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# Stature estimation from footprint measurements in Bangladeshi adults

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**ABSTRACT**

The estimation of stature is very important in forensic investigation, as it provides useful data that can narrow the pool of potentially matching identities. The purpose of this study was to develop formulae for the estimation of stature from footprint measurements in Bangladeshi adults. This study included 118 randomly selected men and 130 randomly selected women, all aged 18–50 years. From each participant, stature and six footprint measurements were taken by means of standard measurement techniques. Footprint measurements were found to be positively correlated with stature. Stature was estimated by using linear regression equations. The right T1 length in men ($R$: $+0.587$, $R^2$: 0.345) and the right T2 length in women ($R$: $+0.506$, $R^2$: 0.256) were the most reliable individual estimators of stature. However, when data were combined for both sexes, the right T2 length was identified as the most reliable estimator of stature, with higher values of $R$ ($+0.792$) and $R^2$ (0.627). In conclusion, human stature can be successfully estimated by using footprint measurements; this finding can be applied in forensic research and investigation.

## Introduction

The estimation of stature based on various human body parts is a common focus in forensic science and medicine, as well as in ergonomics and human factors engineering. Human body measurements have been used to identify criminals and victims in accidents, natural disasters, and terrorist attacks or as war casualties. The examination of footprint measurements is important in developing countries (e.g. Bangladesh, India, and Pakistan), because people walk barefoot for socioeconomic reasons. Footprints are present at the locations of crimes, such as theft and murder; footprints can be found on mud, dust, cement, oil, and painted surfaces, as well as in blood during murder cases. Therefore, analyses of feet and footprints during stature estimation can be useful in identification of criminals [1–6]. Previously, researchers have attempted to estimate human stature from feet and footprints in various populations. For instance, Kanchan et al. [3] conducted research on footprints and their components for stature estimation among Indian individuals. Krishan [7] performed a study involving 1 040 Gujjar men and 1 040 Gujjar women in northern India, aged 18–30 years, for stature determination. Hemy et al. [2] estimated stature using anthropometry of foot and footprint data from 200 adults (90 men, 110 women) in Western Australia. Other stature estimation studies using footprints were performed by Fawzy and Kamal [1] in Egyptian individuals, Abledu et al. [6] in

Ghanaian individuals, Caplova et al. [8] in Slovak adults, and Khan and Nataraja Moorthy [9] in indigenous individuals from Malaysian Borneo.

The measurement of individuals varies among populations [10, 11]. Therefore, models to estimate stature are population-specific [10, 12]; a single model cannot represent all populations worldwide [9, 13, 14]. In Bangladesh, Asadujjaman et al. [15] examined foot measurements to estimate the stature of unknown individuals. However, to the best of our knowledge, there is no established standard formula to estimate stature from footprints in Bangladeshi individuals. Therefore, the present study was performed to investigate the relationship of stature with footprint measurements, and to develop a standard model for estimating the stature of Bangladeshi adults. This study used linear regression analysis for stature estimation, because this method exhibits considerable accuracy [9, 16].

## Materials and methods

### Materials

This study included 248 adults (118 men and 130 women) without any physical disorders. Previous studies [17] have shown that increasing age is associated with smaller foot dimensions. Moreover, the thickness and cross-sectional area of most foot muscles are significantly smaller in older adults specially over 50 years

old [18], as is abductor hallucis muscle size [17]. Therefore, participants selected for this study were within the age range of 18–50 years. Data for this study were collected from different regions of Bangladesh between May 2018 and August 2018; data collection was performed between 10:00 am and 2:00 pm. This research was performed in a manner that protected the personal information of each participant.

## Method

In this study, a standard measuring tape and a digital slide calliper were used for a single stature measurement and six footprint measurements, including five toe-print lengths (named T1, T2, T3, T4, and T5) and footprint breadth at ball (FPBB). All measurements were performed in accordance with the methods of Hemy et al. [2] and Kanchan et al. [3]. Landmarks of the various footprint measurements are shown in Figure 1; Figure 2 presents the technique used to take footprint measurements.

Stature is the natural height of a person in an upright position [2, 3]. The toe-print lengths T1, T2, T3, T4, and T5 are the distance from the mid-rear heel point (A) to the most anterior point of each toe (B, C, D, E and F, respectively; Figure 1) [2, 3]. The FPBB was measured from the metatarsal lateral (N), the most lateral point of the metatarsophalangeal joint of T5, to the metatarsal medial (M), the most medial point of the metatarso-phalangeal joint of T1 [2].

Static footprints were obtained from the right and left feet of all participants. A novel method was used for collection of footprint measurements. Initially, participants were asked to walk over muddy soil in bare feet; they were then asked to stand on a clean glass plate, thus capturing the footprint on the glass plate. Subsequently, a marker pen was used to mark some points on the feet for use in footprint measurements. Finally, footprint measurements were taken using digital callipers. All the measurements were taken by one observer to avoid the interobserver error. Measurements were taken from both right and left footprints. Each measurement was taken two times; when measurements difference remained within 0.4 mm, the average value was recorded to minimise error. If the two preliminary measurements did not agree the 0.4-mm threshold criterion, two additional measurements were taken, and the average value of the second set of measurement was recorded.

