonly observed in children under seven years of age as part of normal growth and development, and are less influenced by BMI. Likewise, Escalona-Marfil et al. (2023) found that waist circumference (WC) and midfoot width (MFW) were more strongly correlated with children's foot dimensions than BMI. Taken together, previous findings suggest that while BMI is a key factor influencing foot shape and arch morphology in adults, its role in children and adolescents remains unclear and may vary with age and analytical perspective. This inconsistency highlights the need to systematically examine whether BMI-related foot shape changes in children and adolescents follow patterns similar to those observed in adults, or whether age-specific characteristics exist, particularly when assessed using three-dimensional foot shape analysis.

Previous studies analyzing the associations between BMI and foot morphology have primarily focused on point-to-point measurements related to foot length, angles, and ratios of the plantar surface or medial arch height. Researchers have considered the negative impact of pediatric flatfoot on healthy foot development and aimed to propose simple methods for its early detection. Studies such as those by Aurichio et al. (2011), Domjanic et al. (2013), and Mallashetty et al. (2019) used ink footprints or three-dimensional (3D) scanning methods to quickly capture foot shapes and calculate arch indexes and arch angles to assess flatfoot. Bautista et al. (2021) reported a high correlation between medial longitudinal arch (MLA) height and BMI. Mauch et al. (2008) utilized 3D foot scan data of German children to classify foot types based on arch, circumference, and length, and analyzed the distribution of foot types according to weight. However, their analysis was limited to foot type classification and dimensional measures, and did not investigate how specific regions of the foot change in shape or geometry with increasing weight. Additionally, Lange et al. (2021) reported that the rate of increase of BMI in U.S. children aged 2–19 approximately doubled during the COVID-19 pandemic compared to the pre-pandemic period, suggesting that high BMI will be an increasingly important issue affecting US children. To address this gap, we used high-resolution three-dimensional surface measurement methods to capture the foot shape of a sample of U.S. children aged 3–17 years, developed a statistical foot shape model to quantify the variations in foot shape, and analyzed the effects of BMI and other covariates.



(a) Relation between stature (mm) and weight (kg) plot



(b) Relation between age (months) and BMI (kg/m²)

Fig. 1. Stature (mm) versus Weight (kg) and age (months) versus BMI (kg/m²) among the participants (blue square: males, red circle: females). Quantiles for the U.S. population based on Fryar et al. (2021) are shown for reference. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Method

2.1. Data acquisition

Surface scan data from 490 U.S. children (246 male and 244 female) ages 3–17 years were collected along with manually measured anthropometric data, and demographic information (Table 1). The stature range of the participants was 942 mm–1942 mm, and the body mass index (BMI) range was 11.9 kg/m² to 52.6 kg/m². Fig. 1 shows the stature and weight (kg) distribution and the age (month) and BMI (kg/m²) distribution of the participants. The 3D foot shape in the standing flat foot posture was captured with portable 3D hand scanner (Revopoint POP 3 Plus, Revopoint 3D, China). In this study, portable scanners were used to capture the foot shapes of children. To enhance measurement accuracy, trained experimenters conducted three-dimensional foot scans. The experimenters repeatedly scanned 3D-printed foot models established a protocol for three-dimensional scanning and ensured measurement stability. Foot shape scans were performed more than three times, and the scan data suitable for analysis were selected after review by the examiner. The foot scan data were processed using manual and automated methods to obtain high-quality foot shape 3D images including detailed toe shape. The children stood on an elevated, transparent platform to allow scanning of both the dorsal and plantar surfaces. Children stood upright with weight approximately evenly

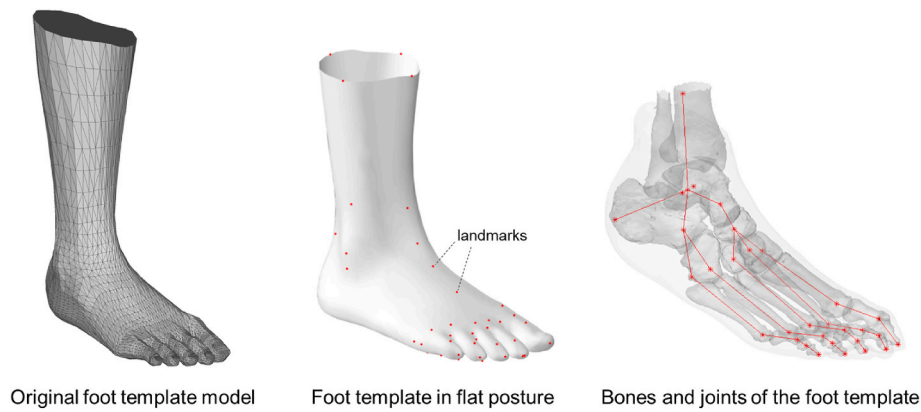


Fig. 2. Foot template in flat posture (original template, mean template, bones and joints).

