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Estimation of Human Stature from Footprint Dimension and Foot Outline Dimension in Uttar Pradesh, India

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ABSTRACT

Background: Personal identification remains the most reliable parameter in forensic science. It is broadly divided into absolute and partial identification. In absolute identification, the complete identity of the individual is established beyond any doubt by considering every aspect of biological and physical characteristics. Partial identification refers to situations where limited evidence points towards the likely identity of the individual. **Materials and Methods:** The present study was conducted among students of Teerthanker Mahaveer University, enrolled in different colleges of the institution. A total of 200 individuals aged between 18 to 30 years were selected through simple random sampling. The study considered both left and right footprints and foot outline measurements from both male and female participants for analysis.

Results: The findings demonstrated that all foot parameters, including footprints, foot outlines, and foot segment measurements, showed a statistically significant positive correlation with stature ($p < 0.001$ across all parameters). The regression equations derived from these parameters were found to provide an accurate and reliable estimation of an individual's height, specifically for the northern Uttar Pradesh population. Since all foot-related measurements displayed a high degree of correlation with stature, they serve as superior predictors of height compared to many other morphometric dimensions. **Conclusion:** The study concludes that all measured footprint, foot outline, and foot segment dimensions show strong correlations with stature, providing a dependable basis for estimating an individual's height. These findings can play a critical role in personal identification, particularly in forensic investigations.

Keywords: Forensic science, Footprint, Foot outline, Morphometric dimensions, Stature estimation.

INTRODUCTION

The role of forensic anthropology is crucial in the identification of individuals, especially in crime investigations where mutilated or fragmented human remains are encountered with increasing frequency (1). Determining the stature of an individual forms one of the fundamental aspects in reconstructing the biological profile, which is of utmost importance in cases involving fragmented skeletal remains (2). In forensic anthropology, identifying individuals from bone fragments, recovered either from crime scenes or other locations after death, is a significant challenge (3).

Personal identification in forensic science comprises two components: absolute and partial identification. In absolute identification, the identity of the deceased is confirmed without doubt, based on comprehensive biological and physical evidence. In contrast, partial identification relies on limited

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parameters pointing towards identity. Among the most crucial factors contributing to personal identification are age, sex, and stature, with stature estimation being particularly relevant to anthropologists (4).

Various body parts, such as the head, trunk, upper limb, and lower limb lengths, have shown a strong correlation with an individual's height. Therefore, height estimation becomes an essential tool for anthropologists by measuring different parts of the human body (5,6). Forensic anthropology is also employed to identify individuals after death, especially in cases involving skeletonized, burnt, or dismembered remains. Additional tools, such as footprints, lip prints, and blood samples for typing and DNA profiling, are utilized for human identification (7,8).

Stature is defined as the vertical distance from the highest point of the head (vertex), when the head is held in the Frankfurt horizontal plane, to the floor. The measurement is taken with the subject standing barefoot in an upright anatomical position on a flat surface. The stature is recorded in centimeters using a stadiometer (9). The determination of stature is an integral part of forensic medicine and anthropology, often used to establish the identity of unknown deceased individuals (10). Numerous researchers have attempted to estimate stature using long bone measurements, each proposing specific formulae based on their studies. Despite these advancements, foot measurements have not been extensively explored for stature estimation (11).

Previous research has indicated that stature estimation using foot outlines and footprint parameters can yield accurate results, particularly when parameters such as heel-to-toe length, big toe pad length, and breadth measurements at the ball and heel are considered (12,13). In instances of mass disasters or criminal investigations where only partial remains are recovered, stature estimation provides essential information that aids in identification (14).

The significance of footprints in estimating stature has long been recognized. The initial detailed study on footprints in the United Provinces of India was conducted by Gayer, whose work laid the foundation for further research in this domain (15). Despite this, the discipline of forensic anthropology has historically given limited attention to the role of human feet and footprints in personal identification (16,17). Nevertheless, studies have shown that both foot measurements (18-21) and footprints (22-25) are strongly correlated with stature, providing valuable data for forensic investigations (26).

Footprints can reveal extensive information about an individual's physical attributes. In forensic science, footprints found at crime scenes are vital in establishing a suspect's presence and can serve as critical evidence linking individuals to criminal activity (27). Despite the known correlation between foot size and stature, the scientific community has only recently begun to extensively explore footprint analysis in forensic investigations. Since different body parts relate proportionally to the body as a whole, the measurement of footprints can reliably indicate an individual's stature, thereby contributing to identification (28).