## Statistical analysis

Statistical analyses were performed using Microsoft Excel 2013 (Microsoft Corp., Redmond, WA, USA) and SPSS Statistics, version 23.0 (IBM Corp., Armonk, NY, USA). The normality of the sample data was assessed using the Shapiro-Wilk test, prior



**Figure 1.** Footprint measurements: AB: T1 toe-print length; AC: T2 toe-print length; AD: T3 toe-print length; AE: T4 toe-print length; AF: T5 toe-print length; MN: footprint breadth at ball.
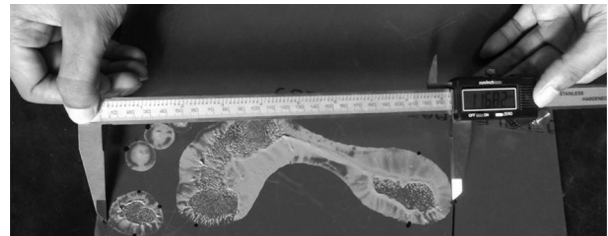


**Figure 2.** Footprint measurement technique.

to selection of parametric or non-parametric comparisons. Sex-based comparisons were conducted using independent $t$-tests and the non-parametric alternative, the Mann–Whitney $U$ test. Differences between two groups were assessed using paired sample $t$-tests and the non-parametric alternative, the Wilcoxon signed-rank test. Linear regression analysis was used to estimate stature from footprint anthropometric measurements. $P < 0.05$ was considered to be statistically significant.

## Results

### Normality tests

Normality tests were performed on stature and other footprint measurements; all measurements

were evaluated separately for men and women. The Shapiro–Wilk test showed that the data for both men and women did not exhibit normal distributions (all $P < 0.05$). After removal of three outlier men and one outlier woman, the Shapiro–Wilk test indicated that the sample data demonstrated a normal distribution (all $P > 0.05$). Therefore, the remaining analyses included 115 men and 129 women. Histograms that demonstrate stature distributions of men and women are shown in Figures 3 and 4, respectively.

Normality tests of stature and footprint measurement data (shown in Table 1) revealed that the right T1 lengths were not normally distributed in either men or women; right T2 length, right T3 length, left T2 length, left T3 length, and left FPBB were not normally distributed in women; right T5 length, right FPBB, left T1 length, and left T5 length were not normally distributed in men (all $P < 0.05$). Hence, the non-parametric Mann–Whitney $U$ test was used for those footprint measurements to examine sexual dimorphism.

Normality tests for footprint measurements by side (Table 2) revealed that T1 length (both sides), T5 length (both sides), and FPBB (right side) did not exhibit normal distributions (all $P < 0.05$) in men. In women, T1 length (right side), T2 length (both sides), T3 length (right side), and FPBB (left side) did not exhibit normal distributions (all $P < 0.05$). Therefore, the non-parametric Wilcoxon
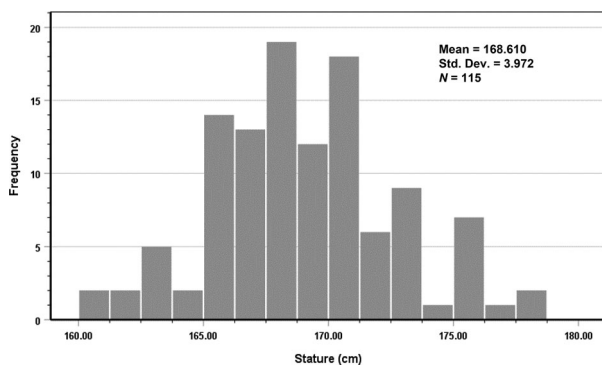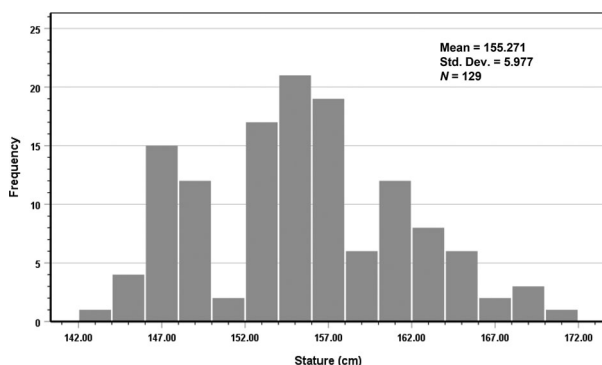
**Table 1.** Normality tests (Shapiro–Wilk) for stature and footprint measurements according to sex (men: $n = 115$; women: $n = 129$).

