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Stature Estimation from Foot Measurements in Primary Students: A Case Study in Bangladesh

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ABSTRACT
This study investigates the relationship between foot anthropometric measurements and human stature among primary school students in Bangladesh, aiming to establish reliable anthropometric models for forensic and ergonomic applications. Employing data from 360 children (180 males and 180 females), the study utilizes linear and multiple regression models to establish predictive equations for stature estimation. Foot measurements, including foot length and width for both feet, were recorded with high precision. Results reveal strong correlations between foot dimensions and stature, with foot lengths showing higher predictive accuracy for males, and foot widths being more effective for females. Multiple regression analysis enhances predictive precision, with gender-specific models significantly improving accuracy. The female-specific multiple regression model demonstrated an almost perfect prediction correlation (R = 0.9997), compared to the male model (R = 0.9524). The findings underscore the necessity of using gender-specific equations due to variations in growth patterns and body proportions. This research fills a critical gap in anthropometric studies focused on children and presents practical applications for forensic science and ergonomic design in resource-limited settings. Additionally, it contributes to the standardization of foot dimensions based stature estimation techniques, enhancing their applicability for diverse demographic groups.

Keywords: Stature Estimation, Foot Analysis, Forensic Science, Anthropometry, Primary School Students.

1. Introduction

The estimation of human stature is an important part of human factors engineering and forensic science, providing crucial insights into personal identification in cases involving partial remains. This is particularly essential in situations involving natural disasters, mass casualties, or cases where skeletal remains are incomplete. Estimating an individual's stature using the relationship between body measurements and height not only facilitates identification but also contributes to understanding population-specific physical characteristics. Researchers have developed numerous predictive models to estimate stature, tailored to the anatomical and genetic diversity of different populations, thereby enhancing accuracy.

Numerous studies have examined the application of anthropometric measurements in predicting stature across diverse populations and age groups [1-5]. Table 1 summarizes the literature to estimate the stature from different anthropometric measurements in different population. To estimate the stature, Madadin and Menezes [1] explored the relationship between hand dimensions and stature among adult males in Eastern Saudi Arabia. Hsieh et al. [2] used advanced three-dimensional foot measurements to estimate height in Taiwanese females. Similarly, Popovic et al. [3] utilized foot length to predict stature in adolescents from the Western Region of Kosovo. These studies underscore the importance of regional and population-specific research, highlighting the role of genetic, nutritional, and environmental factors in influencing body proportions.

Brits et al. [5] estimated stature in Black South African sub-adults using femur and tibia lengths, emphasizing the importance of anatomical variations across populations. Additionally, Banik et al. [6] identified upper arm length as a reliable predictor for Mexican children aged 4 to 7 years. These findings demonstrate that universal models often fall short of accurately predicting stature in different groups, particularly among pediatric populations where growth patterns can vary significantly.

The application of stature estimation methods to younger populations has revealed unique challenges. Researchers such as Aboelnasr et al. [4] and Uche et al. [7] have addressed these complexities by developing models tailored to children and adolescents. For instance, Aboelnasr et al. [4] validated the use of normalized truncated navicular height in Egyptian children, aged 6 to 18 years, showcasing its relevance for stature estimation during growth phases. Similarly, Uche et al. [7] proposed predictive models based on hand dimensions for Nigerian school children, 10 to 17 years old, demonstrating the adaptability of anthropometric techniques to evolving body proportions.

In Bangladesh, substantial progress has been made in developing stature estimation models specific to local populations. Yeasmin et al. [8] analyzed various body dimensions, including shoulder breadth and knee height, to estimate stature among Bangladeshi adults. Moreover, Asadujjaman et al. [9–12] conducted extensive research on the applicability of handprints, footprints, hand and foot anthropometric measurements, to estimate the stature among Bangladeshi adults. Asadujjaman et al. [9–12] showed that the estimation of stature from various body measurements such as handprints, footprints, hand and foot are possible and reliable. These studies emphasize the utility of various anthropometric

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measurements in creating accurate and efficient predictive models to estimate the stature.

Despite these advancements, there is limited research focusing on foot anthropometric measurement-based stature estimation among primary school-aged children. This demographic presents unique challenges due to rapid and variable changes in body proportions during early growth stages. Most existing models are designed for adults or adolescents, leaving younger children underrepresented in anthropometric studies. Therefore, to address this gap, this study aims to investigate the potential of foot measurements for estimating stature in primary school-aged children. The findings of this study can provide useful information for estimating Taiwanese male stature from foot dimensions in a practical forensic application. The findings of this study can provide valuable insights into estimating stature based on foot dimensions in primary school students of Bangladeshi.