Instances of body part recovery, particularly feet, are common in scenarios such as airplane crashes, high-impact traffic accidents, and mass disasters like bomb explosions. In these situations, forensic identification from foot parts plays an essential role (29). The uniqueness of footprints has led to the development of individual identification through emerging biometric techniques (30). Stature determination holds significant importance within forensic anthropology, often referred to as part of the "big four" parameters of forensic identification, alongside age, sex, and ancestry (31).

Forensic podiatry, the specialized application of podiatric expertise in forensic investigations, assists in associating individuals with crime scenes or addressing legal matters involving feet or footwear (32,33). In mass casualty events such as terrorist attacks, tsunamis, floods, earthquakes, and transportation accidents, forensic podiatrists play a critical role in identifying victims based on foot evidence.

Stature estimation is fundamental in forensic anthropology, contributing significantly to human identification, particularly when skeletal remains are recovered at crime scenes (34-38). Forensic identification from foot parts has proven valuable in determining an individual's identity during mass disasters, bomb blasts, airplane crashes, and other traumatic events. The use of human foot bones and footprints in personal identification is well-documented (39).

Footprints provide two-dimensional (2D) impressions of the plantar surface, created by direct contact with hard surfaces, while foot outlines capture the three-dimensional (3D) impression of the foot's boundary, typically recorded in soft substances like soil or mud (40).

Footprints are frequently encountered as physical evidence at crime scenes in India, where walking barefoot is culturally prevalent due to spiritual, religious, socio-cultural, climatic, and socio-economic factors. The morphology of the human foot is influenced by both genetic predispositions and lifestyle factors, contributing to variations in size and shape that can be uniquely attributed to individuals. Careful scientific examination of footprints can generate critical information for linking suspects to crime scenes, making footprints valuable evidence for personal identification (41).

This study aims to evaluate the relationship between footprint dimensions, foot outline parameters, and stature among young adults from Uttar Pradesh, India, and to derive population-specific regression models for stature estimation, thereby enhancing forensic identification techniques.

MATERIALS AND METHODS

Source of Data:

The data for this study were collected from students enrolled at various colleges of Teerthanker Mahaveer University, Uttar Pradesh, India. The study was conducted over one year using a simple random sampling technique.

Study Population:

A total of 200 healthy individuals of both genders, aged between 18 and 30 years, were included in the study based on the following inclusion and exclusion criteria:

Inclusion Criteria:

The inclusion criteria for the study comprised individuals aged between 18 to 30 years who were permanent residents of Uttar Pradesh, India.

Exclusion Criteria:

The exclusion criteria included individuals with any inflammation, trauma, deformities, disorders, or diseases affecting the foot. Subjects presenting with any foot-related impairments, pregnant females, individuals below 18 years or above 30 years of age, and those not belonging to Uttar Pradesh, India, were excluded from the study.

Materials Used for Data Collection:

Plain glass plate (8 mm thickness)
Kores quick-drying black duplicating ink (4746)
Footprint roller
A4-size plain white paper
Standard measuring scale
Stadiometer

Procedure for Footprint and Foot Outline Collection:

A uniform smear of Kores quick-drying black duplicating ink (4746) was applied to a clean glass plate of 8 mm thickness using a footprint roller. The participant was instructed to place the left foot onto the inked glass plate with minimal pressure and then carefully transfer the inked foot onto an A4-size white paper. Before lifting the foot from the paper, essential anatomical landmarks were marked using a sharp, pointed pencil. The same procedure was repeated for the right foot.

Anatomical Landmarks Marked:

Heel point (pternion)
Medial metatarsal point (mt.m)
Lateral metatarsal point (mt.l)
Medial concavity of calcaneum (cc.m)
Lateral tubercle of calcaneum (ctu.l)

Measurement Orientation and Parameters:

In accordance with the methodology described by Krishan (42), a designated longitudinal axis (DLA) and baseline (BL) were drawn on each footprint to establish standard orientation for length measurements:

Designated Longitudinal Axis (DLA):

A straight line drawn from the pternion (posterior-most point of the heel) to the lateral border of the first toe.

