UNDERSTANDING THE ROLE OF ETHNICITY, AGE, SEX AND OBESITY ON FOOT MORPHOLOGY: A SYSTEMATIC REVIEW

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ABSTRACT

The morphology of the human foot varies considerably due to the combined effects of heredity, culture, lifestyle, nutrition and climatic factors, and these have anthropological, clinical and forensic importance. The shape of the foot has been of great interest to numerous authors because of its variability and its importance from both the morphological and functional points of view. Foot morphology determines the size and shape of feet or footprints and thereby makes them unique data to establish human identity. This review study is an attempt to explore the variation in human foot morphology in different ethnic populations as well as the effect of age, sex and obesity on the morphology of the human foot. The database was searched from June 2021 to December 2021 using Google Scholar, ResearchGate and PubMed employing unique and specific combinations of keywords, such as ethnic differences, foot anthropometry, foot dimensions, foot morphology, footprints, gender differences in foot dimension, sexual dimorphism in foot anthropometry, foot shape, obesity and foot morphology, and the effect of age on foot morphology. A total of 55 studies were retrieved covering the years from 1975 to 2020. Literature revealed that foot morphological characteristics vary among different ethnic groups and also exhibit sexual dimorphism and reflect specific characteristics at different ages of life. Obesity was found to have a significant impact on selected foot morphological parameters. Studies on quantitative variations in foot morphology from the anthropological point of view in the Indian context are limited, and,

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therefore, similar studies should be instigated among different ethnic groups living in different parts of India.

Keywords: *foot anthropometry; foot dimensions; foot morphology; footprints; foot shape; obesity; sexual dimorphism*

INTRODUCTION

Every foot is unique in terms of morphology, shape and proportions. No two people possess the same foot and footprint. Even identical twins do not make identical footprints [1, 52, 62, 90].

The morphology of the human foot varies greatly due to the combined effects of heredity, ethnicity, geographical locations, lifestyle (e.g. body weight, shoe-wearing habits), climatic factors, nutritional factors and physical activities. This makes foot individualistic to a person and, thereby, provides unique data to establish human identity, which has clinical, forensic and anthropological implications [2, 3, 4, 42, 53, 61, 68, 75, 95, 96].

Anthropometric data are vital for product design and development in global markets, since they are a necessary element in generating standardized sizing. Appropriate use of anthropometric measures has the potential to improve well-being, health, comfort and safety; particularly in footwear design [14, 81]. Foot anthropometry is the measurement of the size and proportion of the foot [71]. Foot morphology determines the size and shape of feet and footprints since, in addition to genetic inheritance, foot anthropometry greatly varies due to ethnicity, culture, environment, socio-economic development and daily habits [5–7,15]. The shape of the foot has also been of great interest to numerous authors due to its variability and importance from both the morphological and functional points of view [18]. The information on footprint (and foot) morphology is especially significant because it elucidates the individuality of each person [45, 67]. Quantitative analysis of foot anthropometry is also important to the study of ergonomics, orthotics design, forensic science and anthropology [16, 21, 33, 71, 79, 80, 87] as the human foot has structurally and functionally evolved and developed to be one of the most remarkable modifications in human evolution and is the only part of the body which is in direct contact with the ground [55, 83]. Furthermore, the length and shape of the foot have changed with evolution, adapting to the upright posture of man and the change in the manner of weight bearing [99]. Thus, the foot, in particular, has proven itself to be a significant organ of the human body and has academic relevance [9]. Therefore, due to large individual differences in foot morphology, it is necessary to collect foot dimensions and analyse the characteristics of the foot shape of different sexes and ethnic groups [39, 56, 57].

The objective of the present review study is to comprehend the existing literature on foot morphology among adult populations of the world based on their unique anthropometric features. It is also an attempt to ascertain the variation in human foot morphology in different ethnic populations as well as to understand the effect of age, sex and obesity on the morphology of the human foot.

MATERIAL AND METHODS

The database was searched for articles from June 2021 to December 2021. The present review has been conducted using Google Scholar, ResearchGate and PubMed search engines employing unique and specific combinations of keywords such as foot anthropometry, foot dimensions, foot morphology, footprints, ethnic differences in foot morphology, gender differences in foot dimension, sexual dimorphism in foot anthropometry, foot shape, obesity and foot morphology, and the effect of age on foot morphology.

The articles were screened based on specific inclusion and exclusion criteria. Foot morphology-related publications in peer-reviewed journals were evaluated. The present review includes articles published from 1975 to 2020. The present study was an endeavour to understand the foot morphology of adults among different ethnic populations. Articles not written in English, book chapters, letter-to-the-editor formats and review papers were eliminated. Additionally, articles with objectives not aligning with the aim of the present study and incomprehensible methodologies were also eliminated.

The article retrieval approach yielded a total of 436 records. The final elimination phase yielded 36 records which included full-length publications on foot morphology in adult populations in different ethnic groups. Record retrieval, inclusion and exclusion as per PRISMA 2020 template for systematic reviews has been represented using a flow diagram (Figure 1). Furthermore, the reference lists of included records were manually searched to identify prospective articles for cross-referencing which were then referenced in the present review. Finally, 55 records were merged in the present report integrating database entries and cross-referencing. Since the purpose of the present review report is to understand how the four major factors, i.e., ethnicity, age, sex, and obesity shape foot morphology, the retrieved full-length articles were further assessed and then classified into four categories, i.e., 1. Ethnicity, 2. Age, 3. Sexual dimorphism,

4. Obesity. Articles that addressed more than one major factor were assigned to multiple categories at the same time. Therefore, the categories assigned to each of the included articles were not mutually exclusive.

