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Development of Sex- and Zone-Specific Regression Equations for Stature Estimation Using Percutaneous Tibial Length - A Cross-Sectional Study

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Abstract

Background: Stature estimation is an essential component of forensic identification, particularly in identifying individuals from skeletal or fragmentary human remains encountered during disasters and medico legal investigations.

Aim: To develop sex- and zone - specific regression equations for estimating stature in the contemporary Indian population using percutaneous tibia length measurements.

Methods: A cross-sectional study was conducted among 480 medical students aged 18-30 years at Sri Devaraj Urs Medical College, Kolar, Karnataka. The study included 60 males and 60 females from each of the four geographical zones of India (North, South, East, and West) selected using a simple random sampling method. The eligible participants were assigned serial numbers, and a computer-generated list was used to select participants. Stature and bilateral percutaneous tibial lengths were measured using standard anthropometric techniques. Pearson's correlation and simple linear regression analyses were performed to derive regression equations for stature estimation.

Results: The mean age of the participants was 23.32± 2.97 years in males and 23.19 ± 2.60 years in females. Males had significantly greater mean stature (173.35 ± 7.36 cm) and tibial length (38.81 ± 2.67 cm) than females (160.19 ± 5.48 cm and 34.96 ± 2.04 cm, respectively; $p < 0.001$), demonstrating clear sexual dimorphism. No significant bilateral differences were observed between the right and left tibial lengths ($p > 0.05$).

A strong positive correlation was observed between stature and percutaneous tibial length (r = 0.73–0.88, R^2 = 0.52–0.78, SEE = 3.26–3.97 cm), indicating a strong relationship and good predictive performance.

Conclusion: Percutaneous tibial length is a reliable predictor of stature in the contemporary adult Indian population. Sex- and zone-specific regression equations may provide more population-appropriate estimates than generalized equations. These equations may serve as valuable tools in forensic identification and anthropological investigations.

Keywords: Stature Estimation, Percutaneoustibial Length, Forensic Anthropology, Regression Analysis, Anthropometry.

Introduction

Human identification is one of the fundamental objectives of forensic medicine. Establishing the identity of unknown individuals is essential in medico legal investigations involving decomposed, mutilated, fragmented, or skeletal human remains.[1]

Identification may be complete or partial depending on the available evidence. Partial identification is performed when only fragmented or incomplete biological information is available, requiring the reconstruction of an individual's identity. Age, sex, ancestry, and stature are among the principal biological parameters used in partial identification.

Stature is an important component of the biological profile used in forensic identification.[2] It is influenced by several factors, including genetics, nutrition, environmental conditions, sex, age, and physical activity. [3] The relationship between stature and long-bone length varies among populations, ethnic origins, and geographical locations. [3] In India, climatic conditions, dietary habits, and ethnic composition vary considerably across regions. Regression equations developed for one population may not be directly applicable to another.[4] Improved socioeconomic conditions over recent decades have contributed to an increase in the average stature of the Indian population, thereby influencing the relationship between stature and long-bone length.[5,6]

Regression equations are widely used for stature estimation from long-bone measurements. Selecting an appropriate regression equation requires consideration of the individual's sex and population of origin.[7]

Tibial length is considered one of the most reliable predictors of stature because it demonstrates a strong correlation with overall body height.[8] Although several Indian studies have reported regression equations for stature estimation using percutaneous tibial length, most were limited to a single geographical region or population group. To date, few studies have compared all four geographical zones of India using a standardized methodology in a contemporary Indian population. In view of this knowledge gap, the present study aimed to develop and compare sex- and geographical zone-specific regression equations for stature estimation using percutaneous tibial length in a contemporary Indian population.

Materials and Methods

A cross-sectional study was conducted in the Department of Forensic Medicine and Toxicology at Sri DevarajUrs Medical College (SDUMC), Tamaka, Kolar, Karnataka, among medical students aged 18–30 years.

Sample Size and Sampling

The study included 480 participants selected using simple random sampling. Participants were equally distributed across the four geographical zones of India (North, South, East, and West),[9] with 60 males and 60 females from each zone, resulting in a total of 120 participants per zone. The eligible participants were assigned serial numbers, and a computer-generated list was used to select participants. Stature and bilateral percutaneous tibial lengths were measured using standard anthropometric techniques. Pearson's correlation and simple linear regression analyses were performed to derive regression equations for stature estimation.

