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ORIGINAL ARTICLE

Estimation of Stature From Foot Length: An Anthropometric Study

S.M. Krishna Sagar[1], Boddepalli Devaraj,[2,*] Md.Shanawaz,[4] Mohit Kumar Moses T[1], Amrutha Rauthu,[3] Anamika Singh,[3] Ganesh Yalla,[3] Roshini Konatham[3] and Kattamreddy Ananth Rupesh[1]

[1]*Assistant Professor of Forensic Medicine and Toxicology, Andhra Medical College, Visakhapatnam*
[2]*Junior Resident, Department of Forensic Medicine and Toxicology, Andhra Medical College, Visakhapatnam*
[3]*Department of Forensic Medicine and Toxicology, Andhra Medical College, Visakhapatnam*
[4]*Associate Professor of Forensic Medicine and Toxicology, KIMS & RF, Amalapuram*

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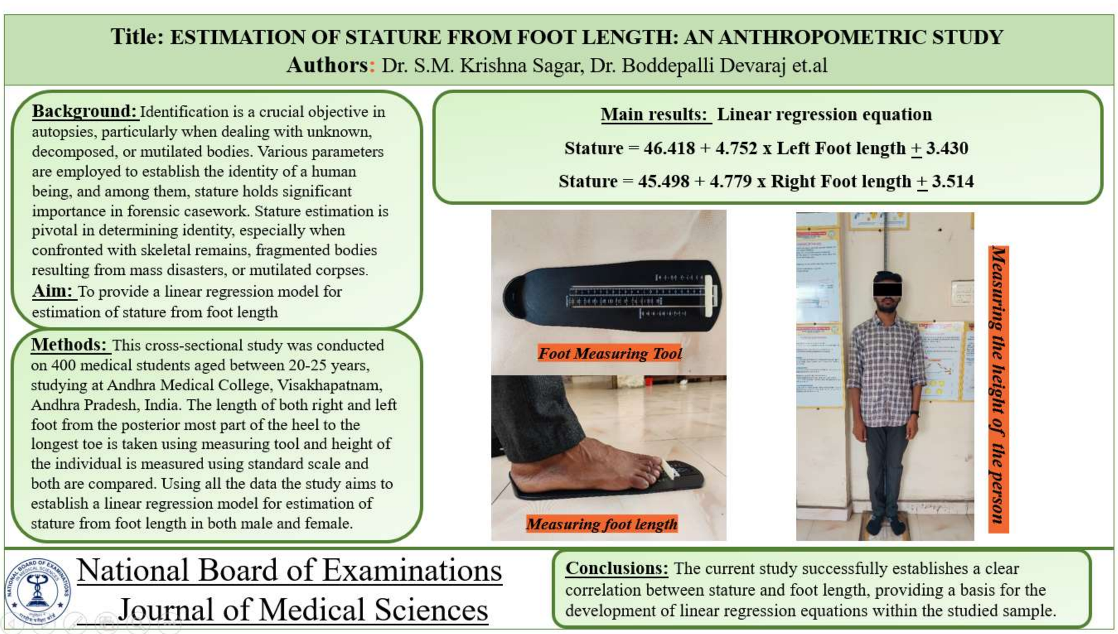
Abstract
Background: Identification is a crucial objective in autopsies, particularly when dealing with unknown, decomposed, or mutilated bodies. Various parameters are employed to establish the identity of a human being, and among them, stature holds significant importance in forensic casework. Stature estimation is pivotal in determining identity, especially when confronted with skeletal remains, fragmented bodies resulting from mass disasters, or mutilated corpses. **Objectives:** The main objective of the present study was to determine the relation between foot length and the stature of individual by using correlation coefficient in both sexes. To provide a linear regression model for estimation of stature from foot length in both males and females. **Methodology:** This cross-sectional study was conducted on 400 medical students aged between 20-25 years, studying at Andhra Medical College, Visakhapatnam, Andhra Pradesh, India. The length of both right and left foot from the posterior most part of the heel to the longest toe is taken using measuring tool and height of the individual is measured using standard scale and both are compared. Using all the data the study aims to establish a linear regression model for estimation of stature from foot length in both male and female. **Conclusion:** In all the groups, a significant and positive correlation between stature and foot length was established, and regression equations were derived for both the feet. An attempt was made to study the correlation between stature and foot length separately in both the sexes. However, owing to no significant difference in the results obtained, entire study sample was taken as a single unit for deriving the regression equation. In conclusion, the individual foot length proves to be useful for stature estimation, offering crucial support for forensic experts and anthropologists.