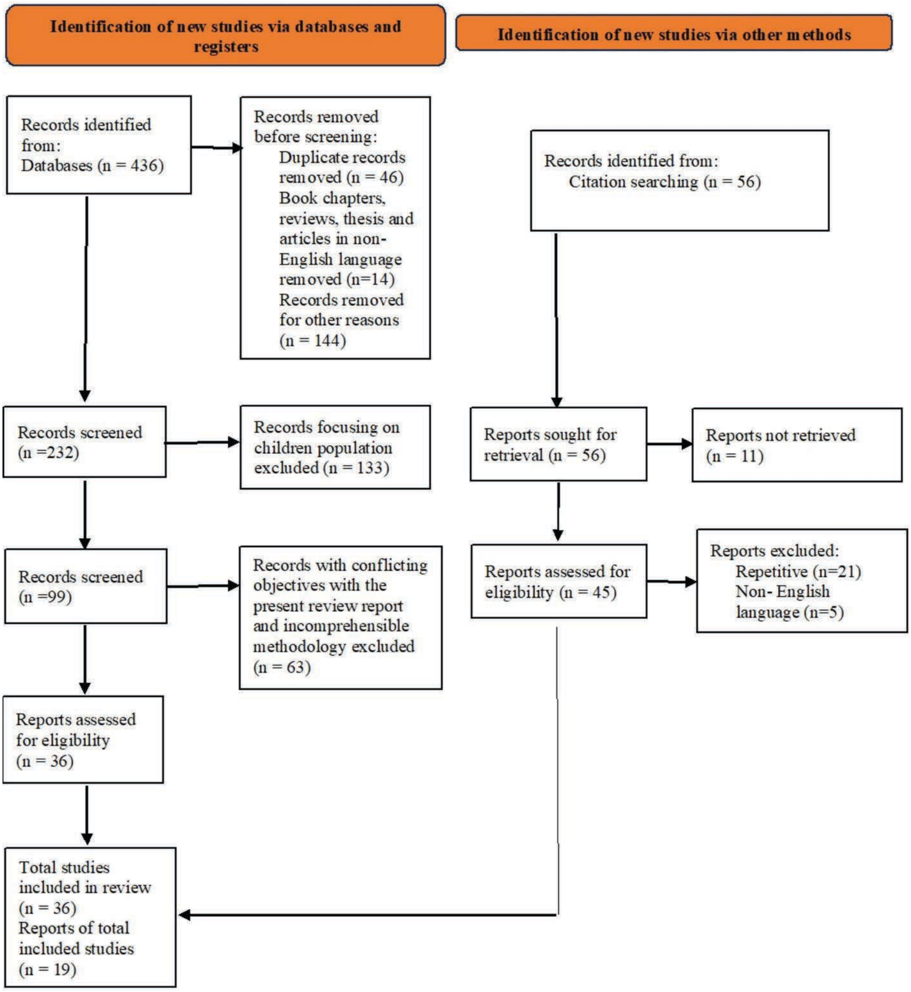


Figure 1. Flow diagram of record retrieval, inclusion and exclusion as per PRISMA 2020 template for systematic reviews.

Litmaps, a recent AI-based technology, was used to identify links between the articles. It uses connecting lines that trace the citations of the articles (Figure 2). It analysed the bibliography using seed paper and overlapping maps which aided in understanding how articles fit together and also highlighted how articles cite each other over time [47]. Initially, DOIs from 41 publications, PubMed IDs from 5 publications, and titles from 9 publications were added to the online software's "visualise" option. Litmaps was unable to locate 3 articles with DOIs in their database. Later, the titles of the unresolved articles were provided to the software because no IDs for those articles were available. Finally, those articles were identified in their database by their titles, and a map featuring 55 articles was generated. The x-axis was set to "publication date," and the y-axis was set to "citations" which assisted in understanding the growth of publications over time, the distribution of citation counts, and trends in citation growth over time. When the publication date option was selected, a linear arrangement of relevant articles was displayed, with older articles on the left and recent papers on the right. The size of the node was related to the momentum that was calculated by the software based on "Cited by count", i.e., log of the citation count and weighed by recency, thus articles with more citations had larger circles.

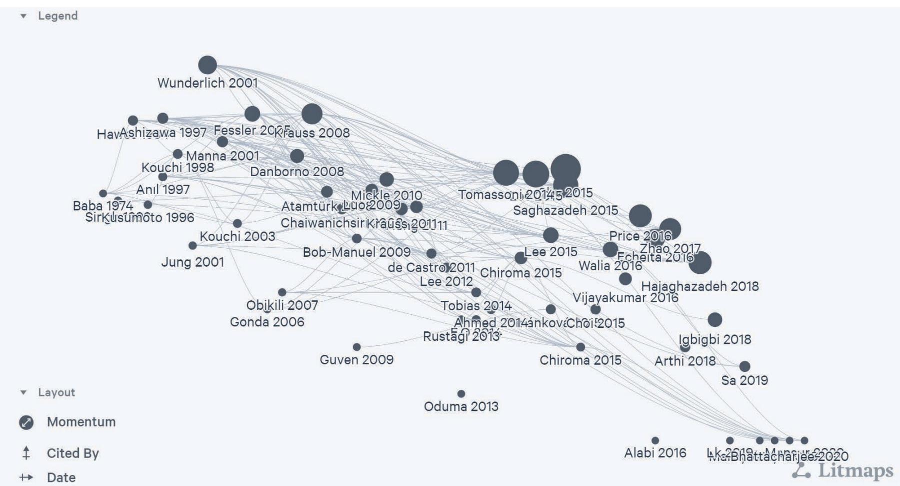


Figure 2. Literature map depicting citation connection of the included articles of the present review report.

RESULTS AND DISCUSSION

The human foot, which serves as the basis for bipedal locomotion, has evolved from a generalised grasping organ to an organ specialized for locomotion and weight bearing. The characteristics of foot morphology are manifold since several factors are associated with it. This review report is significant because it thoroughly evaluated several salient factors impacting human foot morphology which has been discussed below in several sections.

Ethnicity and foot morphology

The human phenotype is diverse, and individual humans can vary in body size and shape, both between and within populations. Due to each ethnic group's unique characteristics and selective adaption to various climatic zones, measurements of various body parts may differ [70, 73]. In addition to population-specific genetic variation, people from different parts of the world bear different morphological features depending upon their geographical distribution, ethnic variation and primary racial characteristics [46, 66] (Table 1).