Table 1 Stature estimation from different anthropometric measurements in different population

Study	**Anthropometric Parameter**	**Population**	**Age range (years)**	**Sample size**
Madadin and Menezes [1]	Hand	Eastern Saudi Arabian	20 to 56	200 males
Hsieh et al. [2]	Foot	Taiwanese	18 to 59	1058 females
Popovic et al. [3]	Foot	Western Region in Kosovo	18 to 20	338 males and 326 females
Aboelnasr et al. [4]	Foot	Egypt	6 to 18	309 males and 304 females
Brits et al. [5]	Femur and tibia	South African	10 to 17	29 males and 30 females
Banik et al. [6]	Upper arm length	Maxican	4 to 7	218 males and 240 females
Uche et al. [7]	Hand	Nigerian	10 to 17	240 males and 243 females
Yeasmin et al. [8]	Shoulder breadth, shoulder height, popliteal height, and knee height	Bangladeshi	21 to 30	150 males and 150 females
Asadujjaman et al. [9]	Handprint	Bangladeshi	18 to 30	100 males and 100 females
Asadujjaman et al. [10]	Footprint	Bangladeshi	18 to 50	118 males and 130 females
Asadujjaman et al. [11]	Hand	Bangladeshi	18 to 60	150 males and 150 females
Asadujjaman et al. [12]	Foot	Bangladeshi	18 to 60	150 males and 150 females
This study	Foot	Bangladeshi	6 to 11	180 males and 180 females

2. Methodology

2.1 Study design and participants

This study was conducted among 360 primary school students (180 males, 180 females) aged 6–11 years from Rajshahi Division, Bangladesh. Participants were selected randomly, ensuring representation across various socioeconomic backgrounds. To maintain the integrity of the data, only healthy children without any visible deformities in their lower limbs or feet were included in the study. Participants were briefed about the purpose of the study, and informed consent was obtained before collecting the data.

2.2 Data collection

Anthropometric data were collected under standardized conditions to ensure accuracy and reliability. Two key measurements were recorded:

Foot Dimensions: The foot length (FL) and foot width (FW) of both the left and right feet were measured using digital calipers with a precision of ±0.01 mm. Participants were seated comfortably during the measurement process to eliminate potential variability caused by weight-bearing on the feet.

Stature: Stature was measured using a stadiometer with an accuracy of ±1 mm. Participants stood barefoot in an upright position with their heels, buttocks, shoulders, and head in contact with the stadiometer’s vertical scale

To minimize measurement errors, all anthropometric measurements were taken twice by trained personnel, and the average of the two readings was used for analysis. The equipment was calibrated before each session to maintain precision. Data collection was conducted in a quiet, well-lit environment to ensure comfort and focus during the process.

3. Results

3.1 Significance test

The table 2 presents the descriptive statistics, including the mean and standard deviation, of foot measurements for both males and females aged 6 to 11. The average foot measurements of the male group exceed those of the female group. The P-values for the t-test exceed the significance level of $\alpha=0.05$ across all parameters, indicating the absence of statistically significant differences between the male and female groups for FLR, FLL, FWR, and FWL.

Table 2 Statistical Analysis of Male and Female Foot Measurements

Parameter	**Male Mean ± SD**	**Female Mean ± SD**	**t-statistic**	**p-value**
FLR	207.49 ± 10.57	205.35 ± 10.91	0.38	0.71
FLL	208.28 ± 10.38	206.27 ± 11.25	0.38	0.71
FWR	79.65 ± 5.74	78.82 ± 5.60	0.32	0.76
FWL	80.08 ± 5.79	79.54 ± 5.66	0.25	0.81

Fig.1 illustrates that both FLR and FLL exhibit a consistent increase with age for both males and females. The growth trajectory for FLR and FLL is nearly identical signifying symmetry between the lengths of the right and left feet. Substantial growth occurs between the ages of 7 and 9, succeeded by a deceleration in growth from ages 10 to 11 for both sexes. Males consistently display marginally greater foot lengths (FLR and FLL) than females across all age groups. The growth trends for FWR and FWL exhibit significant symmetry, comparable to foot lengths. Male foot widths (FWR, FWL) are marginally greater than female foot widths across all age groups, while the disparity is not significant.