Keywords: Identification, Stature, Foot length, Correlation coefficient, Linear Regression Equation.

*Corresponding author: Boddepalli Devaraj
Email: devarajboddepalli@gmail.com

Graphical Abstract



Introduction

Identification involves determining an individual's identity based on specific physical characteristics such as age, sex, and stature. Positive and negative identification are crucial aspects of forensic medicine, playing pivotal roles in investigations. Opinions formed through identification can serve as valuable investigative leads, and well-evaluated opinions can contribute to solving cases. In the investigation of the assassination of former Prime Minister of India, Rajiv Gandhi, foot length and footwear became critical pieces of evidence, aiding in collecting adjoining mortal remains and guiding the investigation.

Estimating stature is a vital factor in forensic investigation, particularly in forensic anthropology. The association between stature and the length of various body parts, such as long bones, trunk, and extremities, has been well-researched by the scientific community. Traditionally, stature has been estimated using long bones like the tibia, ulna, and humerus. Foot length has also been employed for the same purpose by several researchers. The field of foot studies in forensic contexts is continually expanding, with a notable example being Forensic podiatry—a specialized branch that utilizes podiatric expertise to investigate and establish connections between individuals and crime scenes, addressing legal inquiries related to feet, footwear, and foot function. Forensic identification from the foot and its parts remains relevant even in the DNA era, especially in mass disasters like explosions, bomb blasts, and transportation accidents. The recovery of feet, often enclosed in shoes, is common and helpful. Moreover, choosing foot length for stature estimation can yield more precise results compared to long bones, given that the foot reaches its maximum length earlier, typically during adolescence. Variations in stature estimation from limb measurements are observed among individuals from different population groups and have been documented in published literature. To understand the relationship between stature and foot length further, a cross-sectional study was conducted to explore the connection among our study participants.

Materials and Methods

Study Design

This cross-sectional study was conducted over a period of three-months from June to August 2023 among 400 healthy subjects, medical students at Andhra Medical College, Visakhapatnam, Andhra Pradesh who belong to south India.

Inclusion Criteria

M.B.B.S. students of Andhra Medical College who belong to south India, aged 20-25 years, without skeletal deformities, who had not undergone any surgical procedures on their limbs or foot skeleton, were included in the study.

Exclusion Criteria

Age below 20 and above 25, subjects diagnosed with lower limb and foot deformities and those who had sustained recent injuries, Obese individuals and Other than south Indians were excluded from the study.

Materials & Methodology

An anthropometer, a stadiometer, a foot measuring tool which can measure in millimetres, a computer with SPSS software. After taking informed written consent, stature of all subjects was measured using stadiometer in upright position with bare foot while standing on flat surface, heels, middle of the shoulders, buttocks and back of head touching stadiometer, with chin parallel to ground. The dimensions of both the left and right feet of each individual were measured and recorded on a data collection form separately. The maximum foot length was measured in sitting position to avoid error due to weight bearing, from the acropodion (tip of the hallux or second toe when the latter is longer than the hallux) to the pterion (most prominent point on the back of the heel), nails crossing the nailbeds were removed and measured. For the purpose of this study, the stature was defined as the vertical distance between the vertex and the floor when the head was held in the Frankfurt Horizontal (F.H) plane. The measurements are taken in the forenoon to avoid diurnal variations. The measurements are not rounded off. All findings were recorded in a proforma. The data analysis was carried out using Statistical Packages for Social Sciences, SPSS 26 (Figures 1 to 3).