Genetic background, ethnicity and shoe-wearing habits i.e., going barefoot or habitually / daily using different footwear can explain significant foot shape differences among peoples and ethnic groups [8, 22, 48, 54]. Interestingly, the shoe-wearing habits across ethnic populations are strongly correlated to each ethnic group's mode of subsistence. For instance, Japanese adults who worked in offices and were citizens of the highly developed tertiary industrial country Japan frequently wore leather footwear. Additionally, Japanese women have worn shoes resembling corsets since the 1940s. Contrarily, Isabela women of the Philippines depended on agriculture for their survival, and a part of their lifestyle involved wearing rubber sandals since childhood continuously throughout the year. Despite their smaller physique, they have been found to have relatively larger foot size and wider foot shape than Tokyo women of Japan [54]. Japanese people who worked in the office wore leather shoes outside of the house and fabric slippers inside. Contrarily, Filipinos in the Philippines habitually wore *zori*-type rubber sandals or flip-flops which were footwear made of bald tires following the style of *zori* (traditional footwear made of straw) in the fields, while remaining barefoot in the home. Similarly, East Javanese people in Indonesia who depended on agriculture preferred to live barefoot and retained their ancestral way of life. They were found to have longer feet for the same stature and body weight and broader feet for the same foot length and body weight compared to the Japanese. Additionally, hallux valgus (also known as bunions), a certain type of foot deformity, was also commonly found among shoe-wearing Filipinos and Japanese [8]. Seoul-based Korean women belonged to the contemporary shoe-wearing society. Alternatively, Maasai, an African indigenous group, enjoyed a semi-nomadic bush lifestyle, and the majority of them spent their time either barefoot or donning their customary footwear made of recycled car tires. They were found to have significantly longer and wider feet, and the majority of them had clawed feet, a trait that was absent among Korean women [22]. Summing it up, the feet of the populations who preferred to remain barefoot most of their life were longer and wider than habitually shod populations. The type of footwear affects foot shape and size as well. Further evidence was provided by a study where female unshod runners (Indian) had longer and wider feet than female shod runners (Chinese), stating ethnicity and wearing ill-fitted shoes for a long time since youth as the main reasons behind such quantitative variation, after taking into account the potential influence of age, sex and body mass index (BMI) [88]. Thus, each ethnic group's feet are a clear reflection of their unique lifestyle, which is impacted by the various subsistence methods they use. Therefore, further research is required to determine whether subsistence pattern, in addition to genetic background and ethnicity, is a significant component that affects foot morphology in different ethnic populations.

Variations in foot morphology among different ethnic groups also follow the theoretical explanation that populations living in warm climates, i.e., tropical climate dwellers would have longer limbs than populations living in cold environments, i.e., temperate climate dwellers due to increased surface area resulting from genetic adaptations to temperature stress in the warmer climate. Large foot dimensions are adaptations to tropical environments as they enhance the surface area available for heat escape [15, 69, 84, 92]. For example, Nigerian males and females had higher mean foot lengths than Caucasians [69]. Furthermore, Bhattacharjee et al. [15] reported significantly longer and wider feet in Chakma females than in their Bangalee counterparts. Interestingly, Tongans of Polynesia are distinguished not only by their heavy body build, but also by their longer and wider feet than the Japanese, French, Australian Aborigines, or Bamanann-Fulbe of West Africa. The Tongans' heavy body build was most likely favoured by selection due to the windy climate that dominated during population bottlenecks brought on by severe and inescapable natural disasters and famine. The genetic modification due to such adaptation resulted in a 'hypermorphic' growth pattern, which produced not only a heavy body build but also distinctively large feet among the Tongans [35]. Genetic adaptation and modification due to temperature stress and climatic factors, i.e., environment in different geographical locations explain the foot morphological variations across ethnic populations. Figure 3a (males) and Figure 3b (females) demonstrate the variation of foot length (the linear distance from the pternion to the longest toe of the foot) in both sexes among different ethnic groups across the globe. Comparison of various ethnic groups represented in the figures shows that Tongan men had the longest feet, followed by the French and Australian aborigine men. On the other hand, Tongan females were found to have the longest feet, followed by Maasai and Indian females. Compared to other groups, the foot length of Japanese males and Indonesian females was the smallest.

Table 1. Summaries of the studies on ethnic variation in foot morphology

Authors*	Sample size	Population and/or area of study	Age group (in years)	Major findings
Baba [12]	1844	Japanese	18–40	Ratios of foot breadth and ball girth to foot length were larger in **Japanese** males than in **French** males.
Singh and Phookan [89]	270	Khamyangs, Turungs, Aitons, Khamtis (Assam)	17–55	Statistically significant differences were observed between the **Turungs** and the **Khamyangs** in foot breadth, between the **Turungs** and the **Aitons** in foot length, and between the **Khamyangs** and the **Khamtis** in stature foot breadth index.
Hawes et al. [38]	1221	North American, Japanese, Korean	17.64–84.89	Significant differences were observed between the **Japanese** and **Koreans** and **North Americans** in foot breadth, height of the hallux, location, angularity of the metatarsal-phalangeal joint axis, and the shape of the anterior margin of the foot. **Koreans** and **Japanese** had a longer foot axis and **squarer** foot shape compared to the North Americans.
Kusumoto et al. [54]	74	Isabela province, Philippines and Taito-ku, Tokyo	18–45	**Isabela** women had relatively larger foot sizes despite their smaller physique and tended to have a wider variation of foot shape than **Tokyo** women.
Ashizawa et al. [8]	1035	East Javanese, Filipinos and Japanese	–	**East Javanese** had longer foot for the same stature and weight, and broader foot for the same foot length and weight than **Japanese** whereas the relationship between BMI and foot shape was nearly the same in **Filipinos** and **Japanese** females.
Kouchi [48]	1098	Japanese, Indonesian, French, Australian Aborigines	19–59	**Japanese** foot was more similar to the **Indonesian** foot and **Australian aborigines'** foot was similar to **French**. **Australian aborigines** and **French** have larger length measurements and relatively narrower feet than **Japanese** and **Indonesians.**
Gonda and Katayama [45]	140	Tongas (Kingdom of Tonga, Oceania)	18–68	**Tongans** were found to have significantly longer and wider feet than the **Japanese, French, Australian Aborigines, Bamanann-Fulbe**
Obikili and Didia [35]	670	Nigerian	20–28	**Nigerians** had longer foot than **Caucasians**.