Baseline (BL):

A line perpendicular to the DLA, extending medially and laterally from the pternion along the rear edge of the foot, ensuring a consistent 90° alignment with the DLA.

Footprint and Foot Outline Measurements Taken:

Footprint/Foot Outline Lengths:

Measurements were taken from the pternion to the distal-most point of each toe (d1.t to d5.t), denoted as T-1 to T-5.

Breadth at Ball of Foot:

Distance between the lateral metatarsal point (mt.l) and the medial metatarsal point (mt.m).

Breadth at Heel:

Distance between the lateral calcaneal tubercle (ctu.l) and the medial calcaneal concavity (cc.m).

Stature Measurement:

Stature was measured with participants standing barefoot, positioned upright with the head in the Frankfurt Horizontal Plane, using a standard stadiometer. Measurements were recorded in centimeters (9).

Statistical Analysis

The primary outcome was the regression equation derived for estimating the stature of an individual from each of the measured morphometric parameters. The correlation coefficient was calculated for each parameter using correlation (r), mean, and standard deviation. The comparison between the right and left foot was done by the paired **t-test. p-Value** <0.05 was considered statistically significant. The data were analyzed by using SPSS (version 23).

Fig.no.1: Procedure for taking a footprint

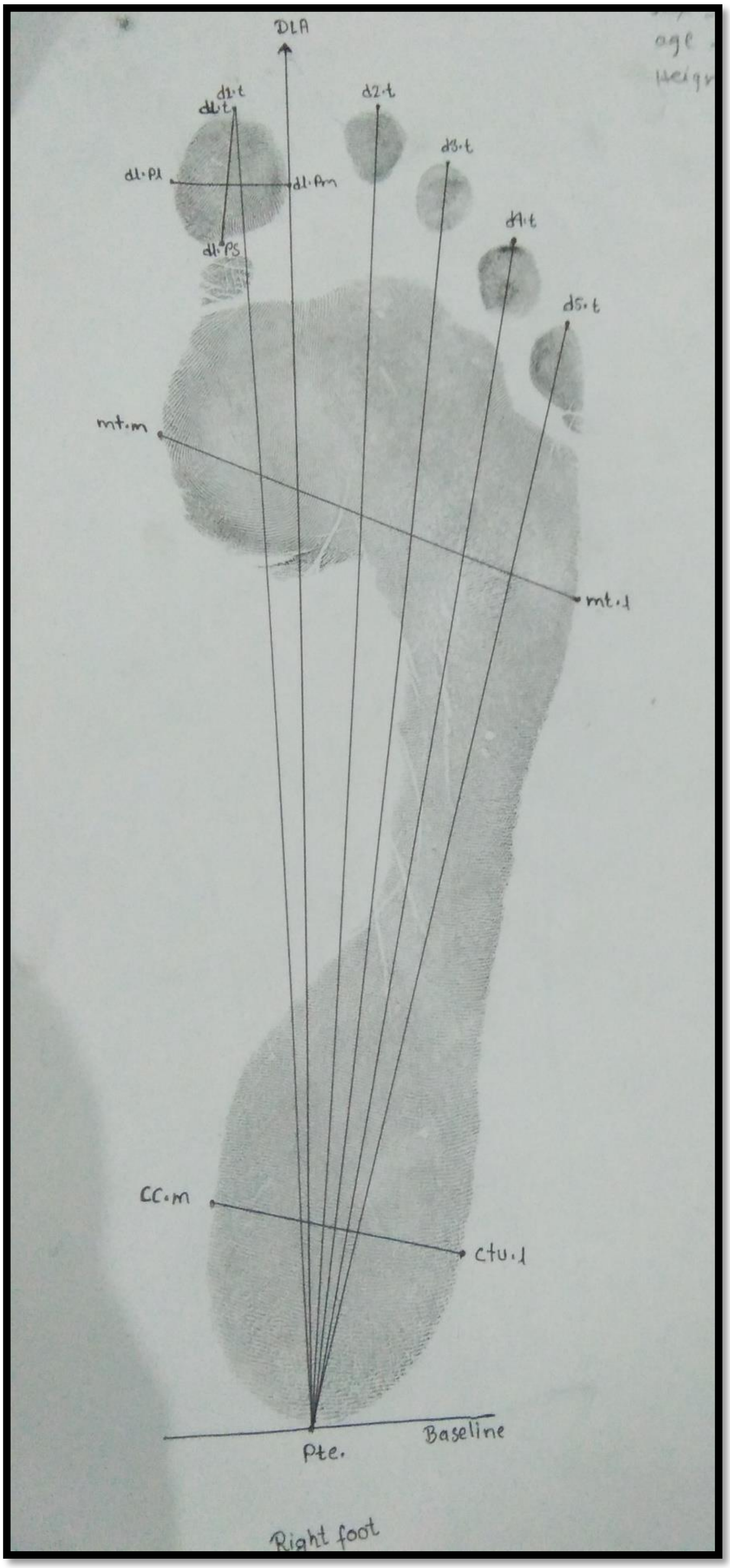

Fig.no.2: Footprint measurements

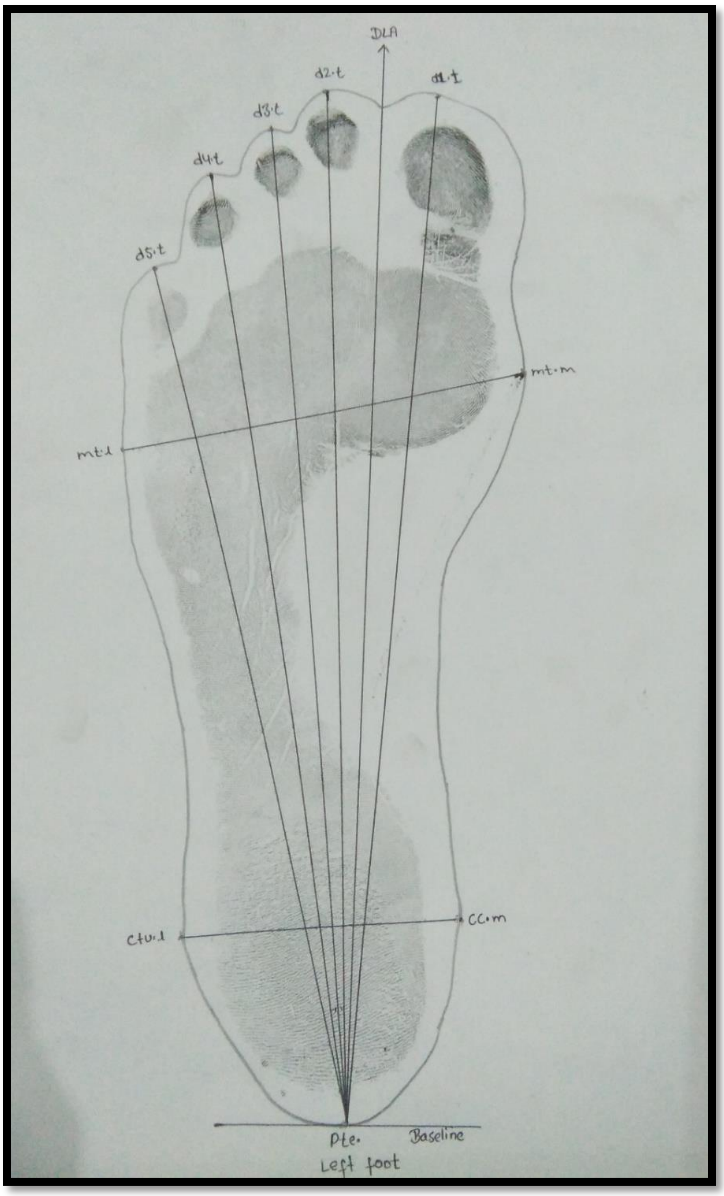

Fig.no.3: Foot outline measurements

Results

Table 1: Comparison between right and left foot outline (cm) using Paired t-test

	Right foot		Left foot				
Parameters	Mean	Standard Deviation	Mean	Standard Deviation	Mean difference	t-test value	p-value
T1	25.45	1.58	25.51	1.55	-0.06	-1.680	0.095
T2	25.03	1.61	25.09	1.63	-0.05	-1.902	0.059
T3	24.16	1.50	24.22	1.53	-0.06	-2.381	0.058
T4	22.89	1.67	23.02	1.43	-0.13	-2.101	0.057
T5	21.35	1.64	21.37	1.89	-0.03	-0.233	0.816

Paired t-test *** Significant difference**

Table 2: Comparison between right and left foot print (cm) by using the Paired t-test

