Original Article

Lower Limb Anthropometry and Stature Estimation: Development of Regression Models in an Iranian Adult Population

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Abstract

Background: Stature estimation is a fundamental component of biological profiling in forensic anthropology, particularly when conventional identification methods are unavailable. Because anthropometric relationships vary across populations, population-specific regression equations are required for accurate stature estimation. This study investigated the association between lower limb anthropometric measurements and stature and developed regression models for stature estimation in an Iranian adult population.

Materials and Methods: In this descriptive cross-sectional study, 218 indigenous adults were recruited from Bushehr, Iran. Thigh length, leg length, foot length, lower limb length, and stature were measured using standardized anthropometric methods. Pearson's correlation coefficient, the independent samples t-test, and multiple linear regression models were employed for data analysis.

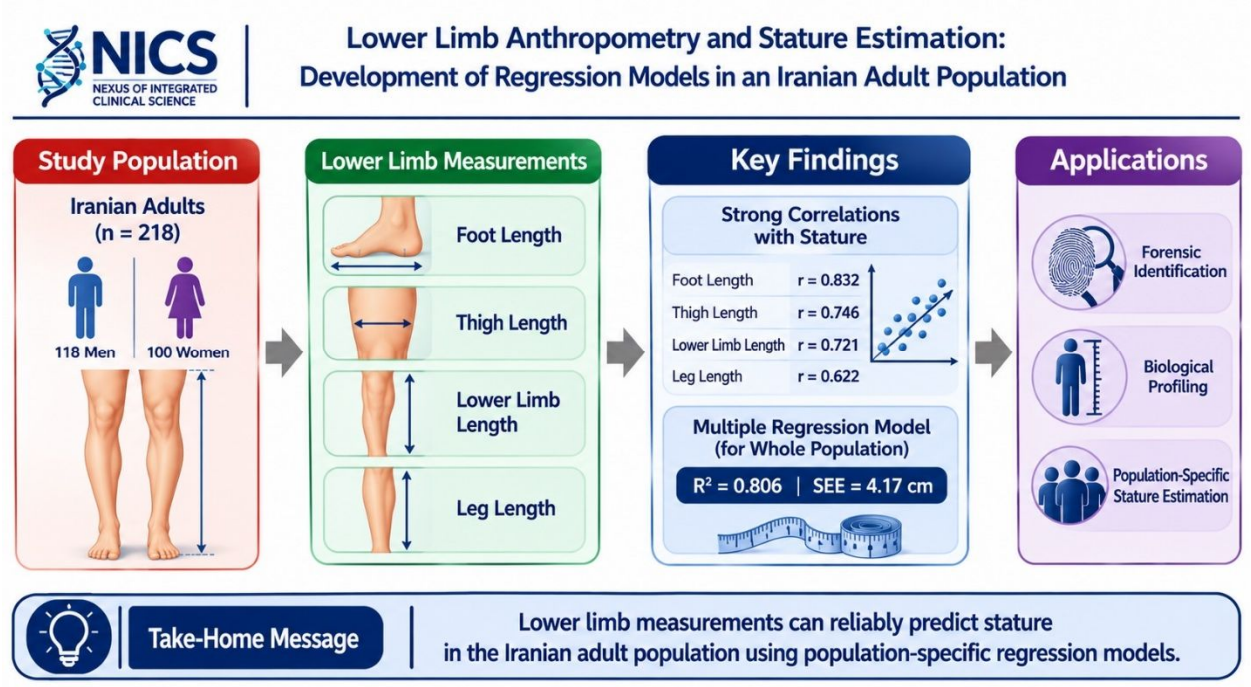
Results: The mean age of participants was 33 years. All lower limb measurements were significantly correlated with stature ($P<0.001$). Foot length demonstrated the strongest correlation with stature ($r=0.832$), followed by thigh length ($r=0.746$), lower limb length ($r=0.721$), and leg length ($r=0.622$). No significant difference was found between measured and estimated stature.