Authors*	Sample size	Population and/or area of study	Age group (in years)	Major findings
Ahmed et al. [5]	180	Santhal and Bangalee (Pirganj, Rangpur)	–	Foot length was significantly greater in **Bengalees** than **Santhals** and slender foot was more common among **Bengalees**, whereas broad foot shape was more common among **Santhals**.
Onuoha et al. [72]	800	Nigerian	18–30	**Nigerians** were found to have the largest foot length and lowest foot breadth compared to **Malays, Chinese and Indians.**
Lee et al. [56]	200	Taiwanese and Japanese	Taiwanese: 22.2 Japanese: 23.7	**Taiwanese** females were taller, heavier, and had larger feet and significantly different forefoot shape than **Japanese** females.
Shu et al. [88]	364	Chinese and Indian (China)	–	Significant differences exist between shod **Chinese** and unshod **Indians** for foot length and breadth (females only), hallux and the minimal distance from hallux to second toe (both sexes).
Lee and Wang [57]	3000	Taiwan (Taiwanese)	18–60	**Taiwanese** adults had wider foot than **Mainland Chinese** and **Europeans**. The foot shapes of **Taiwanese** and **Japanese** females were similar.
Choi et al. [22]	40	Maasai (Tanzania) and Korean (Japan)	46–55	Foot length and breadth were significantly greater in **Maasai** women than in **Korean** women.
Shariff et al. [87]	1210	Chinese, Malaya and Indian (Malaysia)	20–60	Foot length was significantly different among **Chinese**, **Malaya** and **Indians**, Significant differences were observed in ball girth between **Chinese** and **Malays** and in foot breadth of **Malays** against **Chinese** and **Indians**.
Igbigbi et al. [41]	384	Delta Igbos and Isokos (Nigeria)	18 - 30	Foot length and breadth were statistically smaller among Isokos than among **Delta Igbos.**
Hajaghazadeh et al. [37]	580	Urmia, Iran	18–30	Foot length and breadth were significantly different between **Iranian** and East Asian Communities like **Chinese, Indian, Malaysian, Japanese and Taiwanese**.
Bhattacharjee et al. [15]	400	Bangalee and Chakma (Chattogram, Bangladesh)	18–44	Foot length, breadth and index of the foot were significantly greater in **Chakmas** than in **Bangalees** and **Bangalees** had slender foot whereas a broad foot shape was noted among **Chakmas.**

***** Authors were listed chronologically (from earliest to latest) as per year of publication.

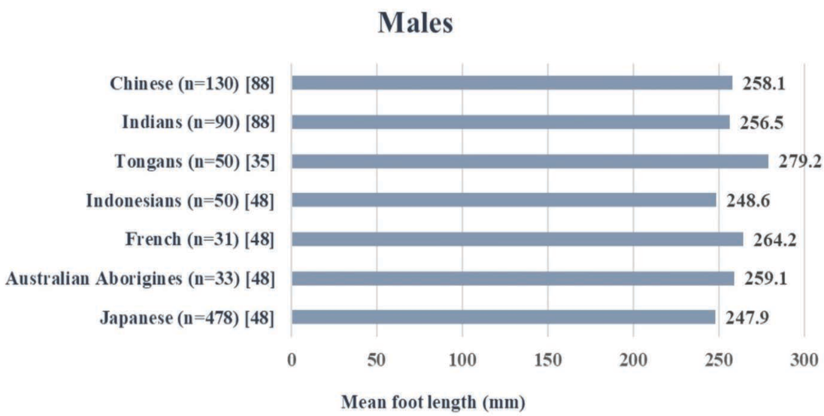


Figure 3a. Variation in foot length (mm) of males among different ethnic groups.

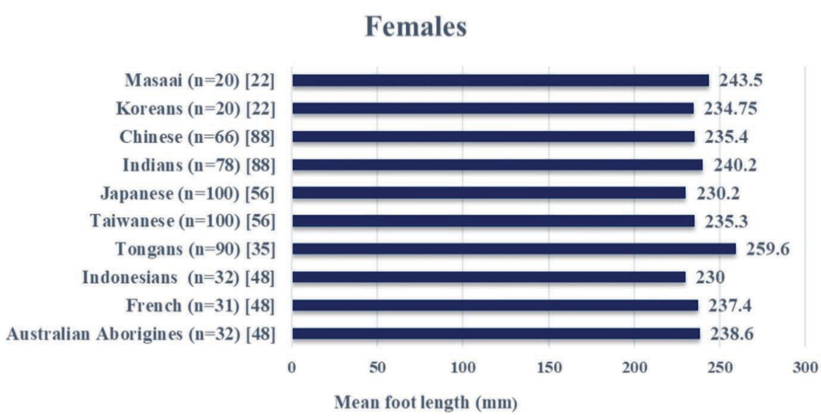


Figure 3b. Variation in foot length (mm) of females among different ethnic groups.

The measurements of the body parts of various ethnic groups can differ due to each ethnic group's unique traits. Furthermore, the human phenotype is diverse both within and between groups and each group has its own features. Several studies have provided strong evidence for this claim [5, 12, 37, 38, 41, 48, 56, 57, 72, 87 ,89]. On the other hand, population heterogeneity brought on by migration and admixture can cause disruptions in foot morphological traits. For instance, Indian and Chinese Malaysian foot morphological traits notably differed from those of indigenous Malay populations [87]. Similarly, the foot morphology of indigenous Javanese and Filipinas significantly differed from that of the Japanese [8, 54]. Further research should focus on ethnic groups that are homogeneous in terms of ethnic composition to clearly illustrate the foot morphological aspects that are specific to each ethnic group.

Thus, it becomes imperative to conduct similar up-to-date research on different homogenous ethnic groups living in different parts of the world so that the combined effect of ethnicity, geographical locations, environment and subsistence pattern could be explored in anthropological terms to make a compendious database.

Age and foot morphology

The foot provides the only direct source contact with the supporting surface, thus playing a crucial role in all weight-bearing tasks. Foot morphology undergoes age-dependent changes, and foot development and maturation are accompanied by variations in its shape and function [85, 94]. Only a few studies (Table 2) have investigated the potential age-related changes in foot morphology.

The feet of the elderly may have distinctive features since tissue alterations, changes in body composition and tensile strength of tendons, and loss of bone and muscle mass (e.g., sarcopenia and osteoporosis) brought on by senescence or ageing can alter foot morphology. These anatomical modifications can alter foot dynamics, resulting in specific overloads and repetitive stress injury [10, 26].