Inclusion Criteria

- Healthy adult students of SDUMC, Kolar.
- Participants aged 18–30 years.

Exclusion Criteria

- Students with a history of congenital or acquired skeletal deformities**.**
- Individuals with a history of fractures, orthopaedic surgeries, or musculoskeletal disorders affecting the long bones.

Anthropometric Measurements

Participants were asked to stand barefoot on a flat surface in the anatomical position, with their heels together, arms relaxed at their sides, and the head positioned in the Frankfort horizontal plane. Stature was measured using a stadiometer as the vertical distance from the most inferior point of the heel to the vertex of the head. The measurements were recorded to the nearest 0.1 cm. [3,4,5]

Percutaneous Tibial Length

Percutaneous tibial length was measured with the participant seated with the knee semi-flexed and the foot slightly inverted. A spreading caliper was used to measure the distance between the most prominent palpable point of the medial tibial condyle and the tip of the medial malleolus. [10] The measurements were recorded to the nearest 0.1 cm. All measurements were obtained by the same observer. Each measurement was recorded twice, and the mean of the two measurements was used for statistical analysis.[1,2,4,5]

Fig 1: Stature measurement using a stadiometer

Fig 2: Tibia measurement from the medial condyle to the tip of the medial malleolus.

Statistical Analysis

The data were analysed using IBM SPSS version 22, and the mean, standard deviation, and range were calculated. Pearson's correlation coefficient was used to assess the relationship between stature and percutaneous tibial length. Simple linear regression analysis was performed to derive regression equations. A p-value < 0.05 was considered statistically significant. The simple linear regression equation was expressed as $Y = A + BX$,

Where Y = estimated stature (cm), A = Regression constant, B = Regression coefficient (slope), X = Percutaneous tibial length (cm).

Prior to regression analysis, the assumptions of linearity and normality of residuals were assessed. Linearity was evaluatedusing scatter plots and residual plots, while normality of residuals was assessed using histograms, Q–Q plots, and the Shapiro–Wilk test. Visual inspection indicated no substantial deviation from these assumptions, supporting the use of simple linear regression models. Residual plots also demonstrated homoscedasticity.

Results

A total of 480 participants were included, with equal numbers of males and females from each geographical zone, allowing balanced comparisons across sex and regions.

Table 1: Baseline characteristics of study participants according to sex and geographical zone.

Zone	Sex	n	Age (years) Mean ± SD	Stature (cm) Mean ± SD	Tibial length (cm) Mean ± SD	Sex comparison p-value Stature / tibial length
South	Male	60	22.97 ± 3.24	173.33 ± 5.99	39.41 ± 2.22	<0.001
	Female	60	22.45 ± 1.60	159.20 ± 4.97	34.92 ± 1.95	
North	Male	60	24.45 ± 2.15	173.91 ± 7.61	38.33 ± 2.65	<0.001
	Female	60	24.45 ± 2.15	161.19 ± 5.31	35.01 ± 2.01	
East	Male	60	22.97 ± 3.24	171.83 ± 8.27	38.35 ± 3.11	<0.001
	Female	60	22.97 ± 3.24	161.11 ± 5.47	35.33 ± 1.83	
West	Male	60	22.90 ± 2.92	174.32 ± 7.31	39.17 ± 2.52	<0.001
	Female	60	22.90 ± 2.92	159.27 ± 5.94	34.56 ± 2.33	

Values are presented as mean ± standard deviation (SD). Tibial length refers to the right-sided measurement. The p-values compare males and females within each geographical zone.

The mean age of male participants was 23.32± 2.97years, and that of female participants was 23.19 ± 2.60 years; the observed differences were comparatively small, indicating a relatively homogeneous age distribution among participants. The mean stature was 173.35 ± 7.36 in males and 160.19 ± 5.48 in females. Male participants were significantly taller than female participants (p <0.001).

The mean tibial length was significantly greater in male participants (38.81 ± 2.67 cm) than in female participants (34.96 ± 2.04 cm), confirming marked sexual dimorphism (p < 0.001).