Conclusion: Foot length showed the strongest association with stature among lower-limb measurements, making it the most useful predictor for stature estimation and forensic identification in the Bushehr indigenous population.

Implications for Patient Care: Population-specific lower-limb anthropometric measurements can provide supplementary information for stature estimation when direct measurement is not possible. The regression equations developed in this study may assist forensic professionals in estimating stature from available lower-limb measurements. These findings may support the identification of individuals with incomplete or fragmented human remains. The proposed equations should be used alongside other forensic evidence to improve the identification process.

Keywords: Anthropometry; Lower limb; Stature estimation; Forensic anthropology; Linear regression; Indigenous population.

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Graphical Abstract. Lower Limb Anthropometry and Stature Estimation: Development of Regression Models in an Iranian Adult Population. This cross-sectional study evaluated the relationship between lower-limb measurements and stature in 218 adults (118 men and 100 women) from Bushehr, Iran. All four anthropometric parameters were significantly correlated with stature, with foot length showing the strongest association (r = 0.832). The combined regression model explained 80.6% of stature variability (R^2 = 0.806; SEE = 4.17 cm). These findings support the use of population-specific lower-limb regression equations as supplementary tools for forensic stature estimation, particularly when human remains are incomplete or fragmented.

Introduction

Anthropometry is the systematic measurement and quantitative assessment of the dimensions and proportions of the human body. Anthropometric techniques are used in several areas of biomedical and anthropological research, including clinical and forensic applications. In forensic anthropology, anthropometric and other metric measurements can contribute to the assessment of the biological profile of unidentified human remains, including the estimation of sex, age, ancestry, and stature. These assessments may assist in narrowing the pool of potential identities and thereby support the overall identification process (1–3). The historical application of anthropometry in forensic identification dates to the late nineteenth century, when Alphonse Bertillon developed an anthropometric identification system that was adopted by the Paris police in the early 1880s for the identification of offenders (4). Known as Bertillonage, the system combined standardized anthropometric measurements with physical descriptions to facilitate the identification of individuals, particularly repeat offenders (4). Extensive anthropometric studies have been conducted in different populations to establish reference datasets of human body dimensions. These datasets provide valuable information for assessing variations in body proportions and morphological characteristics among populations (2,5). In situations such as mass disasters, severe trauma, extensive burns, advanced decomposition, or incomplete human remains, conventional identification methods may be challenging to apply. In such circumstances, anthropological information, including stature,

sex, and age, can provide valuable supporting evidence for forensic identification (1,6,7).

Among the biological characteristics assessed in forensic anthropology, stature estimation is an important component of the biological profile. The relationship between stature and various anatomical structures has been extensively investigated, and regression-based methods have been developed to estimate stature from skeletal elements and external body measurements (1,7,8). Long bones, particularly those of the lower extremities such as the femur and tibia, are among the most commonly used anatomical structures for stature estimation due to their strong correlation with body height. Numerous studies have demonstrated significant relationships between lower limb measurements and stature, leading to the development of population-specific regression equations for height estimation (9,10). Two major approaches are commonly applied for stature estimation: anatomical and mathematical methods. The anatomical method reconstructs stature by summing the lengths of skeletal components contributing to body height and incorporating a correction factor to account for soft tissues. In contrast, mathematical methods estimate stature using regression equations derived from measurements of specific bones or body segments. Although the anatomical method can provide accurate estimates when complete skeletal remains are available, regression-based approaches are more frequently used in forensic practice because they can be applied to incomplete remains and require fewer measurements (9,11).

Numerous studies have reported significant associations between lower limb anthropometric parameters and stature in various populations. Based on these findings, population-specific regression equations have been developed to estimate stature from lower limb skeletal dimensions (12_14). Ozaslan et al. demonstrated significant associations between body measurements and stature in a Turkish population (15). Similarly, studies among Han Chinese adults showed that foot and hand dimensions could be reliable predictors of stature (16). These findings indicate that although anthropometric parameters are strongly associated with height, the most appropriate predictor variables may differ among populations due to variations in body proportions and population-specific characteristics (16,17).