| Measurement | Sex | Statistic | P-value |
|---|---|---|---|
| Stature | Women | 0.980 | 0.051 |
| | Men | 0.983 | 0.148 |
| Right T1 | Women | 0.971 | 0.007[a] |
| | Men | 0.963 | 0.003[a] |
| Right T2 | Women | 0.965 | 0.002[a] |
| | Men | 0.983 | 0.170 |
| Right T3 | Women | 0.974 | 0.016[a] |
| | Men | 0.981 | 0.101 |
| Right T4 | Women | 0.993 | 0.819 |
| | Men | 0.989 | 0.521 |
| Right T5 | Women | 0.990 | 0.495 |
| | Men | 0.958 | 0.001[a] |
| Right FPBB | Women | 0.994 | 0.843 |
| | Men | 0.959 | 0.001[a] |
| Left T1 | Women | 0.984 | 0.131 |
| | Men | 0.972 | 0.018[a] |
| Left T2 | Women | 0.965 | 0.002[a] |
| | Men | 0.991 | 0.624 |
| Left T3 | Women | 0.978 | 0.033[a] |
| | Men | 0.988 | 0.423 |
| Left T4 | Women | 0.986 | 0.208 |
| | Men | 0.987 | 0.340 |
| Left T5 | Women | 0.984 | 0.132 |
| | Men | 0.959 | 0.001[a] |
| Left FPBB | Women | 0.978 | 0.037[a] |
| | Men | 0.981 | 0.103 |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of the thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.
[a]Denotes absence of normality for the indicated measurement ($P < 0.05$).

signed rank test was used for those footprint measurements to examine bilateral asymmetry.

## Significance test

Descriptive statistics, including maximum value, minimum value, and mean and standard deviation values for footprint dimensions, are presented in Table 3. All footprint dimensions were larger in men than in women. When stature and footprint measurement data were compared according to sex (Tables 4 and 5), significant ($P < 0.001$) sexual dimorphism was observed in all measurements.

Bilateral asymmetry analyses of footprint measurements (Table 6) revealed that T1, T2, and T3 lengths were significantly different in men, whereas the T4 and T5 lengths and the FPBB were not. Furthermore, the T1 and T2 lengths were significantly different in women, whereas the T3, T4, and T5 lengths and the FPBB were not.

## Linear regression analysis

Linear regression models to estimate stature based on right and left footprint dimensions in both sexes are presented in Table 7. Investigators and police did not know whether a footprint was made by a man or a woman; therefore, regression equations were developed by combining data for both men and women. Values of the coefficient of correlation ($R$), coefficient of determination ($R^2$), standard error



**Figure 3.** Histogram of stature in men.

Mean = 168.610
Std. Dev. = 3.972
N = 115



**Figure 4.** Histogram of stature in women.

Mean = 155.271
Std. Dev. = 5.977
N = 129

**Table 2.** Normality tests (Shapiro–Wilk) for footprint measurements according to side.

| Measurement | Side | Men ($n = 115$) | | Women ($n = 129$) | |
|---|---|---|---|---|---|
| | | Statistic | P | Statistic | P |
| T1 | Left | 0.972 | 0.018[a] | 0.984 | 0.131 |
| | Right | 0.963 | 0.003[a] | 0.971 | 0.007[a] |
| T2 | Left | 0.991 | 0.625 | 0.965 | 0.002[a] |
| | Right | 0.983 | 0.170 | 0.965 | 0.002[a] |
| T3 | Left | 0.988 | 0.423 | 0.978 | 0.033 |
| | Right | 0.981 | 0.100 | 0.974 | 0.016[a] |
| T4 | Left | 0.987 | 0.341 | 0.986 | 0.209 |
| | Right | 0.989 | 0.521 | 0.993 | 0.819 |
| T5 | Left | 0.959 | 0.001[a] | 0.984 | 0.132 |
| | Right | 0.958 | 0.001[a] | 0.990 | 0.495 |
| FPBB | Left | 0.981 | 0.104 | 0.978 | 0.037[a] |
| | Right | 0.959 | 0.001[a] | 0.994 | 0.843 |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of the thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.
[a]Denotes absence of normality for the indicated measurement ($P < 0.05$).