Figure 1. Foot Measuring Tool

Figure 2. Measuring foot length

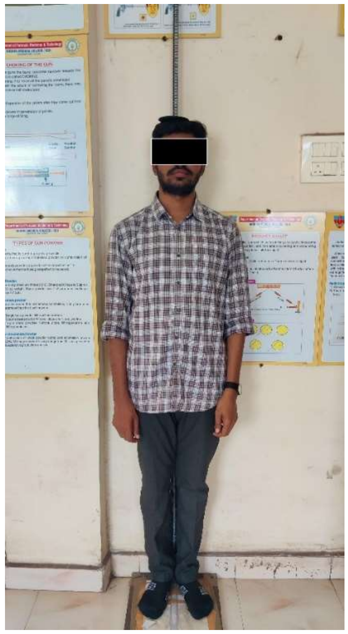


Figure 3. Measuring the height

Results

A total of 400 subjects (200 boys and 200 girls) participated in this study, their minimum and maximum heights, mean height, range, standard deviation and standard error are summarised in Table 1. Gender wise distribution of the stature is tabulated under Table 2. Distribution of foot lengths in males and females is tabulated under Tables 3,4 respectively. An attempt was made to study the correlation between stature and foot length separately in both the sexes. However, owing to no significant difference in the results obtained, entire study sample was taken as a single unit for deriving the regression equation. Similarly, the preliminary statistics calculated showed a promising difference between left and right foot. Hence, separate regression equations were derived. Pearson's correlation (r) between the stature and foot lengths is tabulated under Table 5. Right and left foot length measurement in both males and females combined together is tabulated under Table 6. Regression equations for stature from foot length is tabulated under Table 7.

Table 1. Height in All the Subjects

Total Number(n)	400
Minimum Height (cm)	143
Maximum Height(cm)	188
Mean Height(cm)	166
Range(cm)	45
Standard Deviation (SD)	9.27
Standard Error (SE)	0.4634

Table 2. Gender Wise Distribution of the Stature

Stature in cm	Male(n=200)	Percentage %	Female(n=200)	Percentage %
143-150	0	0%	11	5.5%
151-160	03	1.5%	110	55.0%
161-170	69	34.5%	71	35.5%
171-180	107	53.5%	08	4.0%
181-188	21	10.5%	0	0%

Table 3. Distribution of Foot Lengths in Males

Foot Length (cm)	Male(n=200)	
	Left foot	Right foot
23-26	76	79
26.1-27.5	86	87
27.6-30	38	34

Table 4. Distribution of Foot Lengths in Females

Foot Length (cm)	Female(n=200)	
	Left foot	Right foot
20-23	40	38
23.1-25	127	124
25.1-28	33	38

Table 5. Right and Left Foot Length Measurememt in Both Males and Females Combined Together

	Left Foot	Right Foot
Minimum Foot length(cm)	20.1	20.3
Maximum foot length(cm)	29.8	30
Mean foot Length(cm)	25.2206	25.2715
Range of foot Length(cm)	9.7	9.7
Standard Deviation	1.694756	1.678177
Standard Error	0.0847378	0.08390885

Table 6. Pearson's Correlation (R) Between the Stature and Foot Lengths

	r	r^2	P value
Left foot	0.869	0.755	<0.001
Right foot	0.865	0.749	<0.001

Table 7. Regression Equations for Stature from Foot Length

	Value of Constant **(A)**	Regression coefficient **(B)**	Error	Regression Equation
Left foot	46.418	4.752	3.430	46.418 + 4.752 x LFL $\pm$3.430
Right foot	45.498	4.779	3.514	45.498 + 4.779 x RFL $\pm$3.514

Figures 4 and 5 shows the scatter plot of relation between the height and foot length of left and right foot respectively. X-axis - Foot measurements & Y-axis - Height of the individual.