To put it in another way, the foot morphology, which the soft tissue has conserved, changes as muscle and tendons get older. Findings strongly suggest the contribution of age in influencing foot morphology (Table 2). According to Kouchi [48, 49] environmental factors, such as nutritional and socioeconomic status affecting the growth period (secular change), were more important than the changes after the end of the growth period (ageing) in the inter-generational disparities in Japanese foot morphology. Furthermore, along with age, foot morphology is influenced by the complex interplay of linked characteristics such as sex and BMI [9, 94, 106]. In essence, these findings emphasized that the impact of environmental influences on foot morphology should not be underestimated. They serve as a reminder that the way the human foot develops and changes is not solely a result of ageing but is intricately linked to sex, BMI, nutrition and socioeconomic conditions, all of which collectively contribute to the unique morphology of the human foot across generations.

Studies have primarily concentrated on a limited number of foot dimensions across populations (Table 2). Figure 4 exhibits age as a significant and positive factor in predicting the foot shape in both feet. Given that foot breadth (breadth or width of the forefoot or ball region), ball circumference (circumference of the forefoot or the ball of the foot), high-instep circumference (circumference of the instep region) and heel instep circumference (circumference of the heel

Table 2. Summaries of the studies on age-related differences in foot morphology

Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major Findings
Kouchi [48]	3062	Japan	3–88	Length measurements were larger for **younger** generations except toe length, but foot girth, foot breadth, heel breadth, relative foot girth and foot index were smaller in **younger** generations.
Jung et al. [43]	252	Korea	60 +	**The elderly** had a tendency of a slenderer foot than young adults.
Kouchi [49]	1065	Japan	18–80	**The younger group** of the same foot length had larger foot circumference, wider breadth measurements, higher dorsal arches and ball and greater toe 5 angle, but shorter fibular instep lengths and shorter 5th metatarsal bones than the **older group**. **The younger group** had a larger foot breadth than the **older group** of the same foot circumference.
Atamturk and Duyar [9]	516	Ankara, Turkey	18–60 +	Foot length and foot length / stature displayed statistically significant differences with **age**.
Tomassoni et al. [94]	1105	Italy	20–70	Smaller instep length, ankle circumference and greater ankle length, toe, ankle and medial foot arch height were found among **adults** than **young adults** whereas foot circumference showed the most relevant age-related differences among the **old** when compared to **adults**.
Echeita et al. [26]	168	North of the Netherlands	20–80	The foot shape of women became wider with **age** and foot breadth, ball circumference, high instep circumference and heel instep circumference were found to be larger in **older age** categories.
Zhao et al. [106]	180	Japan	25–82	When confounding factors gender and BMI were considered, the foot length and medial and lateral ball of foot length were significantly associated with ageing and the values decreased with increasing **age.**

*Authors were listed chronologically (from earliest to latest) as per year of publication.

instep region) were all shown to be larger in older age groups, it is evident that women's feet get wider with age. Additionally, ball width, ball circumference and left high-instep circumference peaked in the 70–75-year age group, and, in the oldest age group, they declined.

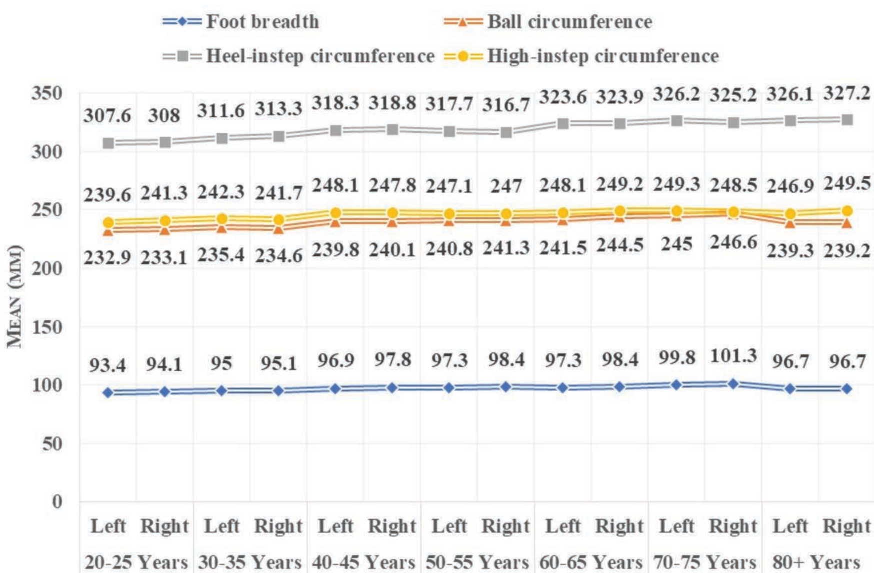


Figure 4. Comparison of left and right foot measures (mm) in different age categories of women (n = 168) [26].

Due to the paucity of literature on the potential impact of age on foot morphology, precise depiction of foot morphology between age groups gets restricted. Therefore, in future studies, anthropometric measurements should be expanded to precisely define foot morphological traits among different age groups. Future research should also address age-sensitive characteristic features of adult foot morphology together with ethnic, sex and body composition differences, which will, in turn, help to develop fit and healthy shoes specifically for younger and older populations, improving their foot health and well-being.

Sexual dimorphism and foot morphology

Sexual dimorphism in the human body is evident from foetal life, although it is most noticeable during puberty [61, 100]. The current review is concerned with the presence of sexual dimorphism in foot morphology. According to the research, there is significant sexual dimorphism in foot dimensions and shapes (Table 3).