**Table 3.** Descriptive statistics for stature and footprint measurements, according to sex.

| Parameter | Men ($n = 115$) | | | | Women ($n = 129$) | | | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | SD | Min | Max | Mean | SD |
| Stature | 157.48 | 177.80 | 168.61 | 3.97 | 142.24 | 171.00 | 155.27 | 5.98 |
| Right T1 | 21.53 | 25.34 | 23.83 | 0.75 | 19.75 | 23.98 | 22.12 | 0.92 |
| Right T2 | 21.65 | 26.66 | 23.81 | 0.87 | 19.45 | 23.89 | 21.88 | 0.94 |
| Right T3 | 21.03 | 24.62 | 22.88 | 0.79 | 18.22 | 23.00 | 21.01 | 0.97 |
| Right T4 | 20.11 | 23.57 | 21.83 | 0.77 | 17.62 | 22.53 | 19.93 | 0.97 |
| Right T5 | 18.69 | 22.83 | 20.36 | 0.64 | 16.07 | 20.49 | 18.39 | 0.90 |
| Right FPBB | 7.65 | 10.41 | 9.28 | 0.50 | 6.87 | 9.81 | 8.43 | 0.55 |
| Left T1 | 21.46 | 25.56 | 23.88 | 0.78 | 19.93 | 24.40 | 22.20 | 0.93 |
| Left T2 | 21.69 | 26.24 | 23.86 | 0.86 | 19.54 | 24.00 | 21.93 | 0.96 |
| Left T3 | 20.93 | 24.76 | 22.94 | 0.81 | 18.46 | 23.02 | 21.04 | 0.97 |
| Left T4 | 20.06 | 23.61 | 21.85 | 0.79 | 17.61 | 22.50 | 19.89 | 0.99 |
| Left T5 | 18.77 | 22.64 | 20.39 | 0.68 | 16.16 | 22.21 | 18.45 | 0.99 |
| Left FPBB | 7.67 | 10.47 | 9.25 | 0.52 | 7.09 | 9.84 | 8.45 | 0.53 |

T1, T2, T3, T4, T5: the distance (cm) from the mid-rear heel point to the most anterior point of the thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth (cm) at ball.

of estimate (SEE), and 95% prediction interval are also shown in Table 7. Values of $R$ varied from $+0.380$ to $+0.587$ in men and from $+0.193$ to $+0.506$ in women. Regression equations developed by combining data for both men and women revealed a higher value of $R$, indicating that the largest value of $R$ was found between stature and right T2 length ($+0.792$) and the lowest value was found between stature and left FPBB ($+0.606$).

Values of $R^2$ varied from 0.145 to 0.345 in men, 0.037 to 0.256 in women, and 0.368 to 0.627 in the combined dataset. The SEE ranged from ±3.230 to ±3.690 cm in men, ±5.177 to ±5.889 cm in women, and ±5.144 to ±6.702 cm in the combined dataset. The 95% prediction interval ranged from ±6.331 to ±7.232 cm in men, ±10.147 to ±11.542 cm in women, and ±10.082 to ±13.136 cm in the combined dataset. All footprint measurements were significantly associated ($P < 0.001$) with stature.

The right T1 length in men and right T2 lengths in both women and the combined dataset were the most reliable individual estimators of stature; they exhibited high values of $R$ and $R^2$, along with low values of SEE and 95% prediction interval. Figures 5–7 show the best fit curves of the most reliable

**Table 4.** Independent $t$-test of means for stature and footprint measurements, according to sex.

| Measurement | t | P (2-tailed) |
|---|---|---|
| Stature | −20.269 | 0.000[a] |
| Right T4 | −16.739 | 0.000[a] |
| Left T4 | −16.929 | 0.000[a] |

[a]Significant ($P < 0.001$).

**Table 5.** Mann-Whitney $U$ of means for stature and footprint measurements, according to sex.

| Mann-Whitney $U$ test Measurement | Mann-Whitney $U$ | P (2-tailed) |
|---|---|---|
| Right T1 | 1045.0 | 0.000[a] |
| Right T2 | 888.0 | 0.000[a] |
| Right T3 | 978.0 | 0.000[a] |
| Right T5 | 403.5 | 0.000[a] |
| Right FPBB | 1896.5 | 0.000[a] |
| Left T1 | 1193.5 | 0.000[a] |
| Left T2 | 854.0 | 0.000[a] |
| Left T3 | 938.0 | 0.000[a] |
| Left T5 | 644.5 | 0.000[a] |
| Left FPBB | 2010.5 | 0.000[a] |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of the thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.
[a]Significant ($P < 0.001$).

estimators of stature for men, women, and combined data, respectively.

**Table 6.** Comparison of means for footprint measurements, according to side.

| Sex | Test | Pair | t/z-value[a] | P-value (2-tailed) |
|---|---|---|---|---|
| Men | Paired sample t-test | Right-Left T2 | −2.571 | 0.011[b] |
| | | Right-Left T3 | −2.820 | 0.006[b] |
| | | Right-Left T4 | −1.002 | 0.318 |
| | Wilcoxon signed rank test | Right-Left T1 | −3.094 | 0.002[b] |
| | | Right-Left T5 | −1.853 | 0.064 |
| | | Right-Left FPBB | −0.717 | 0.473 |
| Women | Paired sample t-test | Right-Left T4 | 1.285 | 0.201 |
| | | Right-Left T5 | −1.454 | 0.148 |
| | Wilcoxon signed rank test | Right-Left T1 | −3.207 | 0.001[b] |
| | | Right-Left T2 | −2.018 | 0.044[b] |
| | | Right-Left T3 | −1.744 | 0.081 |
| | | Right-Left FPBB | −1.151 | 0.250 |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.
[a]t for paired sample t-test; z for Wilcoxon signed rank test.
[b]Significant ($P < 0.05$).