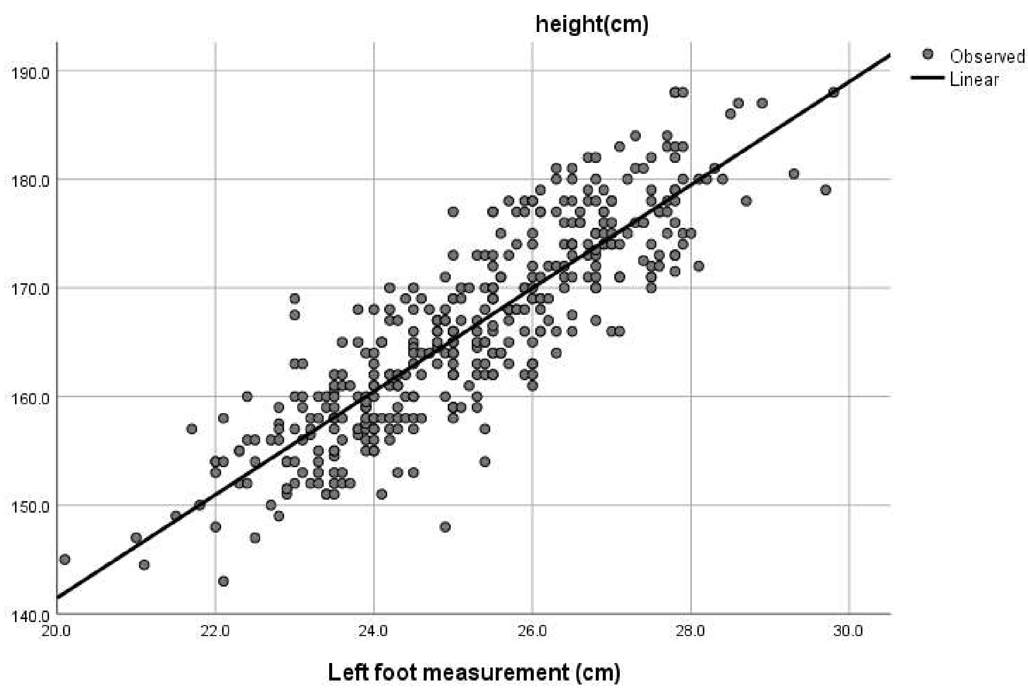


Figure 4. Scatter Plot –Relation between the height and left foot length.

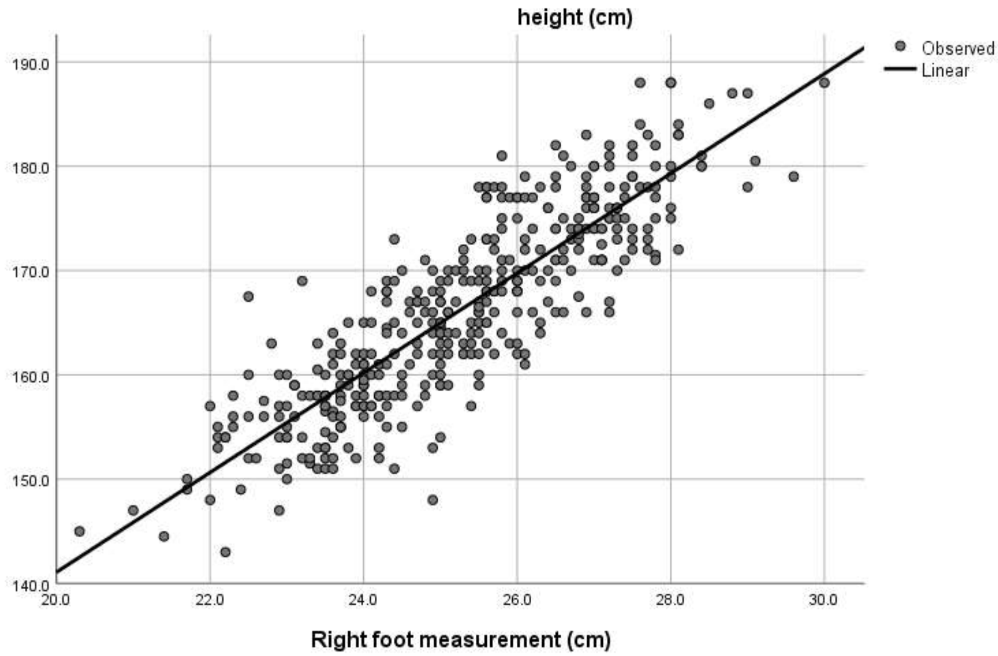


Figure 5. Scatter Plot –Relation between the height and right foot length.

The correlation coefficients between the parameters height and foot lengths are positive. "The low standard errors of estimates (SEE) for both left (4.5932) and right (4.6514) foot lengths, along with highly significant one-way Analysis of Variance (ANOVA) results (F=1226.587, P<0.001 for left foot; F=1186.247, P<0.001 for right foot), suggest that foot length is a significant and reliable predictor in estimating stature. This significance implies that the foot length provides highest reliability and accuracy in estimating stature of an unknown individual.

Based on this study, Regression equation is established for both left and right foot.

STAURE (S) = VALUE OF CONSTANT (A) + REGRESSION COEFFECIENT (B) x FOOT LENGTH ± ERROR

S (LEFT FOOT) = 46.418 + 4.752 x LF length ± 3.430

S (RIGHT FOOT) = 45.498 + 4.779 x RF length ± 3.514

Discussion

Several studies were carried out for estimation of human stature so far and researchers employed a multitude of methods. However, regression equation was used as a statistical tool by most of them. The chronological order of a few studies is summarized in the Table 8 below.