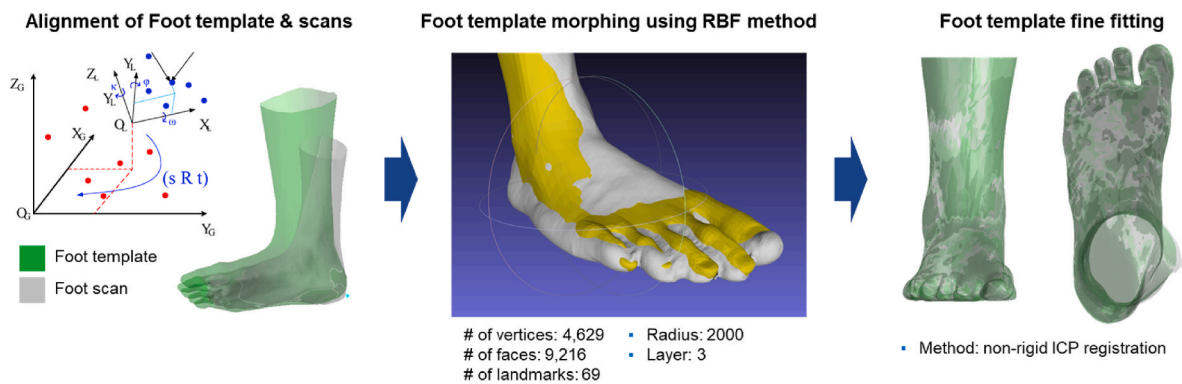


Fig. 3. Foot template fitting process using radial basis function interpolation (RBF) and non-rigid iterative closest point (ICP) methods.

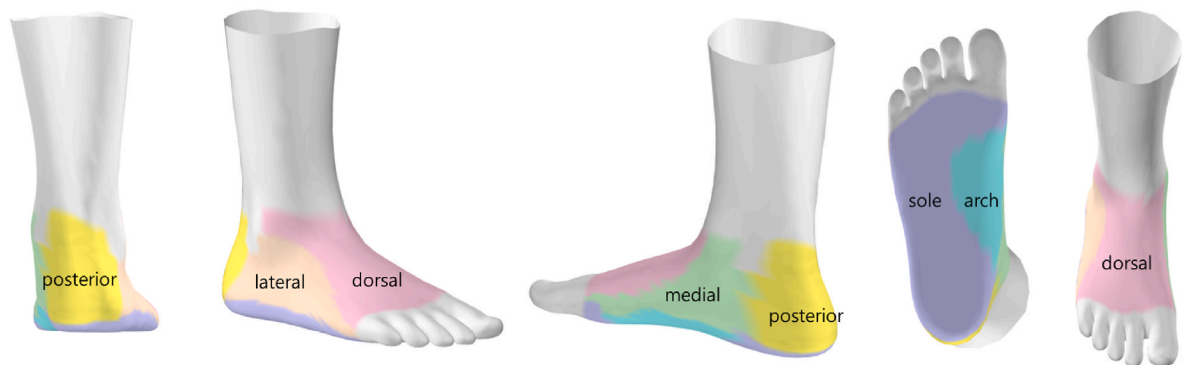


Fig. 4. Surface segmentation of the foot template.

distributed between their left and right feet. This study was approved by the Institutional Review Board (IRB) of the University of Michigan (HUM00231054).

2.2. Data standardization

To generate a structured foot scan dataset, a foot template model developed in a preliminary study (Jung et al., 2024) was used for standardization of the raw foot 3D scans. The foot template model consists of a surface mesh (4,789 vertices, 9,536 faces), 32 joints, 28 links, and 69 landmarks (Fig. 2). The foot template fitting was conducted using radial basis function (RBF) and non-rigid iterative closest point (ICP) methods (Fig. 3). For purposes of shape analysis, the foot was divided into seven surface regions (Fig. 4).

2.3. Foot dimensions

Although the primary emphasis of the current work is on foot shape, linear dimensions and angles defined in prior studies related to BMI were computed for comparison with prior work (Mauch et al., 2008; Barisch-Fritz et al., 2014; Hassan et al., 2020; Wang et al., 2021; Williams and McClay, 2000). Table 2 and Fig. 5 list the dimensions and sources.

2.4. Statistical analysis

Shape variability of the standardized foot meshes was analyzed using a principal component analysis. 60 principal components (PCs) were retained to represent the foot shape variation. A regression model was built to associate PC scores with anthropometric characteristics of in-

Table 2
Foot dimensions and definitions (Mauch et al., 2008; Barisch-Fritz et al., 2014; Hassan et al., 2020; Wang et al., 2021; Williams and McClay, 2000).