**Table 7.** Linear regression equations for stature estimation (cm) from footprint measurements.

| Sex | Side | Equation | R | $R^2$ | SEE | 95% prediction interval | P |
|---|---|---|---|---|---|---|---|
| Men ($n = 115$) | Right | S = 94.412 + 3.114 T1 | 0.587 | 0.345 | 3.230 | 6.331 | 0.000[a] |
| | Left | S = 101.996 + 2.789 T1 | 0.550 | 0.302 | 3.333 | 6.533 | 0.000[a] |
| | Right | S = 109.279 + 2.492 T2 | 0.547 | 0.299 | 3.340 | 6.546 | 0.000[a] |
| | Left | S = 107.850 + 2.547 T2 | 0.549 | 0.302 | 3.333 | 6.533 | 0.000[a] |
| | Right | S = 108.304 + 2.636 T3 | 0.523 | 0.274 | 3.400 | 6.664 | 0.000[a] |
| | Left | S = 109.498 + 2.577 T3 | 0.525 | 0.276 | 3.396 | 6.656 | 0.000[a] |
| | Right | S = 112.577 + 2.567 T4 | 0.499 | 0.249 | 3.457 | 6.776 | 0.000[a] |
| | Left | S = 115.481 + 2.434 T4 | 0.485 | 0.235 | 3.489 | 6.838 | 0.000[a] |
| | Right | S = 102.931 + 3.225 T5 | 0.522 | 0.273 | 3.402 | 6.668 | 0.000[a] |
| | Left | S = 107.067 + 3.019 T5 | 0.519 | 0.270 | 3.410 | 6.684 | 0.000[a] |
| | Right | S = 140.762 + 3.001 FPBB | 0.380 | 0.145 | 3.690 | 7.232 | 0.000[a] |
| | Left | S = 141.212 + 2.960 FPBB | 0.388 | 0.151 | 3.677 | 7.207 | 0.000[a] |
| Women ($n = 129$) | Right | S = 87.810 + 3.050 T1 | 0.472 | 0.223 | 5.291 | 10.370 | 0.000[a] |
| | Left | S = 85.621 + 3.137 T1 | 0.489 | 0.239 | 5.236 | 10.263 | 0.000[a] |
| | Right | S = 85.171 + 3.204 T2 | 0.506 | 0.256 | 5.177 | 10.147 | 0.000[a] |
| | Left | S = 90.573 + 2.951 T2 | 0.475 | 0.225 | 5.282 | 10.353 | 0.000[a] |
| | Right | S = 102.341 + 2.519 T3 | 0.411 | 0.169 | 5.472 | 10.725 | 0.000[a] |
| | Left | S = 104.093 + 2.432 T3 | 0.397 | 0.157 | 5.506 | 10.792 | 0.000[a] |
| | Right | S = 110.502 + 2.246 T4 | 0.366 | 0.134 | 5.585 | 10.947 | 0.000[a] |
| | Left | S = 110.318 + 2.260 T4 | 0.374 | 0.140 | 5.565 | 10.907 | 0.000[a] |
| | Right | S = 108.695 + 2.532 T5 | 0.382 | 0.146 | 5.545 | 10.868 | 0.000[a] |
| | Left | S = 118.351 + 2.001 T5 | 0.333 | 0.111 | 5.659 | 11.092 | 0.000[a] |
| | Right | S = 132.905 + 2.748 FPBB | 0.252 | 0.064 | 5.806 | 11.380 | 0.000[a] |
| | Left | S = 137.090 + 2.151 FPBB | 0.193 | 0.037 | 5.889 | 11.542 | 0.000[a] |
| Combined ($n = 244$) | Right | S = 36.242 + 5.467 T1 | 0.781 | 0.610 | 5.260 | 10.310 | 0.000[a] |
| | Left | S = 37.310 + 5.404 T1 | 0.775 | 0.600 | 5.331 | 10.449 | 0.000[a] |
| | Right | S = 47.027 + 5.026 T2 | 0.792 | 0.627 | 5.144 | 10.082 | 0.000[a] |
| | Left | S = 48.143 + 4.996 T2 | 0.784 | 0.614 | 5.234 | 10.259 | 0.000[a] |
| | Right | S = 52.982 + 4.960 T3 | 0.762 | 0.580 | 5.459 | 10.700 | 0.000[a] |
| | Left | S = 54.382 + 4.886 T3 | 0.758 | 0.575 | 5.494 | 10.768 | 0.000[a] |
| | Right | S = 60.248 + 4.865 T4 | 0.750 | 0.562 | 5.579 | 10.935 | 0.000[a] |
| | Left | S = 62.510 + 4.759 T4 | 0.752 | 0.566 | 5.553 | 10.884 | 0.000[a] |
| | Right | S = 61.143 + 5.197 T5 | 0.780 | 0.609 | 5.269 | 10.327 | 0.000[a] |
| | Left | S = 67.275 + 4.869 T5 | 0.749 | 0.562 | 5.580 | 10.937 | 0.000[a] |
| | Right | S = 91.618 + 7.919 FPBB | 0.637 | 0.405 | 6.450 | 12.642 | 0.000[a] |
| | Left | S = 93.597 + 7.696 FPBB | 0.606 | 0.368 | 6.702 | 13.136 | 0.000[a] |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball; SEE: standard error of estimate.
[a]Significant ($P < 0.001$).