Table 8. Data from a few previous studies on estimating stature from foot length in a chronological order.

S. No	Authors (Year of study) (Place of study)	Sample size (Male+Female) (Age)	Regression Equation	Correlation Coefficient (r)
1.	Krogman Pg.no. 175,177 **Macdonnel** (2001)	3000 (>21yrs)	**Height** =166.45716+4.0301 x Foot Length – 25.68770 ± 2.94453	N.A
2.	**Hilmi Ozden et al.** [1] (2004)	569 (294+275) (>19yrs)	**Right foot**: stature = 47.93 + 1.083 (maximum foot length) + 0.788 (shoe length) x 1.813 (shoe number).	RF: 0.579 0.500
			Left foot: stature = 47.33 + 1.139 (maximum foot length) + 0.593 (shoe length) x 1.924 (shoe number)	LF: 0.614 0.490
3.	**Bhavna et al.** (2005) Delhi	N.A	**Height** = 119.74 + 1.92 x Foot length ± 4.77 Multiplication factor to calculate stature from foot length to be 6.76	N.A
4.	**Arun Kumar Agnihotri MD et al.** (2006) Mauritius [2]	250 (125+125) (18-30yrs)	Stature = 67:568 + 3:862 RFL + 3:393 Sex + 0:437 Age (Sex: M =1, F =0) Male Stature= 68:586 + 4:036 RFL Female Stature=77:059 + 3:536 RFL	Mean: 0.877 Male:0.720 Female:0.608
5.	**Tanuj Kanchan et al.** (2007) Punjab [3]	200 (100+100) (18-80yrs males 18-65yrs females)	**Males:** RFL 93.269 + 2.819(RFL) ± 3.878 LFL 90.275 + 2.930(LFL) ± 3.842	0.759 0.764
			Females: RFL 103.270 + 2.365(RFL) ± 4.398 LFL 105.200 + 2.287(LFL) ± 4.427	0.512 0.502
6.	**Theodoros Grivas et al.** (2007) [4]	5093 school children	**Mean Height**= 17:369 + 5:879 x (right foot length) cm 17:592 + 5:861 x (left foot length) cm	
			Boys: Height = 34:113 + 3:716 (right foot length) cm + 2:499 (age) years 33:869 + 3:689 (left foot length) cm + 2:533 (age)years	Boys: RF = 0.903 LF =0.898
			Girls: Height = 34:113 + 3:716 (right foot length) cm + 1:558 + 2:499 (age)years 33:869 + 3:689 (left foot length) cm +1:774 + 2:533(age) years	Girls: RF =0.855 LF =0.841

7.	**Gulsah Zeybek et al.** (2008) Turkey [5]	249 (136 + 113) 18-44yrs	• **Stature** = 545.070 + 3.707 x RFL - 0.308 x RFW + 1.583 x RFMH + 2.058 x RFNH $\pm$ 38.69.	RF: M:0.741 F:0.678 LF: M: 0.711 F:0.667
8.	**Derya Atamturk et al.** (2008) Ankara, Turkey [6]	516 (253+263) (17.6-82.9yrs)	• S = 5.295 x FL + 38.903 $\pm$ 5.142 • S = (4.211 x FL) + (4.981 · Sex) + 62.208 $\pm$ 4.835 (sex; female = 0 and male = 1)	Height and FL: 0.737 Height, FL and Sex: 0.768
9.	**Jaydip Sen and Shila Ghosh** (2008) Darjeeling, West Bengal [7]	350 (175+175)	**Male**: S= 83.518 + 3.282(FL) RFL 84.041 + 3.264(RFL) LFL 84.076 + 3.255(LFL) **Females**: S= 67.009 + 3.707(FL) RFL 68.642 + 3.638(RFL) 0.682 LFL 68.663 + 3.632(LFL) 0.682	0.626 0.624 0.623 0.692 0.682 0.682
10.	**Tanuj Kanchan et al.** (2009) Punjab [8]	100 (50+50) (18-32yrs)	**RFL**: Males: H= 88.116 + 3.007 (RFL) $\pm$ 3.746 Female: H= 106.709 + 2.219 (RFL) $\pm$ 4.313 **LFL**: Males: H=95.202 + 2.737 (LFL) $\pm$4.024 Female: H=104.302 + 2.324 (LFL) $\pm$ 4.387	 0.750 0.558 0.704 0.536
11.	**Nivedita Pandey et al.** (2011) Mumbai [9]	200 (100+100) (18-23 years)	**Males:** S = 128.951+1.695(RFL) $\pm$ 0.339 S = 106.265 +2.236 (LFL) $\pm$ 0.385 **Females:** S = 118.533 +1.692 (RFL) $\pm$ 0.368 S = 128.233 +1.726 (LFL) $\pm$ 0.344 **Mean:** Males: S = 128.039+0.761 (RFL)+0.971 (LFL) $\pm$ 3.176 Females: S = 106.623+0.297(RFL)+2.520 (LFL) $\pm$ 1.492	**Males:** 0.451 0.452 **Females:** 0.421 0.506