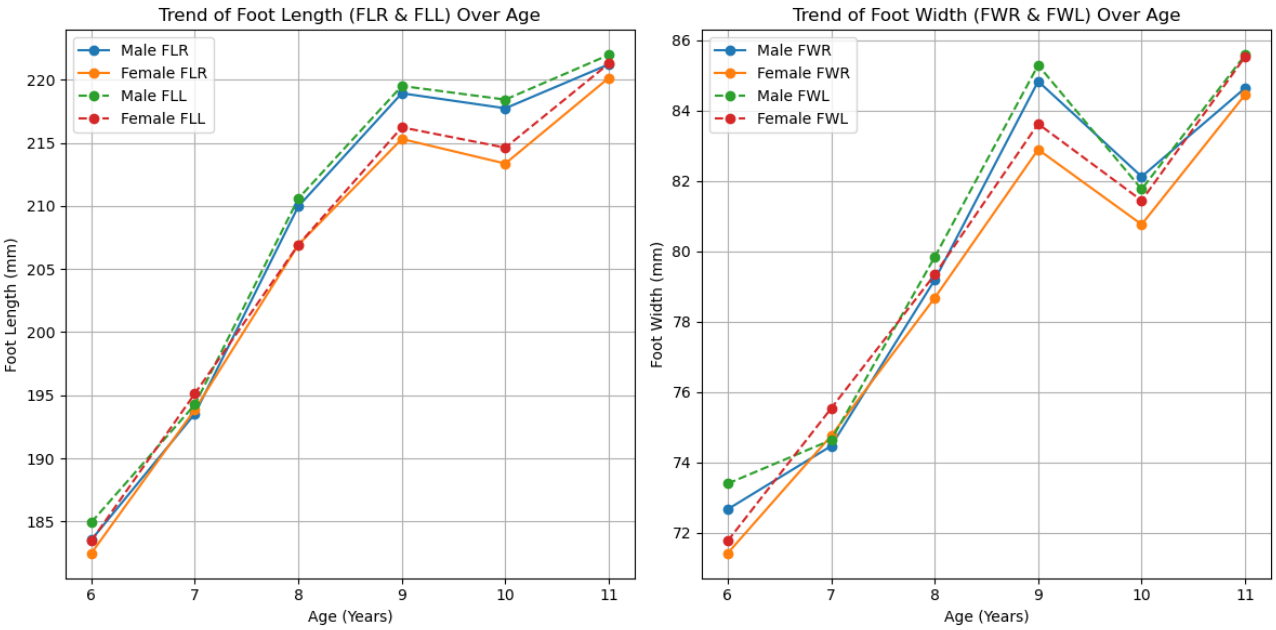

Fig.1 Analysis of Trends in Foot Length and Width by Age for Males and Females

3.2 Linear regression analysis

The linear regression equation for estimating stature (S) based on foot measurements of males and females is presented in Table 3. The coefficient of correlation (*R*) values for all parameters are exceedingly high (>0.90), signifying robust positive correlations between foot measures and stature in males. Furthermore, foot measures account for 81%–88% of the variations in stature. FLL (+0.9394) is the most robust predictor of male height, somewhat surpassing FLR (+0.9379) of the considered parameters. The *R* values for females are marginally lower than those for males, ranging from +0.866 (FLR) to +0.8908 (FWR).

Table 3 Linear Regression Measures for Predicting Stature in Males and Females Using Foot Measurements

Group	Parameter	Regression Equation	*R*	*R²*	*SEE*	*t*-value	*p*-value
Male	FLR	S = 94.79 + (5.89 * FLR)	0.9379	0.8796	37.7578	5.405	5.67E-03
	FLL	S = 69.50 + (5.99 * FLL)	0.9394	0.8825	37.2941	5.4813	5.39E-03
	FWR	S = -57.52 + (17.27 * FWR)	0.9179	0.8426	43.1627	4.6278	9.82E-03
	FWL	S = -37.59 + (16.92 * FWL)	0.9027	0.8149	46.8038	4.1971	1.37E-02
Female	FLR	S = 17.43 + (6.18 * FLR)	0.8660	0.7499	57.5414	3.4633	2.57E-02
	FLL	S = -10.38 + (6.29 * FLL)	0.8806	0.7755	54.5234	3.7168	2.05E-02
	FWR	S = -167.42 + (18.44 *FWR)	0.8908	0.7935	52.2867	3.9206	1.72E-02
	FWL	S = -126.93 + (17.77 * FWL)	0.8898	0.7918	52.502	3.9003	1.75E-02

FWR (+0.8908) is the most robust predictor for females, closely succeeded by FWL (+0.8898). SEE values span from 37.29 mm (FLL) to 46.80 mm (FWL), demonstrating considerable precision in stature estimations of the males. Foot lengths (FLR, FLL) yield more precise estimates than foot widths (FWR, FWL). SEE values for females exceed those of males, varying from 52.29 mm (FWR) to 57.54 mm (FLR). Prediction accuracy is superior for males compared to females, with foot lengths (FLR, FLL) exhibiting enhanced performance for males and foot widths (FWR, FWL) demonstrating improved performance for females. All factors are statistically significant for stature prediction in both genders, with a greater relevance shown in males.

3.2 Multiple regression analysis

Multiple regression models were developed to enhance the precision of stature estimate for both genders**.** Table **4** presents multiple regression equations to determine stature by integrating all foot measurements.