Table 3. Summaries of the studies on sexual dimorphism in different foot morphological parameters

Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major findings
Baba [12]	1844	Japanese	18–40	**Female** subjects had narrower foot breadth and smaller ball girth than **males** having the same foot length.
Anil et al. [7]	305	Turkey	17–25	Foot breadth and ball girth of the **male** students were greater than of the **female** students.
Manna et al. [60]	300	Indian (Bengalee)	20–35	Foot length, breadth, volume, foot depth at base and joint, heel breadth and ankle volume were significantly greater in **males** than in **females.**
Wunderlich and Cavanagh [103]	784	North American	–	**Men** had longer and broader feet than **women** for a given stature and after normalisation of the measurements by foot length, **men** and **women** differed significantly in calf, ankle and four-foot shape variables.
Fessler et al. [29]	–	North, Central and South American and Turkish populations	–	Across the populations, proportionate to stature, the **female** foot was smaller than the **male** foot.
Obikili and Didia [69]	670	Nigeria	20–28	
Krauss et al. [50]	847	Germany (European heritage)	14–60	**Males** had significantly longer, broader and higher foot than **females.**
Bob-Manuel and Didia [17]	477	Port Harcourt (Nigerians)	18 +	
Chaiwanichsiri et al. [18]	213	Bangkok	60–80	With the same foot length, **men** had larger foot breadth and circumference, as well as upper ball, arch, toe depth and ankle height than **women**.
Danborno and Elukpo [23]	400	Zaria, Nigeria	Males: 24.50 Females: 22.22	Foot length, breadth and index of both feet in **males** were significantly higher than in **females**.
Luo et al. [58]	90	–	20–72	**Male** participants' feet were longer and wider than of the **female** participants' feet.

Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major findings
Mickle et al. [63]	312	New South Wales, Australia	60 +	**Men** had significantly higher normalised 1^{st} and 5^{th} toe heights and a greater 5^{th} toe angle than **women**, and **women** had a significantly longer normalised medial ball length and greater first toe and heel bone angles than **men**.
Hong et al. [39]	2,321	China	18–30	Chinese **women** showed significantly smaller foot measures in breadth, height, and girth than Chinese **men**, differences in the foot shape between them were also observed.
Krauss et al. [51]	287	Caucasians	18–65	**Male** feet were wider and higher for the same foot length than **female** feet.
De Castro et al. [24]	285	São Paulo, Brazil	Males 69.05 Females 68.97	**Women's** feet were proportionally wider than the **men's**, whose feet had proportionally larger values for height of the dorsal foot. 1^{st} and 5^{th} metatarsophalangeal angles were greater among **women**.
Onuoha et al. [72]	800	Edo, Delta and Rivers States, Nigeria	18–30	**Male** feet were larger in all the mean dimensions, i.e., foot length, foot breadth and foot height than **female** feet.
Rustagi et al. [79]	300	Ambala, Haryana	18 +	Foot length, foot breadth and foot height were found to be significantly greater in **males** than in **females**.
Tobias et al. [92]	500	Benin City, Nigeria	18–26	
Ewunonu et al. [28]	504	Nigeria (Igbo people of South-Eastern part)	18–30	**Male** foot was found to be significantly larger and broader than **female**.
Tomassoni et al. [94]	1105	Italy (Caucasians)	20–70	In young adults and adults, the morphological parameters investigated were significantly lower in **females** than in **males**. In old individuals, no differences in the parameters between **males** and **females** were found after normalisation for foot length.
Lee and Wang, [57]	3000	Taiwan (Taiwanese)	18–60	Significant **gender** differences were found in seven of the nine foot dimensions, and with the same foot length, **males** had greater breadth, girth and height dimensions than **females**, except for toe height.

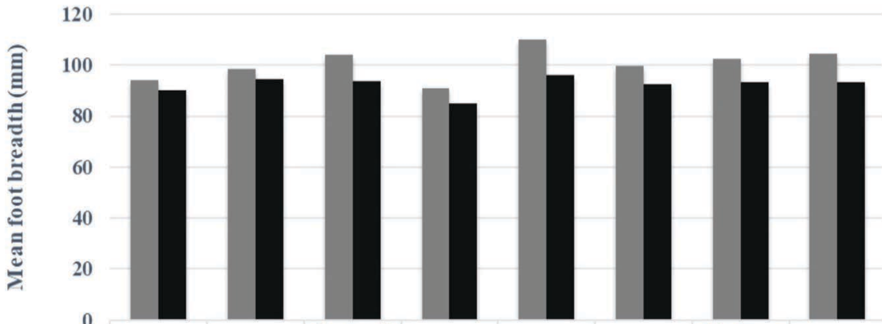
Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major findings
Chiroma et al. [21]	130	Gombi town, Adamawa State (Ga'anda tribe)	18–45	Foot length, height and breadth studied were significantly larger in **males** than **females**, **female** foot were relatively more slender than **males**.
Chiroma et al. [20]	120	Maiduguri, Nigeria (Yoruba students)	–	**Male** foot length, height, breadth and index were significantly higher than their **female** counterparts.
Saghazadeh et al. [82]	291	Kasama City, Japan	Males 74.5 Females 73.9	In **men**, the measurement values for navicular height, first and fifth toe and instep heights, ball and heel width, ball girth, arch height index (just standing), arch rigidity index and instep girth were significantly greater than **women**, whereas the first toe angle, in both sitting and standing positions was significantly smaller in **men**.
Alabi et al. [6]	420	Nigeria (Igbo descent)	18–65	**Males** displayed significantly higher mean values than **females** in all measured parameters (T1–T5).
Zhao et al. [106]	180	Japan	25–82	**Men** had longer, higher and larger feet than **women**, even when confounding factors such as age and BMI were adjusted.
Walia et al. [100]	400	Haryana, India (Jaat Community)	21 +	Length and breadth of foot and footprints were greater in **males** as compared to **females**, whereas foot index and footprint index were higher in **females**.
Hajaghazadeh et al. [37]	580	Urmia, Iran	18–30	The absolute values for **males** were significantly higher than those for **females**; however, the relative data (standardized by foot length) were not always higher in **males**, i.e., **females** with the same foot length had higher values in some dimensions such as foot breadth and ball girth.
Igbigbi et al. [41]	384	Abraka, Nigeria (Delta Igbos and Isokos)	18–30	Right and left foot length and breadth were larger in **males** than in **females.**

Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major findings
Vidona et al. [97]	1200	Nigeria (Igbo-western and Igbo-eastern ancestral tribe)	21–70	Foot length, foot breadth and toe length were significantly higher in **males** than in **females** for both the right and the left foot.
Adelakun et al. [4]	500	Ondo State, Southwest Nigeria	18–50	Foot length, foot breadth and foot index were significantly higher in **males** compared to **females.**
Ayobami et al. [11]	500	Oyo State, Southwest Nigeria	18–50	Differences in foot length and foot breadth among the **males** and **females** of the population were highly significant.
Mansur et al. [61]	556	Dhulikhel, Nepal	18–25	**Males** were found to have longer and broader foot than **females**.