Foot dimension	Definition
Foot length (FL, FE-FT1)	Distance between foot end (FE; heel) and foot tip (FT: anterior point of the most protruding toe) along the medial tangent of the foot across point B1 and point Hm
Ball-of-foot width (BFW, B1-B5)	Distance between the first and fifth metatarsophalangeal protrusions (MTP; B1, B5)
Ball circumference (BC, B1-B5)	Maximum circumference over the first (B1) and fifth MTP joint protrusion (B5)
Plantar arch width (PAW)	Narrowest section of the plantar medial longitudinal arch (AW1-AW2), used for the indices CSI and SI
Heel width (HW, HW1-HW2)	Widest part of the heel (plantar print; HW1-HW2) parallel to the ball line (B1-B5)
Ball angle (BA)	Angle between the horizontal (90 to foot measuring line) and diagonal ball line (B1-B5) in B1
Arch angle (AA)	Angle between line connecting the first MTP joint (B1) and the medial heel (Hm) with a second line drawn to the apex of the medial longitudinal arch concavity (AP)
Dorsal arch height (DAH, DA1-DA2)	Height of medial dorsal junction of the foot and leg to the floor
Medial longitudinal arch/Navicular height (MLAH)	Floor to the most anterior-inferior portion of the navicular bone
CSI (Chippaux-Smirak-Index, %)	Ratio between plantar arch width (AW1-AW2) and ball-of-foot width (B1-B2), BFW/PAW
SI (Staheli-Index, %)	Ratio between plantar arch width (AW1-AW2) and heel width (HW1-HW2), HW/PAW
Area (AR, mm ²)	Area inside the section outline extracted from planes (P1: the plane for measuring ball-of-foot circumference, P2: a plane parallel to the prior plane crossing the medial dorsal junction point (DA2), P3: a transverse plane at the midpoint height of the lateral and medial malleolus, P4: a transverse plane with 2 mm offset from the ground)
Volume (VL, mm ³)	Volume of the foot under the upper marginal plane (P3)

terest. In the current study, foot length and body mass index (BMI) were used as independent variables to analyze their respective impacts on foot shape. Because age and foot length are strongly correlated in this cohort, a relative foot length measure was computed by subtracting off the median foot length for each one-year age cohort. Two-way interactions between prediction variables were included in the model. The PC scores of a certain foot shape are given by

$$y = \beta_0 + \beta_1 \cdot \text{foot length} + \beta_2 \cdot \text{BMI} + \beta_3 \cdot (\text{foot length} \times \text{BMI}) \quad (1)$$

where $y = [y_1, y_2, \dots, y_{60}]$ is resulting PC score vector,

β_0 is the intercept,

$\beta_1, \beta_2,$ and β_3 are the coefficients for each term.

The vertex coordinates of a foot shape are computed from the PC scores, y , given by

$$v^T = \bar{v}^T + My \quad (2)$$

where v^T is vertices coordinate vector,

\bar{v}^T is the mean foot shape vector,

M is principal component coefficient matrix

Because the distribution of BMI varies with age, quantiles of BMI by age were used to visualize the effects of BMI. To improve the clarity of presentation, the analysis focused on ages 4, 10, and 17 years. Quantiles of BMI by age for the U.S. population were obtained from the Fryar et al. (2021) summaries of the U.S. National Health and Nutrition Examination Survey (NHANES) data for the years 2015–2018 (the latest available). For example, 5th, 50th, and 95th percentile BMI are respectively 14.3, 16.1, and 19.5 kg/m² for 4-year-old children and 17.8, 23.5, and 38.3 kg/m² for 17-year-old children. To measure the foot volume, the foot-shaped mesh produced by the regression model was segmented at the ankle area using the upper margin plane (P4) with midpoint height between medial and lateral malleolus and transformed into a closed mesh by filling the split area. The volume of the foot mesh, segmented by the ankle boundary for each condition, was measured using CAD software (Rhinoceros 7, Robert McNeel & Associates, TLM, Inc.).

3. Results

From the 3D foot shapes reconstructed using the regression model, foot dimensions such as foot length and ball-of-foot width were extracted (Table 3) and the variations in foot shape were compared (Fig. 6). Foot shape variations associated with higher BMI are more pronounced in 10- and 17-year-olds compared to 4-year-olds, especially with enhanced foot flattening, especially with larger foot width, circumference, and smaller arch height. As shown in Table 3, in 4-year-old children, the BMI differences between the 5th percentile (14.3 kg/m²) and the 95th percentile (19.5 kg/m²) resulted in foot dimension differences of 6.4 % in ball-of-foot width (BFW), 7 % in ball-of-foot circumference (BC), 13.1 % in heel width (HW), 7.6 % in dorsal arch height (DAH), 8.4 % in medial longitudinal arch height (MLAH), and 12.1 % in the Staheli-index (SI). For 10-year-old and 17-year-old children, higher BMI was linked to greater values in BFW (10.1 %–11.4 %), BC (7.0 %–8.9 %), plantar arch width (PAW; 26.4 %–78.0 %), HW (11.2 %–29.2 %), and ball angle (BA; 6.1 %–10.7 %), while resulting in lower values for arch angle (AA; 7.9 %–17.9 %), MLAH (1.3 %–11.7 %),

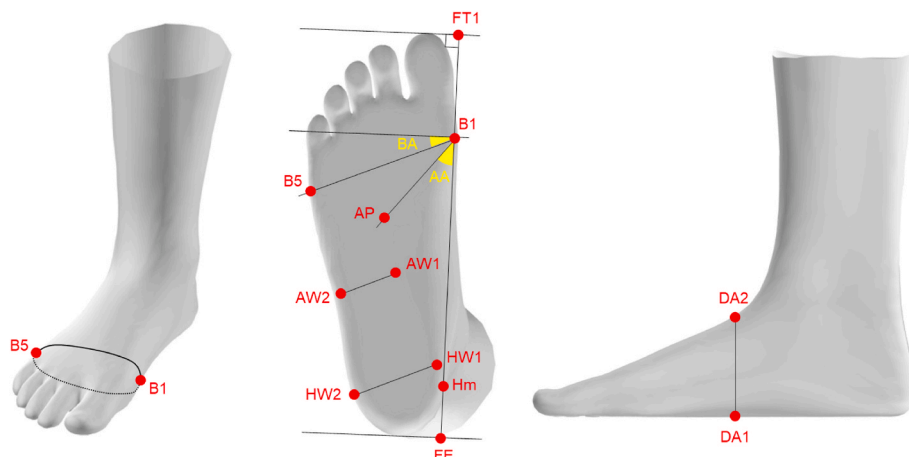


Fig. 5. Foot dimensions with landmarks and reference lines.