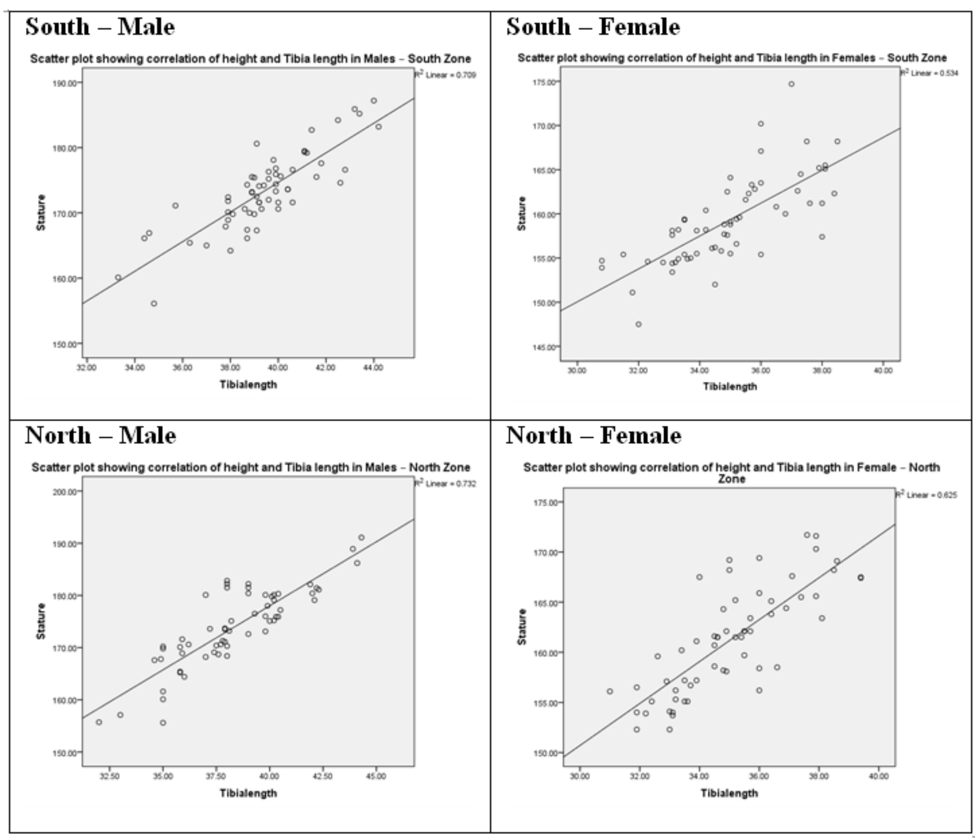
Table 2: Paired comparison of right and left tibial lengths in males and females according to geographical zone.