## Discussion

In this study, significant bilateral asymmetry was found for the T1, T2, and T3 lengths in men, as well as for the T1 and T2 lengths in women (Table 6). Previously, Kanchan et al. [3] found significant bilateral asymmetry for the T1 and T2 lengths in Indian men, as well as for the T1, T2, T3, T4, and T5 lengths in Indian women. Khan and Nataraja Moorthy [9] did not find significant ($P > 0.05$) bilateral asymmetry for footprint measurements among indigenous Melanaus men in Malaysian Borneo; however, they found that the right-left side differences for the T1 and T2 lengths were statistically significant ($P < 0.01$) in women. Moreover, Krishan et al. [7] found significant ($P < 0.01$) bilateral asymmetry for the T2 and T4 lengths among Gujjar men in North India.

In our study, the combined data exhibited greater accuracy in stature estimation from footprint measurements (Table 7). The right T2 length was the most reliable estimator when combined data were used (R: 0.792; $R^2$: 0.627). Tables 8 and 9 show comparative

analyses of the values of $R$ and $R^2$ between stature and different footprint measurements among various populations. In the present study, all footprint measurements were positively correlated with stature. In previous studies, the values of $R$ between stature and a variety of footprint dimensions were also positive

(Table 8). In the present study, the right T1 length in men and right T2 length in women were the most reliable individual estimators of stature, with higher values of $R$ (0.587 in men and 0.506 in women) and $R^2$ (0.345 in men and 0.256 in women). In the study of Egyptian men by Fawzy et al. [1], higher values of



$$S = 94.412 + 3.114\, RTTPL$$
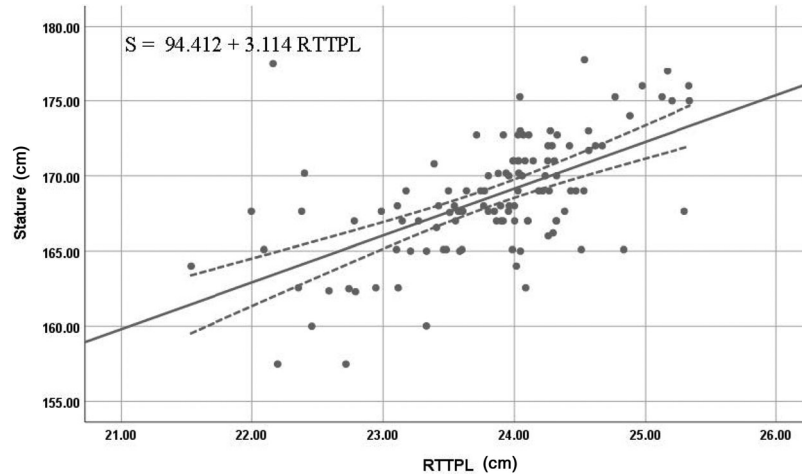
**Figure 5.** Best fit curve to estimate stature from right T1 length in men. RTTPL: right thumb toe-print length. The straight line indicates the best fit line and the dotted line indicates the 95% prediction interval.



$$S = 85.171 + 3.204\, RITPL$$
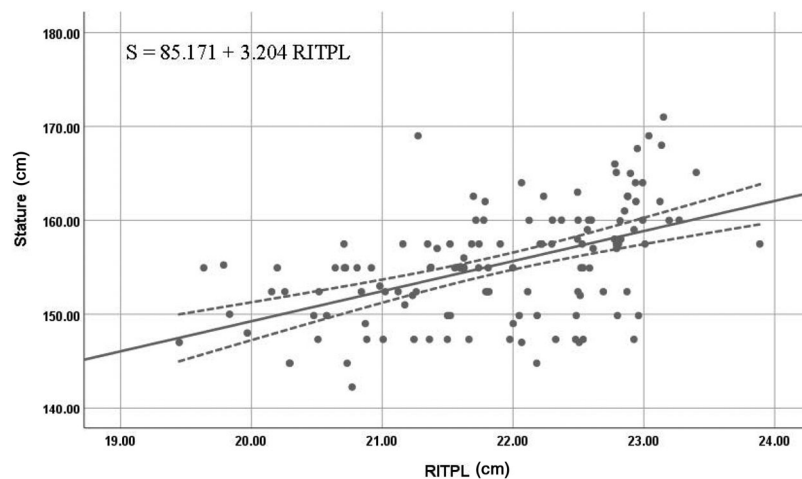
**Figure 6.** Best fit curve to estimate stature from right T2 length in women. RITPL: right index toe-print length. The straight line indicates the best fit line and the dotted line indicates the 95% prediction interval.