Table 3
Foot dimensions by age and BMI level.

Demographic information			Foot dimensions																
Age (year)	Foot length (mm)	BMI %ile	BMI (kg/m ²)	FL (mm)	BFW (mm)	BC (mm)	PAW (mm)	HW (mm)	BA (deg.)	AA (deg.)	DAH (mm)	MLAH (mm)	CSI (%)	SI (%)	AR-P1 (mm ²)	AR-P2 (mm ²)	AR-P3 (mm ²)	AR-P4 (mm ²)	VL (mm ³)
4	169	5th	14.3	171	67	168	39	37	38.6	17.9	46	19	1.69	0.94	1,591	2,122	2,452	6,512	257,936
4	169	50th – 2 ^a	14.1	170	66	167	39	37	38.5	17.8	45	19	1.69	0.94	1,562	2,053	2,487	6,481	256,675
4	169	50th	16.1	172	68	172	38	38	38.7	18.1	47	19	1.77	0.98	1,738	2,195	2,572	6,665	273,434
4	169	50th + 2	18.1	174	69	191	39	41	38.9	18.3	48	20	1.78	1.05	1,809	2,372	2,805	6,873	291,806
4	169	95th	19.5	176	71	180	40	42	39.0	18.5	49	20	1.78	1.05	1,885	2,449	2,817	6,947	305,179
10	229	5th	14.5	230	84	218	35	43	37.3	20.1	61	28	2.37	1.21	2,479	3,276	3,611	9,681	544,661
10	229	50th – 2	17.1	232	85	218	36	43	37.7	19.7	61	28	2.34	1.19	2,585	3,480	3,973	9,984	569,238
10	229	50th	19.1	232	86	224	37	44	38	19.5	62	28	2.31	1.18	2,678	3,497	4,003	10,267	587,313
10	229	50th + 2	21.1	232	88	234	38	45	38.4	19.3	62	28	2.28	1.17	2,912	3,787	4,359	10,489	607,077
10	229	95th	28.4	235	92	237	45	47	39.6	18.5	64	27	2.07	1.07	3,185	4,209	4,850	11,434	677,636
17	257	5th	17.8	258	93	245	35	45	37.5	20.1	68	31	2.64	1.26	3,042	4,311	4,532	11,797	756,178
17	257	50th – 2	21.5	258	95	253	42	49	38.2	19.4	68	31	2.29	1.18	3,276	4,470	4,930	12,301	788,327
17	257	50th	23.5	258	96	256	43	50	38.6	19.1	68	30	2.25	1.16	3,374	4,607	5,077	12,605	804,566
17	257	50th + 2	25.5	258	97	261	46	50	38.9	18.7	68	30	2.09	1.08	3,417	4,662	5,419	12,906	823,618
17	257	95th	38.3	260	104	263	63	58	41.5	16.5	68	28	1.65	0.92	4,067	5,321	6,695	14,834	929,143

^a Indicates the median BMI for the age cohort ± 2 kg/m². These lines show the effects per unit of BMI.

Chippaux-Smirak-index (CSI; 12.9 %–37.5 %), and SI (12.0 %–27.4 %). Across all ages, a higher BMI correlated with larger overall width, circumference, and thickness, but with a smaller arch height. Overall, the differences in foot dimensions due to BMI levels were most pronounced in 17-year-olds, followed by 10-year-olds, and least in 4-year-olds. Specifically, the average differences in foot dimensions were 21.1 % for 17-year-olds, 9.5 % for 10-year-olds, and 6.2 % for 4-year-olds.

As shown in Figs. 6–8, variations in foot morphology associated with BMI are evident in the overall size of the foot, with high deviations in the lateral, medial, arch, dorsal, and sole areas. Comparison of mesh vertex positions across different BMI levels revealed that the lateral, medial, arch, sole, and dorsal regions exhibited relatively large differences, while the posterior and toe regions showed smaller differences. Foot shape differences due to BMI varied by age, showing more substantial changes of 41 % and 36 % in the 10- and 17-year age groups, respectively, compared to the 4-year-old age group. In 17-year-olds, higher BMI was linked to average positional differences of approximately 10–12 mm in the lateral and medial regions, 11 mm in the arch region, and 11 mm in the dorsal region. For 10-year-olds, differences between higher BMI (95th percentile) and lower BMI (5th percentile) were also notable, with average differences of 8 mm in the lateral region, 7 mm in the medial and arch regions, and 9 mm in the dorsal region. In 4-year-olds, similar positional discrepancies of approximately 4 mm on average were observed across all foot regions across the range of BMI levels.