	Right foot		Left foot				
Parameters	Mean	Standard Deviation	Mean	Standard Deviation	Mean difference	t-test value	p-value
T1	23.81	1.63	23.98	1.66	-0.17	-2.920	0.054
T2	23.59	1.65	23.72	1.61	-0.13	-4.985	0.060
T3	22.74	1.56	22.89	1.59	-0.15	-2.769	0.056
T4	21.50	1.71	21.63	1.67	-0.13	-1.492	0.137
T5	19.97	1.69	20.19	1.32	-0.22	-2.894	0.004

Paired t-test *** Significant difference**

Table 3: Pearson's correlation test between stature and foot outline (cm) – right and left foot

	Right foot		Left foot	
Parameters	Pearson Correlation (r)	p-value	Pearson Correlation (r)	p-value
T1	0.827	<0.001*	0.768	<0.001*
T2	0.809	<0.001*	0.805	<0.001*
T3	0.801	<0.001*	0.777	<0.001*
T4	0.724	<0.001*	0.693	<0.001*
T5	0.706	<0.001*	0.826	<0.001*

Pearson's correlation test

Table 4: Pearson's correlation test between Stature and Foot print (Cm) – Right and Left foot

	Right foot		Left foot	
Parameters	Pearson Correlation	p-value	Pearson Correlation	p-value
T1	0.838	<0.001*	0.800	<0.001*
T2	0.817	<0.001*	0.795	<0.001*
T3	0.798	<0.001*	0.784	<0.001*
T4	0.731	<0.001*	0.795	<0.001*
T5	0.704	<0.001*	0.639	<0.001*

Table 5: Regression equations for estimating stature from foot outlines, where stature = X and foot outline = Y, accordingly for the Right and Left foot

	Right foot		Left foot	
Foot outlines	**Beta Coefficients**	**Regression equations**	**Beta Coefficients**	**Regression equations**
T1	51.889	X= 51.889 + 4.427 x Y	53.734	X= 53.734+ 4.344 x Y
T2	58.291	X = 58.291 + 4.245 x Y	61.027	X = 61.027 + 4.127 x Y
T3	55.341	X= 55.341+ 4.521x Y	60.031	X= 60.031+ 4.316x Y
T4	80.741	X= 80.741+ 3.662 x Y	56.947	X= 80.741+ 4.676 x Y
T5	86.870	X= 86.870+ 3.693 x Y	103.510	X= 103.510+ 2.856 x Y

Table 6: Regression equations for estimating stature from footprint, where stature X and footprints = Y, accordingly for the right and left foot.

	Right foot		Left foot	
Foot prints	**Beta Coefficients**	**Regression equations**	**Beta Coefficients**	**Regression equations**
T1	61.331	X= 61.331 + 4.336x Y	71.150	X= 71.150 + 3.895x Y
T2	65.965	X = 65.965 + 4.180 x Y	64.602	X = 64.602 + 4.214 x Y
T3	66.042	X= 66.042+ 4.332x Y	70.364	X= 70.364+ 4.115x Y
T4	87.165	X= 87.165+ 3.600 x Y	88.976	X= 88.976+ 3.495x Y
T5	94.385	X= 94.385+ 513 x Y	58.208	X= 58.208+ 5.268 x Y

DISCUSSION

Footprint and foot outline measurements are increasingly recognized as reliable tools for personal identification, especially in forensic sciences, where human remains may be fragmented. Such morphometric evaluations hold significant value at crime scenes for suspect identification. Considering these practical applications, the present research was designed to explore the correlation between footprint dimensions, foot outline, and stature among young adults from northern India.

In this study, stature estimation was performed using both linear regression equations and multiplication factors, derived from footprint and foot outline measurements of both male and female participants. A slight asymmetry was observed between the right and left foot dimensions, with left-sided measurements showing a marginal predominance. The findings suggest that footprint and foot outline parameters provide more accurate stature estimation compared to foot breadth or other foot dimensions, applicable to both sexes.

The linear regression models developed in this study demonstrated a strong relationship between footprint/foot outline dimensions and stature for both males and females, supporting the use of these measurements in forensic investigations. When compared to earlier research by Kewal Krishan (42), our study showed that the mean values of right and left footprints and foot outlines were slightly higher, possibly reflecting population-specific variations.