In Iran, several studies have evaluated stature estimation using anthropometric measurements of different body regions. Mahakizadeh et al. and Akhlaghi et al. reported significant relationships between upper limb anthropometric measurements and stature among Iranian adults (18,19). Furthermore, Soltani et al. demonstrated that foot dimensions could be used for stature estimation in Iranian adults (20). However, differences in anthropometric characteristics among populations highlight the importance of developing population-specific regression equations rather than applying generalized models (18_21). Despite advances in forensic anthropology, limited information is available regarding lower limb anthropometry and stature estimation among indigenous populations of southern Iran. Therefore, the present study was designed to investigate the relationship between lower limb anthropometric parameters and stature among the indigenous adult population of Bushehr City and to develop regression equations for stature estimation based on lower limb measurements. The findings of this study may provide additional anthropometric references for forensic identification and biological profiling in Iranian populations.

Materials and Methods

Study design and participants

This descriptive cross-sectional study was conducted among 218 residents of Bushehr City,

southern Iran. Based on the correlation coefficient (r = 0.30) reported by Ahmad et al. (22), a type I error of α = 0.05, and a type II error of β = 0.10, the minimum required sample size was calculated as 109 using the following formula:

$$n = \left[\frac{(z_{1-\frac{\alpha}{2}} + z_{1-\beta})}{0.5ln\left(\frac{1+r}{1-r}\right)}\right]^2 + 3$$

Considering the design effect (DE = 2), the final sample size was increased to 218 participants. Participants were selected using a two-stage random sampling method. First, three of the ten Comprehensive Health Service Centers in Bushehr City were randomly selected by lottery. Subsequently, the list of registered individuals at the selected centers was extracted from the national Integrated Health System (SIB). The required sample size for each selected center was determined using proportional allocation based on the population covered by that center. Participants were then randomly selected from each center's list using a lottery method. The selected individuals were contacted by telephone to determine their eligibility for participation. Those who met the inclusion criteria were invited to participate in the study. If a selected individual did not meet the inclusion criteria or declined to participate, another participant was randomly selected from the remaining list as a replacement. The inclusion criteria comprised men and women who were born in Bushehr and whose parents and grandparents had also been born and had lived in Bushehr. Individuals with a history of injuries to the lower limbs, head and neck, or vertebral column, as well as those with congenital abnormalities of the limbs or spine, were excluded from the study. Before the measurement procedure, all participants received a detailed explanation of the study objectives and procedures, and written informed consent was obtained from each participant.

Anthropometric Measurements

To ensure standardization of anthropometric measurements, the measurements were performed using internationally standardized anatomical landmarks, in accordance with the recommendations adopted by the International Congress of Anatomy and Anthropology in 1954. This approach enhances the reliability, reproducibility, and comparability of anthropometric data (23). Accordingly, the following lower-limb anthropometric parameters were measured.

- Thigh length (TL): the distance from the greater trochanter of the femur to the knee joint.
- Leg length (LL): the distance from the superior border of the lateral tibial condyle to the distal tip of the lateral malleolus.
- Foot length (FL): the maximum longitudinal distance from the posterior aspect of the heel to the tip of the longest toe.
- Lower limb length (LLL): the vertical distance from the iliac crest to the floor.
- Body height (stature): the vertical distance from the vertex of the head to the floor.

For anthropometric measurements, participants stood barefoot on a flat surface in the anatomical position. Thigh length, leg length, foot length, lower limb length, and body height were measured using flexible and steel measuring tapes. All measurements were obtained from the left side of the body, based on previous studies reporting greater measurement reliability on the left side. Each measurement was repeated three times, and the mean value was recorded for analysis. All measurements were expressed in

centimeters and recorded to two decimal places (24).