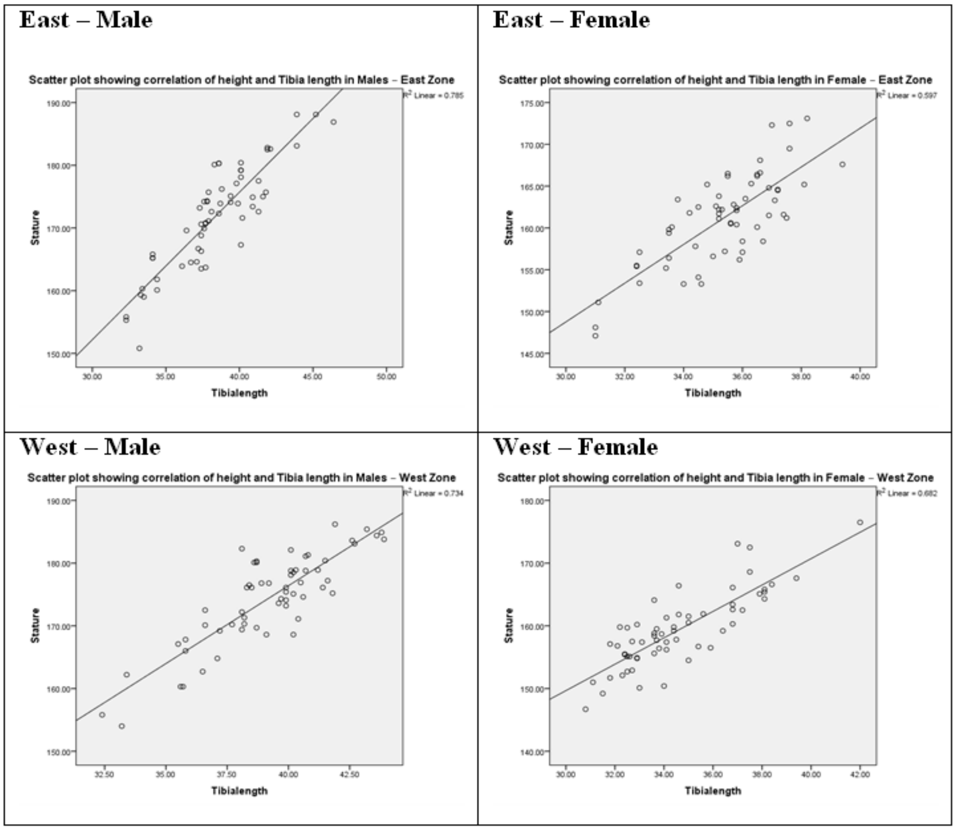
Zone	Bone	Male		Comparison			Female		Comparison		
		RT	LT	T	DF	P	RT	LT	T	DF	P
South	Tibia	39.41 ± 2.22	39.15 ± 2.22	0.62	59	0.958	34.91 ± 1.95	34.65 ± 1.98	0.72	59	0.928
North		38.33 ± 2.65	38.02 ± 2.66	0.63	59	0.960	35.01 ± 2.00	34.72 ± 2.02	0.78	59	0.990
East		38.35 ± 3.11	38.00 ± 3.08	0.61	59	0.959	35.33 ± 1.82	34.99 ± 1.82	1.02	59	0.933
West		39.16 ± 2.52	38.76 ± 2.45	0.88	59	0.832	34.56 ± 2.33	34.18 ± 2.34	0.89	59	0.966

t = paired-samples t-test statistic; df = degrees of freedom; p = p-value.

The paired-samples t-test showed no statistically significant differences between the right and left tibial lengths in either sex, suggesting bilateral symmetry of tibial length (p > 0.05).

Fig 3: Scatter plots showing the relationship between stature and percutaneous tibial length in male and female participants across the four geographical zones of India.





Scatter plots demonstrated a linear relationship between stature and tibial length across all groups. Residual plots and Q–Q plots confirmed that regression assumptions were adequately satisfied.

Table 3: Correlation coefficients (r) between stature and right percutaneous tibial length according to geographical zone.

Zones	Bone	Male		Female		Combined	
		r	p	r	p	r	p
South	Tibia	0.84	< 0.001	0.73	< 0.001	0.91	< 0.001
North		0.85	< 0.001	0.79	< 0.001	0.89	< 0.001
East		0.88	< 0.001	0.77	< 0.001	0.89	< 0.001
West		0.85	< 0.001	0.82	< 0.001	0.92	< 0.001

A strong positive correlation between right tibial length and stature was observed in all groups, with correlation coefficients (r) ranging from 0.73 to 0.88. The highest correlation was observed among male participants from the East zone (r = 0.88), while the lowest correlation was observed among female participants from the South zone (r = 0.73).

The correlation between stature and tibial length was statistically significant across all geographical zones ($p < 0.001$).

Table 4: Simple linear regression equations for stature estimation using right and left tibial lengths in the combined-sex sample according to geographical zone

Zone	Right-sided regression equation	R^2	SEE	95% CI for b	Left-sided regression equation	R^2	SEE	95% CI for b

	(Y = A+BX)				(Y = A+BX)			
South	Stature =67.43+2.65 x tibial length	0.83	3.71	2.44-2.87	Stature =68.85+2.63 x tibial length	0.82	3.75	2.41-2.86
North	Stature =66.70+2.76 x tibial length	0.80	4.06	2.51-3.01	Stature =65.11+2.81 x tibial length	0.78	4.23	2.55-3.08
East	Stature =68.52+2.65 x tibial length	0.79	3.98	2.41-2.90	Stature =69.12+2.66 x tibial length	0.79	4.02	2.41-2.91
West	Stature =64.78+2.76 x tibial length	0.84	3.93	2.55-2.98	Stature =65.06+2.78 x tibial length	0.84	3.96	2.57-3.00

b = unstandardized regression coefficient (slope); R^2 = coefficient of determination; SEE = Standard error of estimate; CI = confidence interval.