$$S = 47.027 + 5.026\, RITPL$$
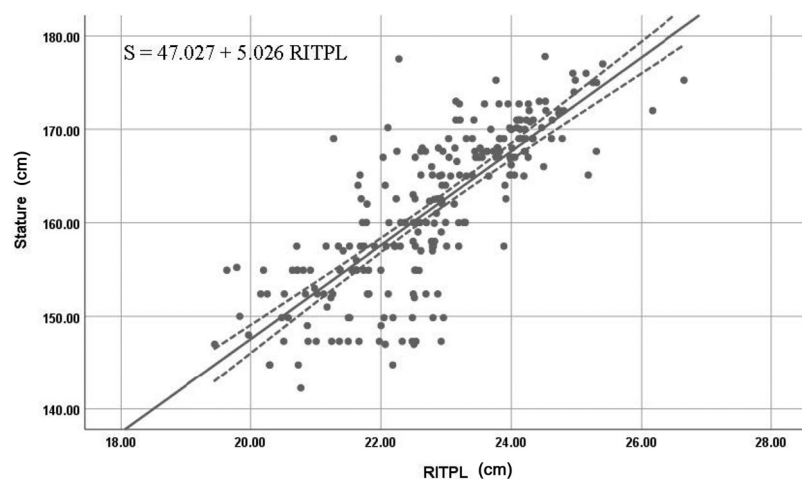
**Figure 7.** Best fit curve to estimate stature from right T2 length using combined data (from both sexes). RITPL: right index toe-print length. The straight line indicates the best fit line and the dotted line indicates the 95% prediction interval.

**Table 8.** Comparison of $R$ values between stature and different footprint measurements among various populations.

| Measurements | Present study | | | | Fawzy et al. [1] | | Hemy et al. [2] | | | | Kanchan et al. [3] | | | | Khan and Nataraja Moorthy [9] | | | |
| | Men | | Women | | Men | | Men | | Women | | Men | | Women | | Men | | Women | |
| | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 0.587 | 0.550 | 0.472 | 0.489 | 0.540 | 0.540 | 0.678 | 0.706 | 0.716 | 0.694 | 0.628 | 0.628 | 0.527 | 0.444 | 0.726 | 0.766 | 0.830 | 0.818 |
| T2 | 0.547 | 0.549 | 0.506 | 0.475 | 0.400 | 0.430 | 0.668 | 0.728 | 0.646 | 0.659 | 0.600 | 0.584 | 0.504 | 0.449 | 0.734 | 0.789 | 0.811 | 0.807 |
| T3 | 0.523 | 0.525 | 0.411 | 0.397 | 0.410 | 0.400 | 0.666 | 0.703 | 0.643 | 0.662 | 0.556 | 0.561 | 0.421 | 0.407 | 0.739 | 0.771 | 0.793 | 0.795 |
| T4 | 0.499 | 0.485 | 0.366 | 0.374 | 0.440 | 0.410 | 0.684 | 0.723 | 0.650 | 0.684 | 0.577 | 0.573 | 0.466 | 0.428 | 0.729 | 0.756 | 0.801 | 0.805 |
| T5 | 0.522 | 0.519 | 0.382 | 0.333 | 0.570 | 0.520 | 0.652 | 0.678 | 0.701 | 0.684 | 0.504 | 0.464 | 0.522 | 0.451 | 0.707 | 0.760 | 0.777 | 0.774 |
| FPBB | 0.380 | 0.388 | 0.252 | 0.193 | 0.040 | 0.210 | 0.427 | 0.507 | 0.296 | 0.259 | – | – | – | – | – | – | – | – |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.

**Table 9.** Comparison of $R^2$ values between stature and different footprint measurements among various populations.

| Measurements | Present study | | | | Fawzy et al. [1] | | Kanchan et al. [3] | | | | Khan and Nataraja Moorthy [9] | | | |
| | Men | | Women | | Men | | Men | | Women | | Men | | Women | |
| | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left | Right | Left |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 0.345 | 0.302 | 0.223 | 0.239 | 0.293 | 0.290 | 0.394 | 0.395 | 0.278 | 0.197 | 0.528 | 0.587 | 0.690 | 0.669 |
| T2 | 0.299 | 0.302 | 0.256 | 0.225 | 0.162 | 0.186 | 0.360 | 0.341 | 0.254 | 0.201 | 0.539 | 0.623 | 0.658 | 0.652 |
| T3 | 0.274 | 0.276 | 0.169 | 0.157 | 0.173 | 0.159 | 0.309 | 0.314 | 0.178 | 0.165 | 0.546 | 0.594 | 0.629 | 0.632 |
| T4 | 0.249 | 0.235 | 0.134 | 0.140 | 0.197 | 0.168 | 0.333 | 0.329 | 0.217 | 0.183 | 0.531 | 0.571 | 0.641 | 0.648 |
| T5 | 0.273 | 0.270 | 0.146 | 0.111 | 0.332 | 0.271 | 0.254 | 0.216 | 0.272 | 0.203 | 0.500 | 0.587 | 0.604 | 0.599 |
| FPBB | 0.145 | 0.151 | 0.064 | 0.037 | 0.094 | 0.064 | – | – | – | – | – | – | – | – |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball.