Variations in BMI affect the volume and cross-sectional area of various regions of children's feet, with the most pronounced differences occurring as BMI moves from the 50th to the 95th percentile, particularly in the forefoot, midfoot, ankle intersection, and sole surfaces (Fig. 8). At age 10, the total volume and forefoot cross-sectional area (AR-P1) showed differences of 24.4 % and 28.5 %, respectively, as BMI shifted from the 5th to the 95th percentile. For ages 17 and 4, the volume differences were 22.9 % and 18.3 %, respectively, while the forefoot area differences were 15.4 % and 23.4 %. The cross-sectional areas of the midfoot (AR-P2), upper foot boundary (AR-P3), and sole (AR-P4) differed by 14.9 %–47.7 %, 18.5 %–33.7 %, and 6.7 %–25.7 %, respectively, with changes in BMI. These differences in cross-sectional area were more pronounced when comparing the BMI between the 50th and 95th percentiles than between the 5th and 50th percentiles.

4. Discussion

Through regression analysis, variations in foot shape and dimensions associated with BMI levels were quantified. Children with higher BMI had larger foot width, greater circumference, and broader thickness, as well as the larger cross-sectional area and volume. Higher BMI was associated with a reduced arch height and more pronounced flatfoot tendencies. In addition, differences in cross-sectional area and contour shape of each area of the foot region were identified based on BMI levels. The vertices in the medial and lateral sides, arch, and dorsal regions were positioned farther outward compared to the posterior and toe regions under higher BMI conditions. The foot shape model for U.S. children developed in this study is currently shared online at <https://HumanShape.org/ChildFoot>.

Previous studies (Aurichio et al., 2011; Domjanic et al., 2013; Escalona-Marfil et al., 2023; Mallashetty et al., 2019; Mauch et al., 2008) have focused on the quantitative evaluation of arch shapes based on the plantar surface foot shape to prevent flatfoot during the development of children's feet. For example, prior research has assessed flatfoot progression by obtaining the plantar cross-sectional shape of a foot and using indicators like plantar arch width, heel width, mid foot width (MFW), CSI, and SI. In contrast, the present study used foot template models and statistical analysis to understand the overall shape changes of children's feet as BMI varies. In addition to measuring foot-related dimensions to confirm flatfoot, this study analyzed the

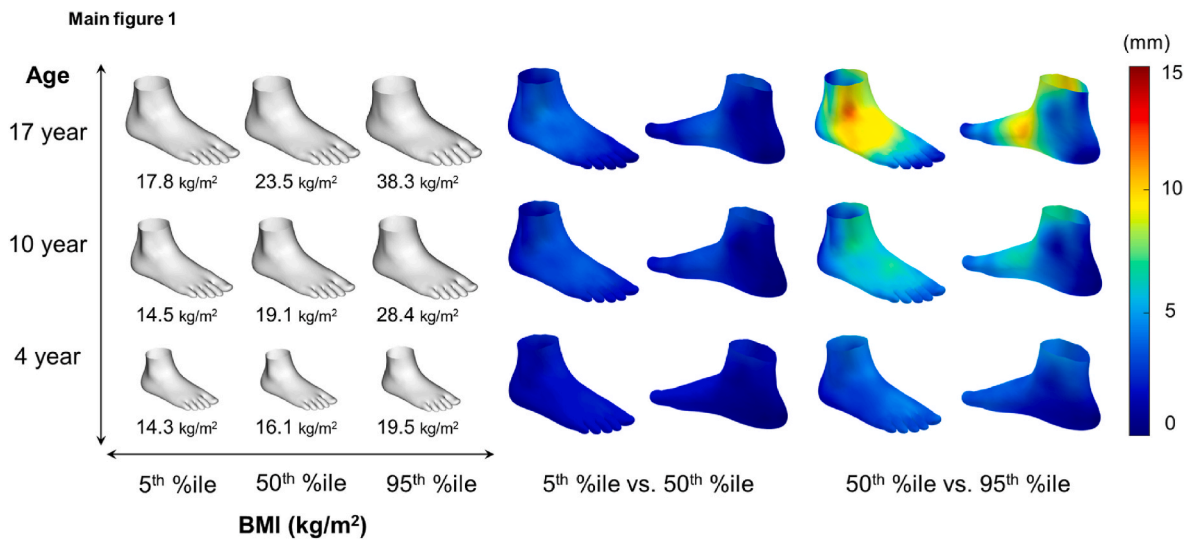


Fig. 6. Comparison of the children's foot shape by age and BMI. The heat maps show that the differences between median and 95th percentile BMI were much higher than the differences between 5th percentile and median BMI, differences were larger for older children, and the differences were concentrated in the dorsal and anterior ankle area.