A strong relationship were observed between tibial length and stature across all geographical zones in the combined-sex sample, with R^2 values ranging from 0.78 to 0.84 and SEE values ranging from 3.71 to 4.23 cm. Only minimal differences were observed between the right- and left-sided regression models.

Table 5: Simple linear regression equations for stature estimation according to geographical zone.

Zone	Male (Y = A+BX)		Female (Y = A+BX)	
	Right	Left	Right	Left
South	Stature =83.89+2.26 x tibial length R^2 = 0.70, SEE = 3.26, 95% CI for b = 1.88-2.65	Stature = 84.74+2.26 x tibial length R^2 = 0.70, SEE = 3.26, 95% CI for b = 1.88-2.64	Stature = 94.20+1.86 x tibial length R^2 = 0.53, SEE = 3.42, 95% CI for b = 1.40-2.31	Stature = 96.42+1.81 x tibial length R^2 = 0.52, SEE = 3.45 95% CI for b = 1.35-2.26
North	Stature =79.86+2.45 x tibial length R^2 = 0.73, SEE = 3.97 95% CI for b = 2.06-2.84	Stature =80.21+2.44 x tibial length R^2 = 0.73, SEE = 3.96 95% CI for b = 2.05-2.83	Stature =88.00+2.09 x tibial length R^2 = 0.62, SEE =3.27, 95% CI for b = 1.66-2.51	Stature =89.91+2.05 x tibial length R^2 = 0.61, SEE = 3.33, 95% CI for b = 1.62-2.48
East	Stature =81.63+2.35 x tibial length R^2 = 0.78, SEE =3.87, 95% CI for b = 2.02-2.67	Stature =81.90+2.36 x tibial length R^2 =0.78, SEE =3.90, 95% CI for b = 2.03-2.69	Stature =79.30+2.31 x tibial length R^2 = 0.59, SEE =3.50, 95% CI for b = 1.81-2.81	Stature =80.75+2.29 x tibial length R^2 = 0.58, SEE = 3.54, 95% CI for b = 1.79-2.80

West	Stature =77.08+2.48 x tibial length R^2 =0.73, SEE = 3.80, 95% CI for b = 2.09-2.87	Stature =76.09+2.53 x tibial length R^2 =0.72, SEE =3.88, 95% CI for b = 2.12-2.94	Stature =86.53+2.10 x tibial length R^2 = 0.68, SEE =3.37, 95% CI for b = 1.72-2.48	Stature =87.42+2.10 x tibial length R^2 =0.68, SEE =3.35, 95% CI for b = 1.72-2.47

The coefficient of determination (R^2) ranged from 0.52 to 0.78, indicating that approximately 52%–78% of the variation in stature was explained by tibial length. The highest R^2 value was observed in East-zone males (R^2 = 0.78), whereas the lowest was observed in South-zone females for the left tibial length (R^2 = 0.52). The standard error of estimate (SEE) ranged from 3.26 to 3.97 cm. The lowest SEE (3.26 cm) was observed in South-zone males, whereas the highest SEE (3.97 cm) was observed in North-zone males.

Discussion

The present study was conducted to develop sex- and zone-specific regression equations for stature estimation using percutaneous tibial length across four geographical zones (South, North, East, and West) of India.

Male participants had significantly greater stature and tibial length than female participants across all four zones ($p < 0.001$). The overall mean stature was 173.35 ± 7.36 cm in males and 160.19 ± 5.48 cm in females. These values are broadly comparable with the findings of Kavyashreeet al.[11] and other Indian studies.[11–14]The observed sexual dimorphism reflects normal biological variation in skeletal growth between males and females and supports the use of sex-specific regression equations for stature estimation.

The overall mean tibial length was 38.81 ± 2.67 cm in males and 34.96 ± 2.04 cm in females.