*Authors were listed chronologically (from earliest to latest) as per year of publication.

A study analysed several genetically disparate populations and discovered that women had smaller feet proportionate to stature than men, which may reflect a history of intersexual selection that favoured reductions in female foot length [29]. Interestingly, the historical practice of binding of Chinese women's feet at a very young age can be construed as an example of extreme cultural exaggeration of a preference for smaller female feet [30–76]. Likewise, a cross-cultural investigation from several geographically disparate populations revealed that small foot size was generally preferred for females, which enhances physical attractiveness [30]. These findings provide secondary support to the hypothesis of intersexual selection [29,30]. Small feet may serve as a direct sign of youthfulness, as children's feet are smaller than those of adults and adult foot size increases with age [13, 19, 29, 105]. Moreover, foot size increases with parity, so small foot size may indicate nulliparity [34, 86]. Subsequently, due to the strong consistent preference for youth and nulliparity by males, they may have evolved a preference for women with small feet. In turn, this innate preference may have exerted selective pressure on female foot morphology, causing a reduction in female foot length [29, 30].

The large disparities in other foot dimensions between males and females can be linked to the biomechanical process of bone epiphysial fusion occurring earlier in girls than in boys. Hormonal factors influence the pattern and duration of growth in both boys and girls. Females experience earlier cessation of bone growth than males due to hormonal influence throughout puberty. Increased oestrogen levels during puberty enhance chondrocyte apoptosis in the epiphyseal plate, delaying bone ossification and development. They also undergo accelerated pubertal growth spurt, reaching maturity earlier and ending their growth faster than the males, leading to an overall smaller bone structure. On the other hand, males reach puberty later than females and experience more sustained growth phases of bone, including increased bone metabolism and mineralization due to high levels of testosterone. As a result, male bones are robust and heavier in structure than in females. These size differences in the bones of males and females are consequently represented in the anthropometric dimensions of the foot, resulting in larger anthropometric measurements of the adult males [3, 16, 40, 44, 75]. Figure 5 demonstrates the presence of sexual dimorphism in foot breadth (breadth or width of the forefoot or ball region). Males were found to have broader feet than females.



	Mansur et al. [61]	Chiroma et al. [21]	Lee and Wang [57]	Onuoha et al. [72]	Tobias et al. [92]	Zhao et al. [106]	Chaiwanichsiri et al. [18]	Chiroma et al. [20]
■ Males	94	98.5	103.9	91	110	99.72	102.6	104.5
■ Females	90	94.7	93.7	85	96	92.6	93.4	93.5

Figure 5. Comparison of foot breadth (mm) between males and females in different studies.

In conclusion, female feet are not simply scaled-down versions of male feet but rather differ in shape and size [17, 37, 58, 103]. Previous studies have focused on a limited number of foot dimensions, so the ability to characterize foot morphology fully also faces limitations. Future studies should expand the set of anthropometric dimensions to accurately describe the three-dimensional morphological characteristics of feet across sexes. Additionally, it is strongly suggested to compare relative or normalized foot dimensions across sexes in addition to absolute foot dimensions because few studies have demonstrated that using relative or normalised foot dimension values can reliably discern between different foot morphologies [37, 39, 50, 51, 57, 103]. This quantitative analysis of sexual dimorphism of foot morphology has vital applications in the fields of anthropology, forensic science and manufacturing of shoes, athletic footwear and, in particular, orthotics.

Obesity and foot morphology

As the body's base of support, the human foot is highly evolved and anatomically distinct to serve the dual role of weight bearing and ambulation [64]. Bipeds' foot receives the weight of the whole body and stabilises the body in shifting postural and environmental conditions [32]. Because the foot is constantly subjected to significant ground reaction forces generated during daily activities, healthy foot morphology is essential for efficient foot posture and ambulation [25, 77]. The foot of an obese adult differs in structure and function compared to the foot of a healthy-weight individual due to increased adiposity, excessive weight-bearing and alterations in morphology, soft tissue properties and functional capability [25, 74, 77]. Previous studies have discovered obesity to be substantially linked with human foot morphology (Table 4).

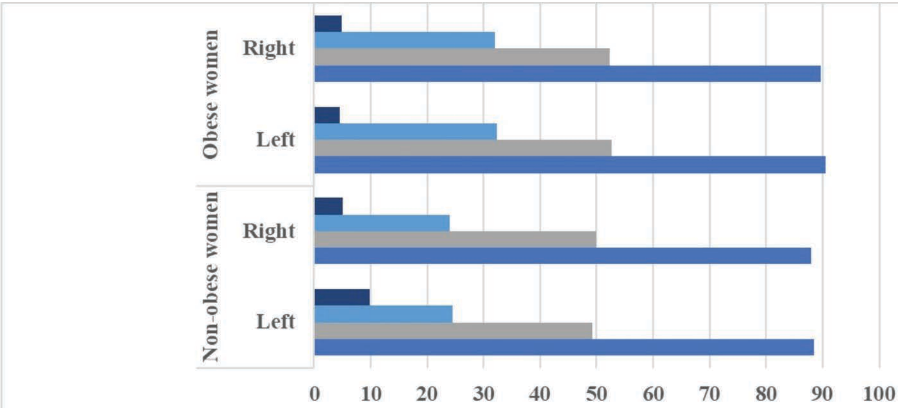
Obese adults suffer from altered foot function and foot pain which directly impact their mobility and quality of life [65]. Several studies support the theory that increased adiposity, increased stress on the soft tissues and joints and localised swelling caused by venous insufficiency or foot deformity may be directly related to high body mass. Such conditions are associated with a higher prevalence of foot discomfort and pain leading to a reduced level of physical activity [64, 65, 102]. The key to providing or prescribing proper footwear to these populations is accurate quantification of foot measurements and morphology [74]. This will enable more sensitive comparisons between populations, increased specificity of footwear interventions to prevent injuries, guarantee more comfort for shoes and a more detailed understanding of the influence of conditions and symptoms on foot morphology [10, 74].