Similarly, Ukoha et al. (9) conducted a study comparing footprint dimensions for stature estimation, and while our results also showed slightly higher mean values, these differences were not statistically significant. Such variations are expected due to differences in genetic makeup, environment, and geographic diversity among populations. In a large-scale study by Qamra et al. (43), foot length and foot breadth were measured in over 1000 individuals aged 17 to 32 years to assess stature. They concluded that foot length provided the most reliable estimation. Differences in multiplication factors across studies, including ours, may stem from the diversity of the study population, as their research was confined to a specific geographic area, whereas our sample represented a more varied group.

Our study also revealed a significant correlation between right and left foot outline measurements and stature in both sexes. When data from both genders were pooled, the correlation coefficients between stature and footprint/foot outline dimensions were statistically significant ($p < 0.05$), indicating a strong overall relationship. Interestingly, the pooled sample demonstrated a stronger correlation than when males and females were analyzed separately. This trend is consistent with similar studies conducted among Malay (44), Malaysian Chinese (45), and Indian (46) populations. Research by Jasuja et al. (47) among Punjabi Jat males reported multiplication factors of 6.88 for the right foot and 6.49 for the left foot length, both slightly higher than the values obtained in our study. These differences can again be attributed to regional variations, as their work focused on a more homogenous group compared to our diverse population from Uttar Pradesh. Differences in multiplication factors may also arise due to varying skeletal proportions linked to geographic or ethnic backgrounds.

The association between foot length and stature has been well-documented, with Giles et al. (48) also establishing that foot length correlates significantly with height, reinforcing its utility in stature prediction. Further, studies in Indian (49,50) and Turkish populations (51) revealed that regression equations for stature estimation vary across different ethnic groups, highlighting the importance of developing region-specific models to account for biological diversity. The formulae proposed for estimating stature from foot and shoe dimensions also show variations among populations, emphasizing this need (52).

Additional research by Surinder Nath and Divya Chang (53) introduced regression models to estimate stature from foot length, foot breadth, shoe length, and shoe breadth, with multiplication factors being refined to minimize estimation errors. Similar studies by Bhavana and Nath (54) reported that tibial length displayed the highest correlation with stature, whereas foot breadth showed the lowest correlation, aligning with our observation that foot length, rather than foot breadth, is a more dependable parameter for height estimation.

Sex-based differences in footprint and foot outline measurements were significant in our study, with males exhibiting larger dimensions for both foot size and stature compared to females ($p < 0.000$). This disparity may be linked to differences in skeletal growth patterns, where epiphyseal fusion occurs earlier in females, limiting bone growth duration relative to males. While significant sex differences were observed, no statistically significant differences were found between right and left foot lengths within individuals. This suggests minimal bilateral asymmetry, reinforcing that either foot can be reliably used for stature estimation.

Previous studies, including those by Singh (55) and Chhibber and Singh (56), proposed that individuals tend to favor their dominant lower limb, potentially leading to larger bone dimensions and footprint size on that side. However, our study, conducted among the urban population of Moradabad, Uttar Pradesh, did not find statistically significant asymmetry between the right and left feet. This aligns with findings by Philip (57) among South Indian populations and Robbins (58) among American participants, both reporting minimal bilateral differences in footprint dimensions.

Overall, the results of this study confirm that both footprint and foot outline measurements can serve as effective tools for estimating stature. The established linear regression equations, derived from a population-specific sample, provide reliable models for stature estimation, contributing to forensic anthropology and personal identification in northern India.

CONCLUSION

The present study establishes that footprint and foot outline measurements can serve as dependable indicators for estimating stature among young adults from northern Uttar Pradesh, India. By analyzing foot dimensions from both the right and left feet in 200 individuals aged 18 to 30 years, a consistent and statistically significant correlation was observed between foot parameters and height. Regression equations developed from this dataset demonstrated that foot length, outline, and segment measurements can predict stature with considerable accuracy.

These results reaffirm the relevance of using foot-based morphometric assessments in forensic investigations, especially in cases where only partial remains, such as foot fragments or footprints, are available for identification. However, given the known influence of geography, ethnicityand lifestyle on human body proportions, a universal formula cannot be applied across all populations. This emphasizes the importance of region-specific research to develop reliable models suited to distinct populations for anthropological and forensic applications.

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