12.	**Petra Uhrova et al.** (2012) Slovakia [10]	71 (18-27yrs)	**Right foot**: 54.354 + 4.715 RFL ± 4.652 **Left foot**: 52.999 + 4.755 LFL ± 4.765 **Multiple regression**: 53.125 + 3.455 RFL + 1.304 LFL ± 4.668	**Females:** RFL:0.722, LFL:0.704 **Males:** RFL:0.759, LFL:0.755
13.	**Sonali khanapurkar et al.** (2012) Maharashtra [11]	1000 (536+464) (19-22 yrs)	'Height = 55.5+4.5 x Foot length'. The correlation coefficient for foot length in females and males was 0.702 and 0.645 respectively.	Females and males were 0.702 and 0.645 respectively.
14.	**Mansur et al.** (2012) Nepal [12]	440 (258+182) (17-25yrs)	**Mean:** Height = 3.179 x foot length + 87.65'.	**Mean**: 0.703
			Males: Height = 2.738 x left foot length + 100.2 Height = 2.74 x right foot length + 100.1	**Male:** 0.689 0.688
			Females: Height = 2.66 x left foot length + 96.40 Height = 2.66 x right foot length + 96.31	**Female:** 0.589 0.587
15.	**Kewal Krishan et al.** (2012) Himachal Pradesh [13]	246 (123 +123) (17-20 years)	**Males**: 69.544 + 3.995 (FL) **Females**:74.820 þ 3.579 (FL)	N.A
16.	**Mohanty et al.** (2012) Odisha [14]	300 (206+94) (18-25yrs)	**Males:** H = -27.77 + 7.695x FL **Females:** H = 77.85 + 3.58 x FL	N.A
17.	**Saranabasavappa Karaddi et al.** (2013) Gulbarg [15]	100 Males (18-23yrs)	**Right foot:** H = 86.9 + 3.40(RFL) **Left foot:** H =112 + 2.41(LFL)	0.82 0.80
18.	**Patel et al.** (2014) Gujrat	150 (72+78) (18-22yrs)	**Males** = 75.45 + 3.64 x Foot length **Females** = 75.41 + 3.43 x Foot length	0.65 0.80
19.	**Sunita Arvind Athavale et al.** (2015) [16]	200 (100+100) (20-30yrs)	**Stature** = 81.978 +.294 x foot length ± 6.91	0.554 0.550

20.	**Arif Rasheed Malik et al.** (2015) Lahore, Pakistan [17]	291 (>20yrs)	**Left foot length:** **Mean:** S = 58 .101+ 4.261(LFL) **Males:** S=104.455 + 2.591(LFL) **Females:** S= 8 8.210 + 2.9 3(LFL)	 0.807 0.590 0.630
21.	**Phang et al.** (2016) Malaysia [18]	150 (75 +75) (20-30 years)	**Mean:** H= 56.6471 + (4.408 x FL) ± 6.2571	0.815
			Male: H= 98.8059 + (2.792 x FL) ± 11.2328	0.594
			Female: H = 60.9966 + (4.167 x FL) ± 11.6854	0.697
22.	**Chauhan Viral et al.** (2017) Gujarat [19]	208 (105+103) (10-60yrs)	**Stature** = 55.427 + 4.633 x Foot length ± 5.126	0.806
23.	**Arun S. Karmalkar** (2021) Kolhapur [20]	1000 (18–50 years)	**Stature**= 63.1858×intercept+1.7392×right foot length –0.2278× left foot length –2.801×right foot breadth +2.7907×left foot breadth +0.4377×right hand length +2.7687×left hand length –4.7225×right hand breadth +5.5211×left hand breadth ± 4.689	0.670
24.	**Trishna Priya Devi et al.** (2021) Assam [21]	200 males (18-65yrs)	**Height** = 4.56414(RFL) + 58.58265	0.9720
			Height = 4.71546(LFL) + 55.78708	0.9749
25.	**Kumar et al.** (2023) South India [22]	200 (100+100) (21-40 y	Mean: Stature=53.591+4.489×RFL Stature=55.195+4.469×LFL	Mean: 0.811 0.823
			Males: Stature=89.297+3.158×RFL Stature=89.163+3.189×LFL	 0.677 0.707
			Females: Stature=84.203+3.087×RFL Stature=82.477+3.203×LFL	 0.592 0.582