**Table 10.** Comparison of results among studies concerning stature estimation from footprint measurements via linear regression.

| Study | Sample size | Ages (years) | Population | Parameters | SEE |
|---|---|---|---|---|---|
| Present study | 115 men and 129 women | 18 to 50 | Bangladesh | T1, T2, T3, T4, T5, FPBB | ±3.230 to ±3.690 cm in men and ±5.177 to ±5.889 cm in women, ±5.144 to ±6.702 cm in combined data |
| Fawzy et al. [1] | 50 men | 18 to 25 | Egypt | T1, T2, T3, T4, T5, FPBB, breadth at heel, big toe pad length, big toe pad breadth | ±3.52 to ±4.69 cm in men |
| Hemy et al. [2] | 90 men and 110 women | 19 to 68 in men and 18 to 63 in women | Western Australia | T1, T2, T3, T4, T5, FPBB, breadth at heel | ±4.885 to ±6.439 cm in men and ±5.006 to ±6.926 cm in women |
| Kanchan et al. [3] | 50 men and 50 women | 20 to 25 | India | T1, T2, T3, T4, T5 | ±4.1088 to ±4.4470 cm in men and ±5.2866 to ±5.6838 cm in women |
| Khan and Nataraja Moorthy [9] | 105 men and 105 women | 18 to 59 | Melanaus indigenous population of Malaysian Borneo | T1, T2, T3, T4, T5 | ±3.506 to ±4.037 cm in men and ±3.316 to ±3.785 cm in women |

T1, T2, T3, T4, T5: the distance from the mid-rear heel point to the most anterior point of thumb toe, index toe, middle toe, fourth toe, and little toe, respectively; FPBB: footprint breadth at ball; SEE: standard error of estimate.

$R$ (0.570) and $R^2$ (0.332) were found between stature and right T5 length. In a Western Australian population [2], the left T2 length in men and right T1 length in women were the most reliable estimators (R: 0.728 in men and 0.716 in women). In an Indian population [3], the left T1 length was the most reliable individual estimator in men (R: 0.628, $R^2$: 0.395); in Indian women, higher values of $R$ (0.527) and $R^2$ (0.278) were found between right T1 length and stature. In the Melanaus indigenous population of Malaysian Borneo [9], the left T2 length in men and right T1 length in women were the most reliable estimators of stature (R: 0.789 in men and 0.830 in women; $R^2$: 0.623 in men and 0.690 in women).

Table 10 shows a comparison of studies regarding stature estimation from footprint measurements, using simple linear regression analysis. In the present study, lower values of SEE were able to estimate stature, using linear regression models. The values of SEE varied from ±3.230 to ±3.690 cm in men, ±5.177 to ±5.889 cm in women, and ±5.144 to ±6.702 cm in the combined data. In Egyptian men [1], SEE varied from ±3.52 to ±4.69 cm. In a Western Australian population [2], the values of SEE varied from ±4.885 to ±6.439 cm in men and ±5.006 to ±6.926 cm in women. In another Indian population [3], SEE varied between ±4.1088 and ±4.4470 cm in men and between ±5.2866 and ±5.6838 cm in women. In the Melanaus

indigenous population of Malaysian Borneo [9], SEE varied from ±3.506 to ±4.037 cm in men and ±3.316 to ±3.785 cm in women.

## Conclusion

This study developed regression formulae to estimate stature from footprint measurements in Bangladeshi adults. The present investigation revealed that human stature can be estimated with reasonably accuracy from footprint measurements in the Bangladeshi population. The findings of this study will be useful in forensic research and crime investigation by law enforcement agencies. The age range of this study was large; therefore, future studies should be performed in specific age groups.

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## Authors' contributions

The study concept and design were outlined by Md Asadujjaman, Md Harun Or Rashid and Md Sohel Rana. Data were collected by Md Harun Or Rashid and Md Sohel Rana. Data analysis, interpretation and manuscript writing were performed by Md Asadujjaman, Md Harun Or Rashid and Md Sohel Rana. All the critical reviews were conducted by Md Asadujjaman and Md Mosharraf Hossain.

## Compliance with ethical standards

The data were collected anonymously from those subjects who gave oral consent for acquisition of body measurements and publication of the study findings. A written consent records the identification of the subjects participated in the study to ensure the anonymousness oral consent was taken. The Human Research Ethics Committee, Rajshahi University of Engineering & Technology ethical granted approval to this study with the participants' oral informed consents.

## Disclosure statement

The authors declare no conflict of interest.

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