No statistically significant differences were observed between right and left tibial lengths in either sex in any geographical zone ($p > 0.05$). Similar bilateral symmetry has been reported in previous Indian studies.[11,13–17] This finding indicates that either side may be used when only one tibia is available, although the side-specific equation corresponding to the available measurement should be applied.

The zone-wise comparisons revealed differences in mean stature and tibial length across the North, South, East, and West regions. These differences may be attributed to genetic diversity, environmental influences, nutritional status, and socio-economic factors prevalent in different parts of India. These findings support the need for population- and region-specific regression equations.[16]

In the South zone, tibial length showed a strong positive correlation with stature in males (r = 0.84) and females (r = 0.73). The sex-specific models explained 70% of stature variation in males and 52%–53% in females, with SEE values of 3.26–3.45 cm. Anithaet al.[18] and Ahmed and Sreenivasan19 also reported strong associations in South Indian populations, whereas Kavyashree et al.[11] reported lower correlations. These differences may reflect variation in sample composition, age distribution, measurement technique, and population characteristics.

In the North zone, the correlation was stronger in males (r = 0.85) than in females (r = 0.79). The models explained 73% of stature variation in males and 61%–62% in females, with SEE values of 3.27–3.97 cm. These findings are comparable with those of Gaur et al.[15]

who reported correlations of 0.82 in males and 0.78 in females, and with the findings of Kumar et al.[20] and Gupta et al.[12]. The consistency across studies supports the usefulness of tibial length for stature estimation in North Indian populations.

The East zone demonstrated the strongest male relationship in the present study ($r = 0.88$), while the female correlation was also strong ($r = 0.77$). The highest coefficient of determination was obtained for East-zone males ($R^2 = 0.78$), indicating that 78% of the variation in stature was explained by right tibial length. Female models explained 58%–59% of the variation. These values were higher than those reported in some earlier East Indian studies by Ghosh[16] and Moitra[17], illustrating the population specificity of regression models.

The regional variations in mean tibial length and stature observed in this group may be influenced by genetic, nutritional, and socio-economic factors.

In the West zone, strong correlations were observed in males ($r = 0.85$) and females ($r = 0.82$). The models explained 72%–73% of stature variation in males and 68% in females, with SEE values of 3.35–3.88 cm. Algotar et al.[14] reported stronger correlations in a Gujarat population, whereas Saknure and Waghmare[21] reported a lower correlation in a combined sample. Ali et al.[22] also demonstrated a strong association in a cadaveric population. The variation between studies emphasizes that equations should not be transferred between populations without validation.

The findings of the present study support the classical work of Trotter and Gleser[5], who established that among the long bones, the tibia is considered a reliable predictor of stature. Regression equations derived from other populations may not be directly applicable to Indian populations because of population differences in body proportions, genetic background, nutritional status, environmental influences, and secular trends.

Overall, the findings demonstrate significant regional and sex-specific variations in stature and tibial length among the Indian population. These variations are likely influenced by genetic diversity, nutritional status, socioeconomic conditions, and climatic factors, underscoring the importance of developing population- and sex-specific regression equations for accurate stature estimation in forensic practice.

These equations may assist forensic experts in estimating stature from incomplete remains encountered during mass disasters, medicolegal investigations, and anthropological examinations.

Limitations and Future Directions

- Participants may not represent the entire Indian adult population because medical students generally have similar educational and socioeconomic backgrounds.
- Environmental, nutritional, and socioeconomic factors were not analysed separately and therefore could not be evaluated for their potential influence on stature and percutaneous tibial length.
- Intra-observer reliability was not assessed using the intraclass correlation coefficient (ICC).

Future studies should include multicentre populations, broader age groups, and diverse ethnic populations.

Conclusion

The present study establishes that percutaneous tibial length is a reliable predictor of stature in the Indian population, demonstrating strong positive correlations across all zones ($r = 0.73$–0.88), with coefficients of determination (R^2) ranging from 0.52 to 0.78 and SEE values ranging from 3.26 to 3.97 cm. Significant sexual dimorphism was observed, with males showing greater stature and tibial length than females.

Regional variations among North, South, East, and West India further highlight the need for population-specific models. The findings support the use of sex- and zone-specific regression equations for stature estimation in forensic and anthropological applications.

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