Statistical analysis

Statistical analyses were performed using SPSS software. Continuous variables are presented as mean ± standard deviation (SD). The normality of data distribution was assessed using graphical methods and the Kolmogorov–Smirnov test. Pearson's correlation coefficient was used to evaluate the relationships between lower-limb anthropometric measurements and stature. Independent-samples t-tests were used to compare anthropometric measurements between male and female participants. Simple and multiple linear regression analyses were performed to develop equations for stature estimation using lower-limb anthropometric parameters. Regression models were evaluated based on the coefficient of determination (R^2) and standard error of the estimate (SEE). Separate regression analyses were performed for the total study population and, where applicable, for male and female participants. The differences between measured and estimated stature were assessed using the paired-samples t-test. A two-sided P value < 0.05 was considered statistically significant.

Results

A total of 218 participants were included in this study, including 118 males and 100 females. The mean age of participants was 33.07 ± 9.30 years. Descriptive characteristics and anthropometric measurements according to sex are presented in Table 1. The mean values of all measured anthropometric parameters, including thigh length, leg length, foot length, lower limb length, and stature, were significantly higher in males compared with females (P<0.001) (Table 1).

Variabe	Sex	Minimum	Maximum	Mean	Std. Deviation	P-value
TL	Male	38.75	61.50	50.2564	4.26530	<0.001
	Female	35.50	52.00	43.7000	3.95301	
LL	Male	32.75	99.25	43.1292	6.87454	<0.001
	Female	30.00	46.00	37.2750	3.55557	
FL	Male	18.75	29.50	25.9936	1.92083	<0.001
	Female	20.50	27.50	23.5125	1.60664	
LLL	Male	76.25	121.00	97.0975	8.14269	<0.001
	Female	57.00	102.00	91.5300	5.42759	
BH	Male	154.75	194.00	173.6970	8.32999	<0.001
	Female	147.00	177.50	162.0100	5.98271	

Table 1. Table 1. Participant characteristics and lower limb anthropometric measurements according to sex. TL(Thigh length), LL(Leg length), FL(Foot length), LLL(lower limb length), BH(Body height)..

Correlation between lower limb measurements and stature

Pearson correlation analysis demonstrated significant positive correlations between all lower limb anthropometric parameters and stature (P<0.001). The strongest correlation with stature was observed for foot length (r=0.832), followed by thigh length (r=0.746), lower limb length (r=0.721), and leg length (r=0.622) (Table 2).

Predictor variable	Correlation coefficient (r)	P-value
TL	**0.746**	**<0.001**
LL	**0.622**	**<0.001**
FL	**0.832**	**<0.001**
LLL	**0.721**	**<0.001**

Table 2. Pearson correlation coefficients between lower limb anthropometric measurements and stature. TL(Thigh length), LL(Leg length), FL(Foot length), LLL(lower limb length).

Linear Regression Model for Height Estimation

Multiple linear regression analysis was performed to develop prediction equations for estimating stature using different lower-limb anthropometric parameters. The prediction equation was defined as follows:

BH (stature) = b (constant) + a (regression coefficient of independent parameter) x

In the total study population, foot length showed the highest coefficient of determination (R^2), whereas the regression model based on lower-limb length yielded the lowest standard error of the estimate (SEE), indicating the highest predictive accuracy among the evaluated anthropometric parameters (Table 3).

variables	Equation	R^2	SEE
Male			
TL	**95.808+1.548 TL**	**0.607***	**5.34**
LL	**145.816+.644 LL**	**0.278***	**7.25**
FL	**85.782+3.377 FL**	**0.582***	**5.51**
LLL	**91.945+0.840LLL**	**0.644***	**5.09**
Female			
TL	**144.848+0.393 TL**	**0.067***	**5.81**
LL	**137.861+.648 LL**	**0.148***	**5.55**
FL	**99.767+2.647 FL**	**0.505***	**4.23**
LLL	**126.868+0.384LLL**	**0.121***	**5.64**
Combined sex			
TL	**105.192+1.335TL**	**.556***	**6.27**
LL	**130.930+0.924LL**	**.387***	**7.37**
FL	**78.472+3.613FL**	**.692***	**5.23**
LLL	**83.158+0.900LLL**	**.520***	**6.52**

Table 3. Linear Regression Model for Height Estimation. TL(Thigh length), LL(Leg length), FL(Foot length), LLL(lower limb length).