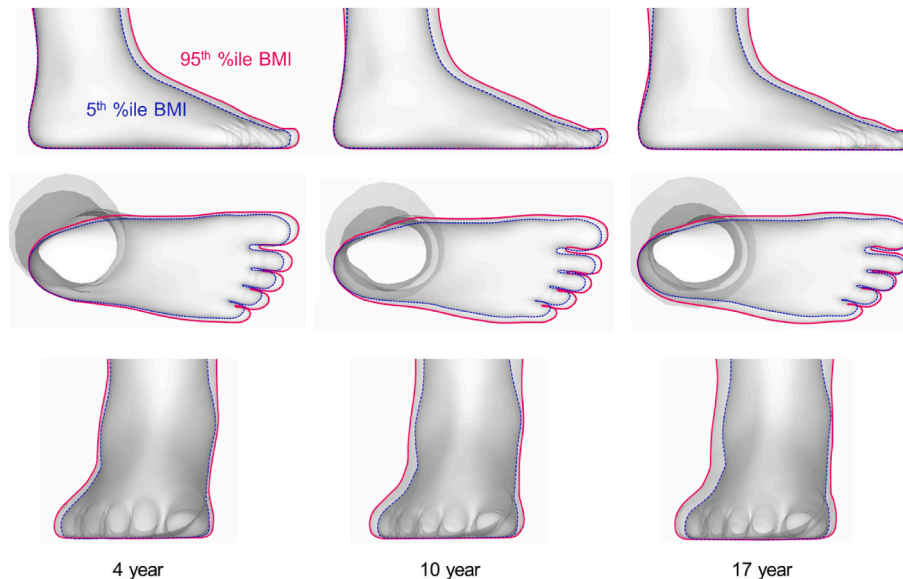


Fig. 7. Comparison of outer contour shape of the feet by age and BMI: 5th percentile vs. 95th percentile.

degree of shape deformation by foot region, the direction vectors of shape deformation, and the changes in cross-sectional area and volume, thereby providing a three-dimensional explanation of foot shape differences.

The development of a three-dimensional foot model may provide opportunities to enhance the design and customization of footwear by accurately representing children's foot shapes and allowing for demographic-based shape estimation. However, the model has some limitations that affect its applicability to shoe design. First, the foot shape was measured on a flat, rigid surface, whereas insole contours in shoes intended to provide good support may change the shape of the foot. Second, the difference in foot shape between the measurement condition and realistic in-shoe conditions may interact with and age. For example, the effects of good insole contours on foot shape may be larger for older individuals and those with higher BMI for their age, based on the observed tendency toward flat foot in individuals with higher BMI. Consequently, care must be exercised in interpreting these results for

shoe design, and future work should aim to study the differential effects of insole design on individuals with a range of BMI. Nonetheless, the findings provide quantitative justification for increased attention to the suitability of current shoe designs for the growing number of high-BMI children and youth.

The model can also be used to make accurate measurements from relatively low-quality foot scans, potentially enabling wider availability of custom footwear and orthotics. The post-processed 3D data of children's foot shapes ensure the inclusion of toe shapes, crotch shapes, and overall foot regions. Therefore, even in cases where some foot shapes are missing or detailed shapes are not obtained, the shape space of the foot model developed in this study can be referenced to estimate a 3D foot shape close to the actual foot shape, supplementing the original data. This foot shape model, which includes demographic information such as foot length, foot width, height, weight, and gender, can also be utilized for estimating foot shapes based on demographic inputs.