In literature, obesity has been identified as an important predictor of foot morphology (Table 4). The feet of obese adults were discovered to be much longer, broader and flatter than in their non-obese counterparts, as the structure of the foot spreads, and the dimensions increase due to an increase in body weight [32, 36, 59, 74, 93, 98, 104, 106]. Figure 6 depicts the significant difference in foot morphology parameters between obese and non-obese individuals. The values were found to be greater in the obese group compared to the non-obese group. Obese women had significantly larger mean values for foot breadth (breadth or width of the forefoot or ball region) heel width (width or breadth of the heel region), Chippaux-Smirak Index (ratio of the widest part of the forefoot and the narrowest part of the midfoot multiplied by 100) and hallux angle (angle formed by the hallux or first toe) on both feet compared to non-obese women. However, the mean values of foot breadth were significantly greater in obese women on the left foot only.

Table 4. Summaries of the studies on the association of obesity with different foot morphology parameters among adults

Authors*	Sample size	Area of study and/or population	Age group/ mean age (in years)	Major findings
Güven et al. [36]	100	Turkey	–	Chippaux-Smirak Index (CSI) and foot breadth were greater in obese women, and footprint angle was smaller in the **obese** group compared to **controls.** In regression analysis, CSI and foot angle were related to BMI in the **obese** group.
Tománková et al. [93]	139	Czech Republic	48–69	Except for hallux angle, direct heel width, CSI, foot breadth and hallux angle (right foot only) were significantly greater in **obese** women compared to **non-obese** women. **Obesity** caused hallux varosity, widening of the forefoot and heel.
Vijayakumar et al. [98]	412	–	25–40	There was a strong relationship between BMI and morphology of the foot, and the prevalence of flat foot was found to be high in **obese** and **morbidly obese** males.
Price and Nester [74]	69	–	20–78	Anatomical measures of foot, ball and heel width, ball and heel circumference, ball height and midfoot regions were all significantly greater in the **obese** group than in the **healthy weight** group.
Zhao et al. [106]	180	Japan	25–82	Compared with **normal-weight** adults, **overweight** and **obese** individuals had higher, larger and wider feet after adjusting to age and gender.
Ganapathy et al. [32]	250	Pondicherry	18–24	There was a significant relation between the **weight** of the individuals and the type of foot.
Mallashetty et al. [59]	106	–	18–22	Arch index was significantly higher and arch angle was significantly lower in **obese** and **overweight** subjects than in **underweight** and **normal** subjects.

*Authors were listed chronologically (from earliest to latest) as per year of publication.



	Non-obese women		Obese women	
	Left	Right	Left	Right
Hallux angle (°)	9.8	5.1	4.5	4.9
Chippaux-Smirak Index (%)	24.5	24	32.3	32
Heel width (mm)	49.2	49.9	52.6	52.3
Foot breadth (mm)	88.4	87.9	90.6	89.7

Figure 6. Comparison of left and right foot parameters between non-obese and obese women (n = 139) [93].

Furthermore, the incidence of obesity among adults differs from population to population [101]; body composition exhibits ethnic differences and age-related changes involving an increase in fat mass and reduction in muscle mass and strength [96, 104]. Furthermore, when compared to age, BMI had a stronger influence on foot breadth, height and girth parameters, and age had a greater influence on length parameters. In contrast, sex had a greater impact on length, breadth, height and girth parameters than age or BMI [106]. Thus, as earlier stated, meticulous investigations of the influence of different confounding inter-linked factors on foot morphology should be further probed.

This review also identified that few studies expressed obesity in adults using the classification of BMI [36, 59, 74, 98, 106]; others expressed obesity as selected body composition measurements [36, 93]. People with higher BMI may not be obese from the aspect of body composition [27, 78, 93], which may also affect the foot morphology among adults. Thus, there is a paucity of evidence to establish an association between body composition and foot morphology. So, it is crucial to undertake studies to investigate further the association of foot morphology and obesity expressed with selected body composition measurements that will further contribute new knowledge to public health.

Strengths and limitations

This comprehensive study aimed to provide critical insight into foot morphology and variability across ethnicity, sex, age groups, and people with diverse body composition. In addition to underscoring the significance of knowing foot morphology, this systematic review explored how numerous interrelated biological elements work together to influence foot morphology. The present extensive report provided sufficient explanations, including potential scientific answers, for why different ethnic groups have different foot morphology, why sexual dimorphism is visible, and why people of different ages and body composition groups have different foot shapes and measurements. In addition, research gaps were identified and expectations and realm of future research were established.

Due to varying sample sizes, considerable differences in methodology and the use of discrete variables in different research, inter-data comparison was not performed. Similarly, intergenerational disparities were not highlighted in the present study. Participants above the age of 18 were included in the discussion part since they have reached adulthood and achieved adult and fixed measurements. This study is limited to using solely anthropometric characteristics of the foot. No radiographic variables were used for discussion. The articles included in this systematic review were limited to those written in English. Moreover, only the articles with comprehensible methodologies and objectives aligned with the aims of this study were incorporated. Due to the scarcity of literature, this study is confined to the articles published between 1975 and 2020. Only three databases were employed in this research. Even with meticulous efforts, the limitation of this research study includes some gap throughout the literature search process. Further analysis could have yielded better results.

CONCLUSIONS

Every foot has its own story of bio-cultural existence and evolution. Each community has a unique subsistence pattern, genetic background and morphological features. The shape and size of the feet change accordingly. This review article was an attempt to concisely summarise the existing literature on foot morphology and the different factors influencing it. Literature revealed that foot morphological characteristics vary among different ethnic groups, exhibit sexual dimorphism and reflect specific characteristics at different ages of life. Obesity was found to have a significant impact on selected foot morphological parameters. Thus, ethnicity, age, sex and obesity collectively contribute to the unique morphology of the human foot. Since India is a multiethnic country and studies on quantitative variations in foot morphology, potential factors influencing it as well as the unique features of footprint from the anthropological point of view in the Indian context are limited, similar studies should be instigated among different homogeneous ethnic groups living in different parts of India. These studies on inter-population variation of foot morphology will contribute to the establishment of population-specific standards for anthropological research, improved forensic identification as well as facilitate the manufacture of ergonomic footwear.

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