Multiple linear regression models for stature estimation

Multiple linear regression analysis showed that combining lower-limb anthropometric measurements improved the accuracy of stature prediction compared with single-variable models. Regression equations were developed using all four lower-limb parameters (TL, LL, FL, and LLL), and stepwise regression analysis was also performed. In the total population, the multiple regression model explained 80.6% of the variance in stature, with a SEE of 4.17 cm, which was lower than that obtained from simple linear regression (5.23 cm).

Sex-specific analyses showed that the SEE values of multiple regression models were lower than those of simple linear regression models in both males and females, indicating better model fit (Table 4). Therefore, multiple linear regression equations provided more accurate stature predictions than single-parameter models.

The comparison between measured and estimated stature showed no statistically significant differences between actual and predicted values in either males or females. The mean estimated stature was comparable to the measured stature in both sexes, confirming the validity and suitability of the developed regression equations for stature estimation in the Bushehr population (Table 5).

Model	Equation	R	R^2	SEE
Male				
1	Y=68.122+0.285TL +0.063LL +1.880FL +0.407LLL	0.880	0.775	4.09469
2	Y=67.587+0.262TL +1.884FL +0.451LLL	0.880	0.774	4.09132
3	Y=67.829+1.957FL+.565LLL	0.878	0.770	4.10289
Female				
1	Y=84.580+.186TL+0.409LL +2.585FL -.073LLL	0.772	0.596	3.88321
2	Y=81.547+0.179TL+0.378LL +2.490FL	0.770	0.593	3.87808
3	Y=86.118+.470LL +2.482FL	0.763	0.581	3.91002
Combined sex				
1	Y=66.148+0.446TL+0.187LL+2.345FL+0.161LLL	0.898	0.806	4.17861

Table 4. Multiple linear regression models for stature estimation. TL(Thigh length), LL(Leg length), FL(Foot length), LLL(lower limb length).

Sex	Variable	Mean (cm)	SD (cm)	t-value	P-value
Male	Measured stature	173.53	8.48	0.001	0.999
	Estimated stature	173.53	7.45		
Female	Measured stature	162.01	5.98	0.001	0.999
	Estimated stature	162.01	4.56		

Table 5. Independent-samples t-test comparing measured and estimated height between men and women.

Discussion

The present study evaluated the relationship between lower limb anthropometric measurements and stature and developed regression models for stature estimation among the indigenous adult population of Bushehr, Iran. The findings demonstrated significant positive correlations between all evaluated lower limb parameters and body height. Among the investigated variables, foot length showed the strongest correlation with stature, while multiple linear regression models provided higher predictive accuracy compared with individual measurements. These results indicate that lower limb anthropometric parameters can be useful complementary indicators for stature estimation in forensic anthropology.

Stature estimation is one of the essential components of constructing a biological profile in forensic investigations (1,8). In cases involving severe trauma, mass disasters, extensive burns, decomposition, or fragmented human remains, conventional identification methods such as fingerprinting and facial recognition may not always be applicable (6,25). Therefore, anthropometric approaches based on population-specific measurements can provide valuable information for identifying unknown individuals (1,3). Since body proportions may vary among populations, regression equations developed for one population may not provide accurate estimates when applied to another population (12_14, 18,21).

In the present study, all measured lower limb parameters and stature were significantly higher in males compared with females. This finding is consistent with previous studies conducted in different populations, which have demonstrated sexual dimorphism in anthropometric characteristics (12,16,18). These differences may reflect sex-related variations in body proportions and skeletal development. Therefore, considering sex-specific equations is important for improving the accuracy of stature estimation (12,18,19).