The regression equations offer reliable predictive models for determining stature (S) based on foot measures (FLR, FLL, FWR, FWL) for both genders. Foot measurements and stature have a very strong positive relationship for males (R= 0.9524), while for females (*R* = 0.9997), the correlation coefficient (*R* = 0.9997) shows an almost perfect correlation. The coefficient of determination (R^2 = 0.9071) for males implies that 90.71% of the variance in stature is elucidated by the regression model, whereas for females, R^2 = 0.9995 signifies that 99.95% of the variance is accounted for by the model. Prediction accuracy, as indicated by the standard error of estimate (*SEE*), demonstrates moderate accuracy for males (*SEE* = 66.33 mm) and exceptionally high accuracy for females (*SEE* = 5.24 mm). Both models exhibit statistical significance, with $p = 1.39 \times 10^{-2}$ for males and $p = 1.00 \times 10^{-3}$ for females ($p < 0.05$ in both instances). The data indicate that both models effectively predict stature; however, gender-specific models are advised for enhanced accuracy due to variations in the predictive contributions of foot measures.

Table 4 Multiple Regression Measures for Predicting Stature in Males and Females Using Foot Measurements

Gender	Regression Equation	*R*	*R²*	*SEE*	*p*-value
Male	*Stature* = − 202.51 −87.47×FLR + 96.43×FLL + 11.26×FWR) −16.38×FWL	0.9524	0.9071	66.3268	1.39E-02
Female	*Stature* = − 522.91 −103.25×FLR + 102.64×FLL + 142.47×FWR −118.06×FWL	0.9997	0.9995	5.2427	1.00E-03

4. Discussion

This research reveals the dependability of foot measurements (FLR, FLL, FWR, FWL) in estimating stature in males and girls aged 6 to 11 using linear and multiple regression models. Descriptive statistics reveal marginally greater foot measurements for males; nevertheless, significance tests demonstrate no statistically significant differences between genders ($p > 0.05$). Age trends indicate steady increase in foot characteristics, with symmetry noted between right and left measurements. Linear regression analysis reveals robust correlations ($R > 0.90$) for males, with foot lengths (FLR, FLL) yielding superior predictive accuracy, but for females, foot widths (FWR, FWL) demonstrate improved predictiveness despite elevated SEE values. Multiple regression models improve accuracy, with the female model attaining an almost flawless prediction ($R = 0.9997$, $SEE = 5.24$) in contrast to the male model ($R = 0.9524$, $SEE = 66.33$). Both models exhibit statistical significance ($p < 0.05$), underscoring the necessity of gender-specific methodologies for precise stature measurement.

5. Conclusion

This study demonstrates the effectiveness of foot measurements as reliable predictors for estimating the stature of primary school students aged 6 to 11 years in Bangladesh. Linear regression analyses reveal significant correlations between foot dimensions and stature, with foot lengths offering superior predictive accuracy for males, while foot widths are more effective for females. The development of gender-specific multiple regression models further enhances prediction precision, with the female model achieving an exceptionally high correlation (R = 0.9997). The findings conclude that the foot measurements are an effective means to estimate the stature of kids between the ages of 6 and 11. These findings highlight the importance of tailoring anthropometric models to specific populations and demographic groups to account for variations in growth patterns and body proportions.

The research not only addresses a significant gap in the field of pediatric anthropometry but also offers practical applications in forensic science, ergonomics, and personal identification, especially in resource-limited settings. By standardizing the use of foot measurements based stature estimation techniques, this study contributes to the advancement of reliable and efficient methodologies for stature estimation across diverse age groups and populations.

This study provides critical anthropometric data on foot dimensions and growth patterns among Bangladeshi children aged 6 to 11, enabling footwear industries to design shoe lasts that align with the unique anatomical characteristics of this demographic. By leveraging the study's precise measurements of foot length and width, along with gender-specific insights (e.g., males tend to have longer feet and females slightly broader widths), manufacturers can create size ranges and designs that maximize fit, comfort, and ergonomic support. The regression models offer scalable predictions for foot dimensions, helping to optimize size gradations and ensure coverage for a wide variety of foot shapes. For future research, development of a Shoe Sizing System will require in details to allow readers to understand the assumption, the choice of 'standard range', novelty and its explicability.

Data were collected exclusively from the Rajshahi Division in Bangladesh, and regional differences in growth patterns and body proportions may limit the applicability of the results to other populations. Human body measurements vary not only between nations but also within different regions of the same country [13]. Thus, further research can be carried out by collecting data of more foot dimensions from the participants of both rural and urban areas of Bangladesh. Besides, a 3D foot scanner can be used in further studies, which could be helpful to collect the foot data of many more dimensions with greater accuracy in the shortest possible times Future research could explore the integration of additional anthropometric parameters and advanced modeling techniques to further enhance prediction accuracy and applicability.

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