This study had additional limitations that could be addressed in

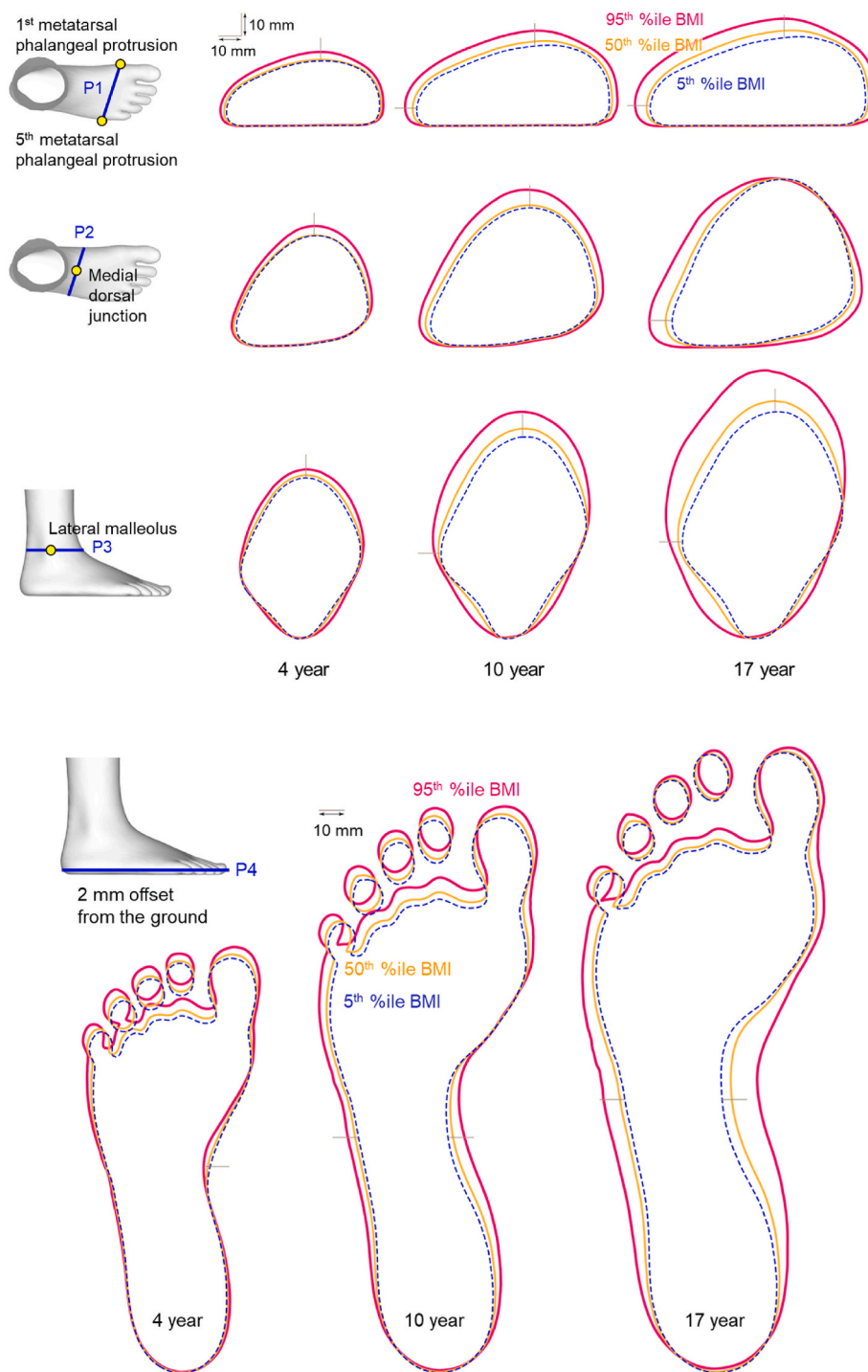


Fig. 8. Comparison of cross-sectional contour shapes of the feet by cutting planes according to age and BMI.

future research. Most importantly, a larger population of children with high BMI would enhance the ability of the model to represent the range of foot shapes. Although this study collected children's foot data with a wide BMI distribution, there was a relative scarcity of high BMI participants aged 3–9 compared to older children (10 years and older). Understanding the foot shapes and deformations during walking or running could be valuable in developing supportive devices or shoes to promote a balanced gait. The model developed in this work is also linear in the age and BMI parameters, although we have addressed BMI-for-age explicitly. BMI effects may be nonlinear, and that nonlinearity may change with age, in ways that the current data do not show. A larger

dataset would be needed to investigate these effects.

5. Conclusion

This study developed a high-resolution statistical foot shape model for U.S. children by integrating a foot template model with 3D foot scans. Our research provided valuable insights into how the Body Mass Index (BMI) influences the three-dimensional shape of children's feet. Through principal component analysis and regression models, we quantified the variations in foot shape and dimensions associated with varying BMI levels. The results indicated that as BMI increases, there are

enlargements in foot width, circumference, and thickness, along with increases in cross-sectional area and volume. Moreover, higher BMI levels were linked to lower arch height, signifying a tendency towards flatter feet. Notably, the study demonstrated that foot shape differences due to BMI levels are more prominent in older children, particularly those aged 10 and 17, with discrepancies being the least in younger children aged 4. Furthermore, variations in foot shape by BMI levels within the same age group exhibited greater differences when comparing the 50th percentile to the 95th percentile than when comparing the 5th percentile to the 50th percentile. Of course this is due to the skewed nature of the BMI distributions, but, since the important secular trends in BMI affect primarily the upper percentiles, these findings underscore the importance of considering BMI when designing children's footwear and orthotic devices to ensure they provide appropriate support and accommodate changes in foot morphology.

CRedit authorship contribution statement

Hayoung Jung: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Byoung-Keon D. Park:** Writing – review & editing, Writing – original draft, Methodology. **Sheila M. Ebert:** Writing – review & editing, Investigation, Data curation. **Monica L.H. Jones:** Writing – review & editing, Writing – original draft. **Matthew P. Reed:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Data availability statement (DAS)

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request. The children's foot model generated during the current study is publicly available at <https://HumanShape.org/ChildFoot>.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the participants and their caregivers for their contributions. We are grateful to the many staff who gathered and processed data for the study. This research was financially supported by Reality Labs Research, a division of Meta.

References

Aurichio, T.R., Rebelatto, J.R., de Castro, N., 2011. The relationship between the body mass index (BMI) and foot posture in elderly people. *Archives of Gerontology and Geriatrics* 52 (2), e89–e92. <https://doi.org/10.1016/j.archger.2010.06.014>.