A significant positive correlation was observed between lower limb measurements and stature in the present study. The strongest correlation was found between foot length and stature (r=0.832). Previous studies have reported similar relationships between foot dimensions and height, although the most appropriate predictor variable has varied among populations (16,17,20,24). Krishan and Sharma reported a significant association between hand and foot dimensions and stature in a North Indian population (24). Zhang et al. demonstrated that foot measurements could effectively predict stature among Han Chinese adults, which is consistent with the findings of the present study (16). However, other studies have identified different parameters as the strongest predictors. Ozaslan et al. reported significant associations between body measurements and stature in a Turkish population, while Malaysian studies identified lower limb length and thigh length as important predictors of stature (12,15). These differences may be explained by population-specific variations in body proportions (12–14,18,21).

The regression analysis in this study showed that individual lower limb measurements could significantly predict stature. Among the single-variable models, foot length demonstrated the highest coefficient of determination in the total population (R^2=0.692). Furthermore, multiple linear regression models improved the accuracy of prediction, and the combined model explained 85.5% of the variation in stature with a standard error of estimation of 4.17 cm. Similar findings have been reported in previous studies, where

multiple anthropometric variables provided better estimates than single measurements (12,15,16,24). The higher predictive accuracy of multiple regression models may be related to the complementary contribution of different body segments to stature estimation (12,16).

The importance of developing population-specific stature estimation equations has been emphasized in forensic anthropology (12–14,21). Although universal relationships exist between body measurements and stature, differences in body proportions among populations limit the applicability of generalized equations (12–14,21). Previous studies in Iranian populations have demonstrated significant associations between anthropometric measurements and stature, supporting the need for population-specific reference data (18–20). Therefore, the equations developed in the present study may provide useful supplementary information for stature estimation in populations with similar anthropometric characteristics.The findings of this study may have practical implications in forensic identification, particularly in situations where only partial human remains are available (1,3,6,25). Lower limb measurements are relatively easy to obtain and can be used as additional evidence alongside other identification methods (12,15). In addition, establishing anthropometric databases for different Iranian populations may contribute to improving forensic investigations and biological profile estimation (18–20).

Conclusion

The findings of this study demonstrate significant associations between lower limb anthropometric measurements and stature in the indigenous adult population of Bushehr, Iran. Foot length and combined lower limb parameters showed strong predictive performance and can be used to develop population-specific regression models for stature estimation. These findings highlight the importance of regional anthropometric data in forensic applications, as equations developed for one population may not be directly applicable to other populations with different body proportions. Therefore, population-specific studies are essential for improving the accuracy and reliability of stature estimation.

Limitations of the study

This study has several limitations. Factors that may influence stature, including nutritional status, socioeconomic conditions, and lifestyle characteristics, were not assessed. Furthermore, the developed regression equations were derived from an indigenous population of Bushehr and should therefore be applied cautiously to other Iranian populations. Future multicenter studies involving diverse geographical regions of Iran are recommended to establish comprehensive anthropometric reference models.

Implications for Patient Care

Population-specific lower-limb anthropometric measurements may provide useful supplementary information for stature estimation when direct measurement is not possible. The regression equations developed in this study may assist forensic professionals in estimating stature from available lower-limb measurements, particularly in cases involving incomplete or fragmented human remains. These estimates may support the identification process when used alongside other forensic evidence.

Conflict of Interest

The authors declared no conflicts of interests.

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Ethics Statement

This study was approved by the Ethics Committee of Bushehr University of Medical Sciences, Bushehr, Iran (Ethics Approval Code: IR.BPUMS.REC.1397.102). All procedures were conducted in accordance with applicable ethical principles. The authors also confirm that publication ethics were observed, including the avoidance of plagiarism, data fabrication, and duplicate publication.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author Contributions

All authors contributed to the study including design, literature search, data interpretation, drafting of the manuscript, and critical revision of the article. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Artificial Intelligence (AI) Disclosure

Artificial intelligence (AI) was used solely for language editing and improving the clarity and readability of the manuscript. The authors reviewed and approved the final text and take full responsibility for the accuracy and integrity of the manuscript.

Publisher's Note

The graphical abstract was prepared by the journal's editorial team using artificial intelligence-assisted design tools and was reviewed and approved by the authors prior to publication.

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