Our study established a positive correlation between stature and foot length, aligning with findings in several other studies as detailed in Table 8 and we used a linear regression method for deriving the regression formula. However, our results indicated no significant differences in estimating stature from foot length, irrespective of left or right side and gender. This observation is consistent with the findings of Hilmi Ozden et al. (2005).[2] Nonetheless, some other studies have suggested that the standard error of estimate is lower when a multiple regression equation is utilized for stature estimation, as opposed to linear regression. Additionally, among females, the standard error of estimate is lower compared to males. This implies that the accuracy of stature estimation is higher in females, as highlighted by Tanuj Kanchan (2007) [5]

Future studies on estimating stature from foot length in India need to consider a multitude of neglected aspects within this subject. Firstly, existing research predominantly focuses on intact foot and more research is needed on relationship between skeletal foot length and stature. The roots of this research lie in dry bones, and delving further into that can help standardise this method further. Secondly, while some studies touch upon parameters like the breadth of the foot and the height of the malleolar bone, there remains a need for more extensive investigations utilizing these metrics in stature estimation. Thirdly, the majority of studies conducted thus far have centred around the living, potentially overlooking the impact of postmortem changes on measurements. Future research should emphasize studies on the deceased, recognizing the potential errors that may arise due to postmortem alterations and ensuring the applicability of findings in forensic contexts. By the same taken, considering the diverse regional demographics in India, it is imperative to conduct age-wise distributions based on previous studies. This approach will not only enhance the specificity of stature estimation methods but also provide valuable data for different age groups, contributing to a more nuanced understanding of the population.

Furthermore, as research on stature estimation in India has yielded varied regression formulas from different states, there is a pressing need for a multicentric project involving several medical colleges in different states. Such an initiative would consolidate findings from across the country, facilitating a standardized approach to stature estimation with an acceptable margin of error.

In advancing future studies on stature estimation from foot length in India, a crucial avenue to explore involves incorporating radiology data. Utilizing large datasets from clinical cases where foot X-rays are routinely taken can significantly enhance the precision of regression formulas. By obtaining consent and recording the height of individuals undergoing foot X-rays for clinical purposes, researchers can establish comprehensive databases.

Estimating stature from foot length has become a popular medical school project for many individuals, and existing literature in this context is abundant. However, the need to delve deeper into standardizing these methods is evident, as the established relationship between stature and foot length may vary across populations. It is crucial to recognize that data generated in one population cannot be universally applied to another. Therefore, the next phase of research requires the compilation of comprehensive datasets to further refine and standardize these techniques. This is especially pertinent for practical applications in forensic anthropology settings, where accurate and population-specific stature estimations are essential.

Conclusion

The current study successfully establishes a clear correlation between stature and foot length, providing a basis for the development of regression equations within the studied sample. Notably, during the calculation of the regression equation, a consistent linear relationship between stature and foot length is observed, aligning with findings from previous studies. The established regression equations offer a valuable tool for forensic practitioners in scenarios such as mass disasters, cases involving dismembered bodies post-homicide, bomb explosions, accidents, and other situations where only partial remains are recovered.

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Ethics committee approval

The present study was approved by the Ethics Committee of Andhra Medical College, Visakhapatnam vide reference (Serial no. 243/IEC AMC/OCT 2023).

Conflict of Interest

The authors declares that they do not have conflict of interest.

Funding

Not Applicable

List of abbreviations used in the table or in the study as a whole

LF= Left foot, RF: Right foot, LFL: Left foot length, RFL: Right foot length, H= Height, S= Stature, FL= Foot Length, RFW= Right Foot Width, RFMH= Right foot Malleolar height, RFNH= Right foot Navicular height, M=Male, F=Female, r = Correlation coefficient, N.A: Not Available.

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