- Cavanagh, P.R., Rodgers, M.M., 1987. The arch index: a useful measure from footprints. *J. Biomech.* 20 (6), 547–551. [https://doi.org/10.1016/0021-9290\(87\)90255-7](https://doi.org/10.1016/0021-9290(87)90255-7).
- Domjanic, J., Fieder, M., Seidler, H., Mitteroecker, P., 2013. Geometric morphometric footprint analysis of young women. *J. Foot Ankle Res.* 6, 27. <https://doi.org/10.1186/1757-1146-6-27>.
- Escalona-Marfil, C., Prats-Puig, A., Ortas-Deunosajut, X., Font-Lladó, R., Ruiz-Tarrazo, X., Evans, A.M., 2023. Children's foot parameters and basic anthropometry - do arch height and midfoot width change? *Eur. J. Pediatr.* 182 (2), 777–784. <https://doi.org/10.1007/s00431-022-04715-1>.
- Farhan, M., Wang, J.Z., Lillia, J., Cheng, T.L., Burns, J., 2023. Comparison of multiple 3D scanners to capture foot, ankle, and lower leg morphology. *Prosthet. Orthot. Int.* 47 (6), 625–632, 2023.
- Fritz, B., Mauch, M., 2013. "3-Foot development in childhood and adolescence. In: Woodhead Publishing Series in Textiles" *Handbook of Footwear Design and Manufacture*. Woodhead Publishing.
- Fryar, C.D., Carroll, M.D., Gu, Q., Afful, J., Ogden, C.L., 2021. Anthropometric reference data for children and adults: united States, 2015–2018. *National Center for Health Statistics, Vital Health Stat* 3 (46).
- Gijon-Noguero, G., Montes-Alguacil, J., Martínez-Nova, A., Alfageme-García, P., Cervera-Marin, J.A., Morales-Asencio, J.M., 2016. Overweight, obesity and foot posture in children: a cross-sectional study. *J. Paediatr. Child Health* 53 (1), 1–96. <https://doi.org/10.1111/jpc.13314>.
- Hassan, N.M., Buldt, A.K., Shields, N., Landorf, K.B., Menz, H.B., Munteanu, S.E., 2020. Reproducibility of foot dimensions measured from 3-dimensional foot scans in children and adolescents with Down syndrome. *J. Foot Ankle Res.* 13 (1), 31.
- Jung, H., Park, B.-K.D., Ebert, S.M., Jones, M.L.H., Reed, M.P., 2024. Development of a foot shape model for U.S. children in flat and toe-off postures. In: *Proceedings of the 22th Triennial Congress of the International Ergonomics*. Jeju, Korea.
- Lange, S., Kompaniyets, L., Freedman, D., Kraus, E.M., Porter, R.M., Blanck, H., Goodman, A.B., 2021. Longitudinal trends in body mass index before and during the COVID-19 pandemic among persons aged 2–19 years — united States, 2018–2020. *MMWR. Morbidity Mortality Weekly Rep.* <https://doi.org/10.15585/mmwr.mm7037a3>.
- Mallashetty, N., Itagi, V., M, V.N., 2019. Effect of body weight on arches of foot—a correlative study between BMI and arch index. *Int. J. Anat. Res.* 7 (3.2), 6877–6881. <https://doi.org/10.16965/ijar.2019.248>.
- Mauch, M., Grau, S., Krauss, I., Maiwald, C., Horstmann, T., 2008. Foot morphology of normal, underweight and overweight children. *Int. J. Obes.* 32, 1068–1075. <https://doi.org/10.1038/ijo.2008.52>.
- Mauch, M., Grau, S., Krauss, I., Maiwald, C., Horstmann, T., 2009. A new approach to children's footwear based on foot type classification. *Ergonomics* 52 (8), 999–1008. <https://doi.org/10.1080/00140130902803549>.
- Puszczalowska-Lizis, E., Ciosek, J., 2017. Foot shape and its relationship with somatic characteristics in pre-school children. *Medical Studies/Studia Medyczne* 33 (3), 214–221. <https://doi.org/10.5114/ms.2017.70348>.
- Rosende-Bautista, C., Munuera-Martínez, P.V., Seoane-Pillado, T., Reina-Bueno, M., Alonso-Tajes, F., Pérez-García, S., Domínguez-Maldonado, G., 2021. Relationship of body mass index and footprint morphology to the actual height of the medial longitudinal arch of the foot. *Int. J. Environ. Res. Publ. Health* 18 (18), 9815. <https://doi.org/10.3390/ijerph18189815>.
- Unger, H., Rosenbaum, D., 2004. Gender-specific differences of the foot during the first year of walking. *Foot Ankle Int.* 25 (8), 582–587.
- Villarroya, M.A., Esquivel, J.M., Tomaas, C., Buenafee, A., Moreno, L., 2008. Foot structure in overweight and obese children. *Int. J. Pediatr. Obes.* 3, 39–45. <https://doi.org/10.1080/17477160701520298>.
- Wang, J., Tang, L., Tang, J., Chen, J., Gong, X., Qin, L., Huang, J., Deng, Y., Liu, X., Hwang, W., Li, M., Hu, N., 2021. The typically developing pediatric foot — The data of the 1744 children in China. *Foot and Ankle Surgery* 27 (5), 534–544. <https://doi.org/10.1016/j.fas.2021.04.005>.
- Williams, D.S., McClay, I.S., 2000. Measurements used to characterize the foot and the medial longitudinal arch: Reliability and validity. *Physical Therapy* 80 (9), 864–871. <https://doi.org/10.1093/ptj/80.9.864>.
- Yan, S., Zhao, Y., Zhang, L., Yang, L., 2023. Arch-Related alteration in foot loading patterns affected by the increasing extent of body mass index in children: a Follow-Up study. *Gait Posture* 100, 247–253. <https://doi.org/10.1016/j.gaitpost.2022.12.019>.